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MAXIMUM POWER POINT TRACKING ALGORITHMS PERFORMANCE COMPARISON FOR PHOTOVOLTAIC SYSTEMS UNDER A WIDE RANGE OF DYNAMIC PARTIAL SHADING CONDITION

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Abstract

In the recent decades, the prolonged and increasing energy demand has caused a significant progress in the renewable energy enhancement and production. Photovoltaic (PV) energy is a fair option each time more considered and developed around the world, becoming more and more a viable option due to the economy of scale and the worldwide rising interest in clean and sustainable energy. PV energy harvest and management has great advantages but some clear inconvenient issues, such as the poor efficiency energy conversion that can be originated as a result of the optical and electrical losses. Within these losses, the first one is usually the most complicated to deal with due to the random component bound to its cause, the partial shading problematic. Therefore, shading mitigation techniques appear as an integrated part of the power converting unit, trying to palliate the negative effect on the extracting power efficiency. Up to now a wide range of diverse methods have been proposed and tested through all the literature, even though all these techniques have their own weaknesses. In this thesis work the study of an efficiency comparison of a set of several maximum power point tracking techniques over a wide range of shading speeds through a MATLAB simulation, where it is designed a PV array configuration in three different setups arrangements under some diverse partial shading scenarios is proposed.

Keywords: Photovoltaic (PV), maximum power point tracking (MPPT), deterministic algorithms, stochastic algorithms

Sommario

Negli ultimi decenni, la prolungata e crescente domanda di energia ha portato a progressi significativi nella produzione di energia rinnovabile. L'energia fotovoltaica Ã¨ una soluzione efficace, sviluppata e diffusa in tutto il mondo, dirigendosi verso logiche di economia di scala, a supporto dell'interesse mondiale per un'energia pulita e sostenibile. La raccolta e la gestione dell'energia fotovoltaica offre grandi vantaggi, ma ci sono alcuni aspetti problematici relativi ad esempio alla scarsa efficienza energetica. All'interno di queste perdite, il primo problema Ã¨ l'ombreggiamento. Pertanto, le tecniche di attenuazione dell'ombreggiatura appaiono come parte integrante dell'unitÃ di conversione dell'energia, cercando di attenuare l'effetto negativo sull'estrazione dell'efficienza energetica. Fino ad ora una vasta gamma di metodi diversi sono stati proposti e testati in tutta la letteratura, anche se queste tecniche hanno i loro punti deboli. In questa tesi si propone una serie di tecniche di tracciamento del punto di massima potenza su una vasta gamma di velocitÃ di ombreggiatura attraverso una simulazione MATLAB, in cui Ã¨ progettata per la configurazione di array FV in tre diverse configurazioni in alcuni scenari di ombreggiamento parziale.

Keywords: Fotovoltaica, tracciamento del punto di massima potenza, algoritmi deterministici, algoritmi stocastici

CHAPTER 1

Introduction

Renewable energy sources are currently increasing while it exists an intentionality and trend towards reducing the wide world clear dependence on conventional sources. In addition, there is an exponential increment in the energy demand by population which implies a counter clock race in the energy supplying industrial development, more specifically in the renewable energy field.

Among all renewable energy sources types, solar energy could be the answer to the mid-long-term future problems with energy supplying around the whole world. It is by far, the strongest source that feeds life on Earth, yielding only in the low stratosphere surface a quantity equivalent to thousands of times the global energy demand of the whole civilization. It seems that developing the harvest systems towards solar energy could be the most logic answer to the main problem of the population growing.

Within all the main characteristics of solar energy, the most important ones to take into account are its reliability, the relative facility to be stored and, of course, the fact that it is the cleanest energy that can be found nowadays, universal and free of cost. Moreover, it is atmospheric friendly and the operational and maintenance costs are relatively low [1], making it attractive not only to investors in the energy field related to grid connected systems, but also to particular citizens that wish to complement their energy source system or even installing a stand-alone PV based system into their homes, since this kind of system amortizes in a quite short period of time.

There exist two main ways to collect solar energy. The solar thermal plants and the photovoltaic cells-based plants. Even though the boom of renewable energies is quite recent, there are already some other systems under study to gather and store solar energy, such as the combustible liquid that captures the photons to energize its molecular form, transforming it into its isomeric shape and being able to maintain this energized form during almost two decades [2].

Anyway, the most used type right now and at least for several years on, are the photovoltaic-based plants. The direct conversion of solar radiation into electrical energy by PV cells has a considerable amount of positive aspects and advantages [3]. However, the optimal extraction of this energy demands a right control of the whole PV system due to the challenge of the energy fluctuation. Therefore, to grant an efficient generation of power, diverse techniques are used. Within them, the most used in the recent years are the maximum power point tracking, MPPT, which predict and track the maximum power point, MPP, at every environmental circumstance, forcing then the PV system to work on that MPP.

In this context, the main objective of this master's thesis is to analyse a diverse set of MPPT techniques, to compare how is their behaviour towards an external scenario that modifies the maximum energy that the PV systems receive, that is the shadow shape which covers the array configuration of solar panels. Furthermore, the range of the shadow dynamism is defined in a quite wide range in order to show which MPPT technique is more successful according to the speed dynamics.

In the second chapter a quick review of the existing literature is provided, specifically about the diverse MPPT techniques that are more used nowadays.

The third chapter describes briefly the functioning of the PV cell and the main mathematical models of the PV cells that are used to simulate it. One of them is chosen to show the curve shape generated and its behaviour towards the external parameters that affect it the most.

The fourth chapter shows the solar panel configuration and the PV array configuration. It also describes the main PV systems configurations based on their distribution and the power converter used. Finally, the partial shading issue and a physical solution approach are presented.

The fifth chapter presents the list of MPPT techniques used and their operative flowchart, then the main functionality of the whole simulation it's explained and its code stages are detailed.

The sixth chapter collects and analyses the data obtained in the simulation, accompanied with the necessary tables and plot charts obtained by MATLAB.

A closure is written in the seventh chapter, drawing some conclusions and considerations in reference to the project results.

CHAPTER 2

Literature Review

The output energy corresponding to a defined photovoltaic system configuration may be modified according to the external parameters, such as temperature, irradiation, wind and humidity, being the two first parameters the most important to consider in the PV control system design.

This energy fluctuation is seen in the power curve corresponding to the PV array and can modify its shape in different ways, moving the MPP bound to a duty cycle of the power converter. Once this MPP is moved, the maximum point of power is not extracted any more, and for countering this issue, a set of MPPT control algorithms have been developed the last decades.

These MPPT techniques can be separated by groups based on their characteristics, such as the control variable and the converter that they use, their accuracy, their efficiency, the application used to implement them and the algorithm method category. In the next sections, the most usual and actual MPPT techniques are described by their algorithm type category, which are: conventional (deterministic algorithms), soft computing (stochastic algorithms) and others (unusual algorithms).

2.1 MPPT techniques for partial shading effects mitigation

Generally, the MPPT conventional algorithms use one or more electrical parameter references to compare with the system values obtained by the sensors in some of the power system electrical characteristics. In this way, the error of the closed loop control system is computed and the corresponding corrections are done.

In a more complex way, stochastic algorithms use several time steps to create a set of values, or family of values, and apply the algorithm corrections to generate the next family of the value set, until the system reaches the convergence point.

The common point in the whole pack of algorithm types is that they must find the system work MPP and hence achieve the maximum efficiency possible of the whole system.

2.1.1 Deterministic MPPT algorithms

This algorithm category is mainly based on a simple cause-effect principle.In most cases, it uses a two-step measure comparison, basically determining how the system reacts after applying a perturbation into it and finally acting in consequence, according to the algorithm definition.

In general, literature coincides in the fact that this kind of algorithm has an adequate performance in cases where the power curve that represents the PV array configuration has a unique maximum or, in other words, where the system can be found in a surrounding where the irradiation is constant and homogeneous in the whole PV panel region.

The next subsections are presenting then, the algorithms that fits better regarding uniform irradiance condition.

Perturb and observe: Fixed perturbation step

This method, that is based on the trial and error process, measures the actual PV power and then perturbs the operating point by moving the operating voltage at each time cycle. From each two time-steps, it monitors the variation of power and actuates in the next perturbation according to this power variation.

If the power increases, the next perturbation will follow the same direction or perturbation sign, whereas if it decreases it shall change the perturbation direction. This simple operation is done in a cyclic way until the MPP is reached, that is $dP/dV = 0$. Once the tracker reaches the MPP, it oscillates around it, depending this oscillation amplitude on how big the perturbation step is.

Several authors have studied this basic MPPT, sometimes to enhance their weak points as in [4], and sometimes to compare it with other MPPT techniques [5], using the first one as a base reference since it is one of the most usual method applied.

Perturb and observe: Variable perturbation step

This technique proposes substantially the same than the one seen before with the only difference found in the duty step change ratio, which depends on the output reaction to the perturbation. In this way, the duty step ratio is modified according to the next equation,

$$\Delta D(n) = \alpha * \frac{(P(n) - P(n-1))}{(V(n) - V(n-1))}$$

where alfa is a weighting parameter, that depends on the PV system model. The sign of this perturbation will follow the same idea, as in the fixed perturbation step.

This variation works appropriately under changing environment since its performance in tracking the MPP is quite fast and the oscillation in the steady-state is low. However, this advantages towards the fixed step Perturb and Observe are compensated with its extra computational load. So it results in a trade-off between accuracy and complexity.

In experimental results, shown in some literature, it is concluded that the proposed algorithm can give significantly faster tracking speed than the conventional P&O method [6].

Perturb and observe: Three weigh point

This method compares three perturbation points instead of two, as in the most common P&O algorithm. It measures the current operating point, A, the next operating point, B after perturbation, and the third one, C, which is double perturbated in opposite direction and from B reference point. The nine possible different scenarios are shown in figure 2.1, from author [7], where the status parameter M gains a positive weight if B is equal or greater than A or if A is bigger than C, and it gains a negative weight if B is smaller than A or A is smaller than C.

The final duty cycle change rate will be defined as A, B or C if M is equal to 0, 2 or -2 respectively.

This method has the advantage to avoid the oscillations found in two perturbation P&O and is also considered in literature as a fast tracker method compared to the fixed step P&O.

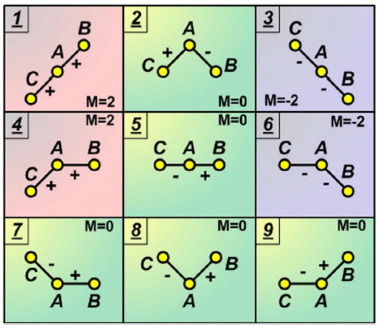

Figure 2.1: *Three weight point scenarios*

Perturb and observe: Power curve slope

This method is specially defined into partial shading scenarios. The main core of the Perturb and Observe code is executed while the shading condition is null, therefore in this moment, any type called above of Perturb and Observe technique based program is used, whereas regarding partial shading condition the global peak searching subroutine part is executed until a criteria condition is achieved.

The searching path is defined through dP/dV sign and the likelihood to start a new global peak tracking depends on the best power peak tracked in a defined period of time. As soon as the new power tracked surpasses the hypothetical local power peak, the algorithm deviates into the conventional Perturb and Observe configuration, doing a normal tracking inside the global peak region. Once the duty cycle reaches the MPP, it oscillates around it, as in the normal case.

This type could be defined as a combined algorithm class, but both routines of the code are done with the Perturb and Observe mechanism basis. In other words, the global peak seeking part is also done as a Perturb and Observe method. Author [8] proposes this method and tests it.

Incremental Conductance: Fixed perturbation step

Incremental conductance method is based on the MPP found in the power curve that can be computed with the partial derivate of the function respect to the voltage. That is the equation 2.1.

Hence, the position of the working point is defined in the MPP or in the left or the right side of MPP according to the sign of dP/dV. This sign of dP/dV is represented in the equation and inequations seen below:

$\left(\frac{\Delta I}{\Delta V}\right) = \frac{-I}{V}$, at MPP

$\left(\frac{\Delta I}{\Delta V}\right) > \frac{-I}{V}$, at the left of MPP

$\left(\frac{\Delta I}{\Delta V}\right) < \frac{-I}{V}$, at the right of MPP

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\left(\frac{dI}{dV}\right) \approx V\left(\frac{\Delta I}{\Delta V}\right) \tag{2.1}$$

This technique is also a well know studied method and can be found in several papers. Author [9] proposes an enhanced incremental conductance technique and author [10] makes a comparative study between IC and P&O.

Incremental Conductance: Multi-tracking duty cycle

This modified method is based on the IC main definition but using three tracking particles simultaneously, applying the IC concept. Once all peaks are found, they are compared with a threshold value to discard the local peaks and the global peak duty cycle value is saved.

Therefore, it is a modified method that can be used in both scenarios, with full irradiated region and with partial shading.

The drawback of this method is the relative slow tracking of the MPP. Hence, the correct algorithm part must be used depending on the scenario situation, that is, tuning correctly the criteria threshold values that will define the electrical condition found under the diverse shading scenarios which will demand, or not, the global peak seeking sub-routine.

This application can be found in [11] where the author proposes and tests in hardware this technique.

Fractional Open-Circuit Voltage

This indirect conventional control method uses the widely observed relationship between the PV output voltage at the MPP and the V_{oc}, which are linearly proportional in a full irradiating scenario. The relationship is given in the equation 2.2, where the proportional constant k_{oc} depends on the PV module characteristics, the cell technology and the climatic conditions. Even though it has several dependences, the constant is usually chosen in a specific case and used for a wide range of climatic conditions. Therefore, in this method the extracted power is not maximized a priori. Typical values of the constant V_{oc} are between 0,73 and 0,80 with the actual technology used in PV systems.

When the algorithm is operating, it matches the theorical V_{MPP} as the reference voltage and it refreshes its value each time it reaches a determined number of time steps. This refreshing is done by calculating the V_{oc} which implies to open-circuit the system, with its corresponding loss of power, due to the time that it is disconnected. However, the simplicity of this algorithm implementation makes it viable for an MPP tracking, and even more viable in cases where climatic variations are minimal.

Author [12] proposes this method as a VMPPT in a full irradiation scenario.

$$V_{MPP} = k_{oc} V_{oc} \tag{2.2}$$

Fractional Short-Circuit Current

In a similar way to the open-circuit voltage tracking, this method uses the observed fact of the linear dependency between the PV current at MPP and the short-circuit current. Its relationship is also similar to the last method and is shown in the equation 2.3, where the constant k_{sc} is normally considered in a range around 0,85 and it depends on the PV system, the cell technology used and the climatologic conditions once again.

It also shares with the last method the negative aspect that causes the I_{sc} value scanning, due to the short-circuit of the whole system. While this happens, there is a loss of power which makes it less efficient than other kind of method in this aspect.

Furthermore, it has a constant value that is imposed based on some strict conditions and then, it can not assure its correct accuracy in different climatic conditions which is also a disadvantage in terms of efficiency.

As in the last technique, its simplicity makes it a fair method to implement a MPPT. With respect to the system parameter changes due to the aging, the short-circuit technique, like in the open-circuit technique, can overcome easily this problem with low maintenance, since the refreshing aspect of the algorithm uses the true and actual parameters of the system.

Author in [13] proposes and tests this method experimentally.

$$I_{MPP} = k_{sc} I_{sc} \tag{2.3}$$

Constant Voltage

The constant voltage method is the MPPT control method with the highest level of simplicity. The operating voltage point is compared at each cycle with a constant voltage reference, making the working point to stay near this match point all the time. The reference voltage is set as it is done in the open-circuit voltage method but this time there is no control on a linear relationship that depends on some conditions of the PV system. That is, the system is not able to notice a change related to the V_{oc}, which implies a higher error toward changes in an external way but also in an internal way. This last point means that in case of a system deteriorating, with their parameters modification involved, the tracker will still chase an even more wrong point related to a previous parameter state of the system.

It makes this system, on the one hand, the simplest one to realize, but on the other hand, the minimal changes, in the external or internal system, will generate a high loss of accuracy in the tracking issue and, therefore, a high loss of efficiency on the whole system. Due to these points, this kind of method is used to be implemented as a part of a combined tracking system with another method too. In this way, it is used as a fast-early point tracker, leaving the accuracy tracking to the next method once the working point is close enough to the MPP region.

As in the open-circuit and short-circuit methods, constant voltage method is highly recommended to be used only under full irradiation scenarios.

Author [14] tests this method performance under different irradiation and temperature conditions.

2.1.2 Stochastic MPPT algorithms

Some conventional MPPT algorithms have been described. As in a typical deterministic algorithm method from this family, they have the enormous advantage of finding a global optimum of the required function. Unfortunately, the multiple local maxima function presents an extra issue to the tracking method, for which this kind of algorithm isn't usually prepared for.

Depending on the situation, the setup configuration and the partial shading conditions, a complex power curve shape will be generated, which will contain one or more maxima. Therefore, the previous presented tracking methods, will have a chance to fail in the mission to find and follow the optimal electrical reference that involves the maximum extracted power of the photovoltaic system. If the point selected is not the optimal one, the system can experiment a high decrease of power extracted which, after a several amount of time, implies a low efficiency and a lesser rentability of the inversion.

To overcome this problem, a new type of algorithm is used, the stochastic MPPT algorithm type. This kind of algorithm samples the searching space of the function, exploring the full range of the function solutions instead of doing a sequential exploration as in the perturbation and observing method.

Nevertheless, it can not always guarantee the optimal solution, since it is a method that depends in a certain way on the probability and uses pseudo-randomness in its way to find out the global maxima. In the end, it is indeed a fair approach that can increase the chance to hit the correct point and, on average, improve the efficiency. If it is well designed and implemented, it shall find out most of the time the optimal point that corresponds to the MPP. Of course, it will depend on the type of the power shape too, being some of them more or less easy to be tracked with this kind of MPPT algorithm.

In relation to the stochastic methods, there can be found several types of them which mostly appeared in the recent years due to the wide spread of computers in the last decades. Therefore, until the last 50 years, only deterministic methods were being used.

The high quantity of variants for each type of stochastic algorithm is due to their application focus, that can be completely different depending on the study scenario. Then, they can be slightly modified to be adapted to a specific case and, consequently, appearing in so many different ways to represent them. However, the main core basis is always the same and normally represents and emulates a natural behaviour easily observed in this world.

In a general point of view, they are usually classified as heuristic or meta-heuristic algorithms, which are learnt with a rule of thumb basis and not following a tough underlying theory. Even though the background theory is quite behind regarding the applicability, their results are fair good.

Particle Swarm Optimization (PSO)

In nature, some species' behaviour moves around the cooperation to reach a better survival capacity. Generally, in information gathering, they take profit of their own knowledge but also of their group members' knowledge and the past memory of their own learning and the social or group learning too. This type of social behaviour allows a fast information exchange and an even faster reaction to avoid dangers or to find the best pathing while travelling, for example.

This statement is observed in swarms of animals like in fish schools or flocks of birds, creating that typical ordered and fluent cooperation phenomena that seems to be alive per se. That can be also called emergent phenomena, where the final result of the cooperation activity of several individual particles is completely different to the individual skills of them (another example seen in nature is the human brain functionality, where single neurons have well-defined and unique purposes, but the activity of the full neural network creates a quite known emergent phenomena, the consciousness).

Taking into account this phenomena, the Particle Swarm Optimization algorithms are based on the same core ideas, where some particles collaborate as a whole to find the best possible solution to a problem, also known as maxima or minima of an objective function. Each particle, which is a potential solution of the objective function of the problem, knows the position of the best solution ever found by the swarm and of the best solution ever found by itself.

Author in [15] proposes and tests this method with different numbers of particles and compares it with a wide set of MPPT techniques.

Genetic Algorithm (GA)

Also known as evolutionary algorithm (EA) that is based on the evolution theory of Darwin, which exposes, in few words, that the strongest survive and the weakest die, leaving every time a stronger living being more able to survive and to procreate.

In the GA context, this can be compared to the optimization of an objective function as in the previous stochastic algorithm. The power curve is the function to be tracked and the 'genes' are the positions (duty cycle values) attached to a value (chromosome). Therefore, the idea of the algorithm is that the strongest genes (closer to maxima or minima) are supposed to survive and procreate, while the weakest just disappear. Every crossover of the genes creates a new potential set of solutions that may mutate and hopefully will be better than the previous ones.

This algorithm uses this point iteratively until the genes reach a solution region where is close enough to the maxima, or in other words, they converge into the same gene code which can not get a further enhancement (optima reached).

In citeShaiek2013, the author proposes a GA method and compares it with some conventional algorithms.

Ant Colony Optimization (ACO)

This evolutionary algorithm is another nature-inspired algorithm. An ant colony behaviour with the environment can also be explained with the concept of emergence named before. It uses a group information sharing to define the best possible pathing to find a food source and move it to the ant-hill.

The algorithm ACO based code uses this idea, which basically consist of stigmergy, evaporation and errors. Firstly, the particle integrant of the family group (ant/duty cycle value) communicates by leaving global information in its environment (stigmergy) under the form of pheromones (odours) that will evaporate with time. Then, ants check an initial position. If there are no pheromones, they move around randomly. On the other hand, when there are pheromones in the track, ants tend to follow them, proportionally depending on the quantity of pheromone concentration that they find in that region of the path. If the ants finds food, they go on walking randomly while leaving a pheromone trail, therefore creating a new track for the next ants. The trails that follow by more than one ant is reinforced (convergence in the optima).

In conclusion, this type of algorithm is robust and has a great adaptability due to the nature of its information sharing. The volatility of the solution trail makes ants to stop pathing the old pheromone trail since it starts disappearing, until it does not exist anymore. Hence, it can be a nice shot into modifying phenomena scenario.

Author [16] proposes this method as an optimization algorithm and compares it with the metaheuristics algorithms.

Artificial Neural Networks (ANN)

ANN technique is inspired by the central nervous system, that is, the brain. This computational model generally defined through three or more layers, depending on how deep and complex is the network, is able to machine learning and, in this case, to generate the relationship between the input layer, with V_{oc}, I_{sc}, time and some environmental characteristics as input parameters, and the output layer, being the MPP voltage reference the output parameter.

The middle layer or set of middle layers, is the hidden layer, a black box which is defined through the network training. Once the neural network is trained, it is used to minimize the error between the expected output power and the obtained one, in a wide range of different shading conditions.

The possibility to adapt towards diverse parameters depends on the input parameters and the deepness of the hidden layer. However, the trade-off between the complexity of the system and the cost of it must be considered, not only the quantity of middle layers but also the number of sensors required for the input parameters.

The example of a neural network is shown in figure(2.2).

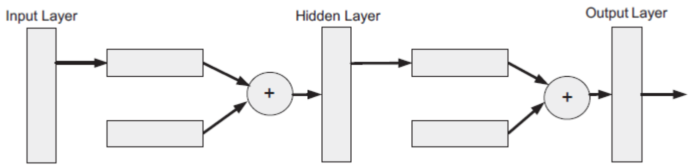

Figure 2.2: *Artificial Neural Network*

Fuzzy Logic Controller (FLC)

Fuzzy logic is a group of multiple-valued logic, where they have two states: true or false. Hence, the logic variables have values from zero to one, which also involve the partial truth zone.

The fuzzy logic controller operates in the main following stages:

- Fuzzification: Stage where the numerical values (in the study field voltage and power are the ones generally used) are converted into linguistic variables.

- Fuzzy rule base: Input-output conditions to the main variables are stablished according to some parameters.

- Defuzzification: The variables are converted back to numerical variables as a multivariable function.

Therefore, the result of the fuzzy logic is a black box function which correlates, through a combination of logic definitions, the output value of interest (MPP reference voltage) with the different ranges of the parameters pre-defined (irradiation, temperature...) bound to the values of interest(power and voltage of the system).

This method allows a fast tracking response. However, it can not work appropriately in shading condition unless a pre-searching stage of the global peak region is done.

In [17], author uses a ANN-FLC based controller to track the MPP under partial shading conditions.

Combined MPPT algorithms

Stochastic algorithms provide the system with an extra robustness against partial shading, but at the same time, makes it less efficient in diverse scenarios. A diverse way to treat this searching control system is to take advantage of the two different algorithm types mentioned before, using the stochastic one to avoid the approximation to an incorrect local maxima, and then using the deterministic method to maintain the system inside a close and narrow region that contains the global maxima.

Only if there is a strong modification the system must test the new power curve shape with the stochastic method, otherwise the deterministic method is maintained to find the new global maxima that has varied in an insignificant quantity, keeping a higher efficiency on the system, since deterministic are generally faster and more accurate.

Therefore, this method is a combination between a main routine code, the conventional algorithm, and the subroutine code that triggers each time a new power shape is required to be tracked, looking for the region that contains the MPP.

2.1.3 Other MPPT algorithms solutions

This last section includes the techniques that are not so used compared to conventional or stochastic but still have interesting performances and can find per se the MPP or help to find the global peak region in a multiple peak objective function as a pre-stage subroutine.

Look up table

In this method the knowledge of the PV system is used, comparing the electrical parameters measured in the actual time step with this information (look up table) and choosing the voltage reference bound to the MPP in those conditions.

The more knowledge is contained, the more efficiency and accuracy is reached in more scenario types. However, there are some drawbacks. On the one hand, the aging of the PV system requires to refresh the data in the look up table method to avoid excessive error, and on the other hand, the changes in environment must be controlled to maximize its efficiency. Therefore, in high dynamic conditions or in fast changing scenarios can not be the adequate method to be used.

To these drawbacks, must be added the requirement of the storage memory, which will also rise the average cost of the system.

Window search

Window search technique also uses the knowledge on the system, to narrow the range where the search is done, predefining the voltage range or duty cycle that will be used in the algorithm. It can be used as a pre-searching method inside a conventional or even a stochastic technique, speeding up the convergence of the algorithms.

Fibonacci search

The well-known Fibonacci sequence (0,1,1,2,3,5,8...), generated by the sequence sum of a number which is the sum of the two previous numbers and which, actually, is quite seen in the whole nature as the proportion between the sizes of shapes found in animals, plants and minerals, is used in this tracking technique.

The value of the searching distance between one time step and the next one is defined by the numbers found in the Fibonacci sequence and the shifting direction depends on the difference between two sequential output power measures.

Therefore, this method has a point in common with the Perturb and Observe with variable step, in which the searching step increases fast until overpassing the MPP. Then, the direction swaps and the Fibonacci number is reinitialized as a low number. The oscillation around the MPP gets smaller until it reaches the convergence criteria, which can be bound to the minimum error between the duty cycle range or the output power range in two different time steps.

Although this method is a robust and fast technique when searching a global peak, it shall not be used for a multiple peak searching, since it can not notice if the maximum found belongs to a global or to a local maximum.

Direct search with Lipschitz function

This method is able to track the global maxima in a partial shading scenario as in the full irradiated one, using an algorithm bound to the Lipschitz function that encloses the searching area inside the objective function in rectangles (two particles defining a rectangle in the objective function), each iteration getting narrower until the convergence criteria is found.

The first rectangle region is divided in sub-segments which are evaluated and defined as a potential optimal interval. This new region is treated in the same manner until the region is small enough to reach the minimum error threshold defined in the stop criteria.

Segmentation search

This technique is used as a pre-tracking method, searching the region where the global peak can be found. The objective function is divided into different segments using a fixed distance between them and evaluated in each point.

This technique can be used in both cases, full irradiating and partial shading condition, and its performance depends on the number of segments used, being a high number the best way to assure the correct global peak region, but consuming more time to achieve this goal.

CHAPTER 3

Solar Cell

3.1 Physic principle

Solar, or photovoltaic, cells can transform solar energy into electrical energy. For that purpose, they rely on the photoelectric effect of the material they are made of, which consist of the ability to emit electrons while a beam of photons is irradiating its photoelectric material region.

The typical material used for the cell fabrication, within the characteristic just named above can be found, is the silicon, a quite known semiconductor which has a mixed type of properties seen in metal and insulator material, which makes possible the phenomena that causes the photoelectric effect.

The material configuration is basically based on the same use for diodes. It is made of a p-n junction, which contains two different layers, where each one has been doped in a different way. The n-type part is the positive side. Since it has been doped with a molecule with more than four electrons in the last valence layer, typically phosphor, the combination generates an extra electron which is ’free’. On the other side, the p-type layer, a different doping is used, where the doping molecule has less than four electrons in the last valence layer, leaving, in this case, a 'hole', or in other words, the last valence layer of the combination lacks one electron.

In this way, the two-layer junction develops a region called depletion layer in the junction zone, where free electrons have occupied the holes, while the n-type zone has become positive due to the loss of the free electrons and the p-type zone negative due to the loss of the holes. Then this depletion layer is already formed and a slightly electrical field between the two sides is generated, impeding the move from more free electrons from the n-type region to the p-type region [18].

Finally, to generate current, it is necessary to apply extra energy, incoming from the photons, into the depletion layer. If this energy is enough to overcome the threshold of the silicon bandgap, an electron-hole pair will be generated, which will be separated by the electric field that exists between the two layers.
If the circuit is closed, electrons can travel through it and a continuous current is generated (Figure 3.1).

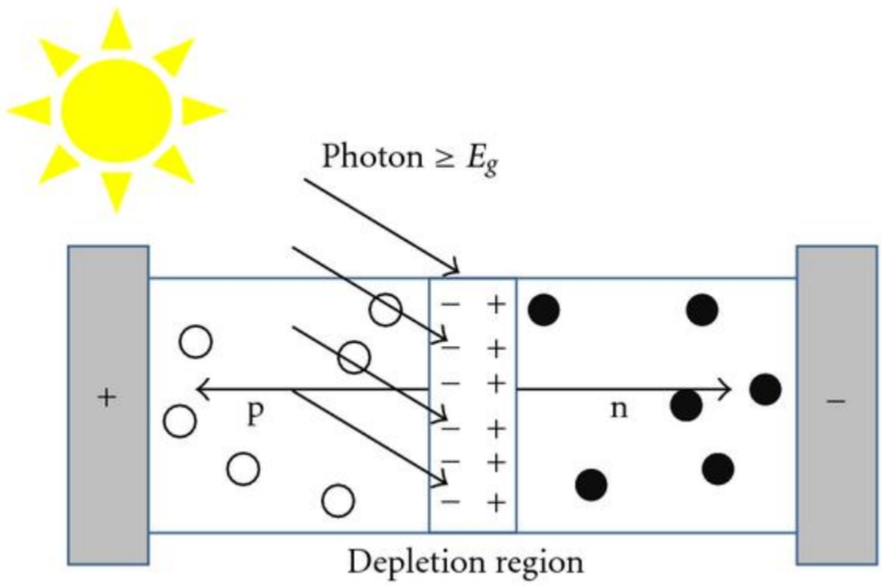

Figure 3.1: *p-n junction*

Although, silicon technology is the most used, and there is a tendency to use it even more while technologies advance through this era, other technologies and different ways to dope the materials exist. CdTe and CIGS, which actually have improved at the same level (and at the level of Silicon cells) their efficiency to transform solar energy in the last 50 years (from a 5% to a 20% approximately in all cases), they still represent less than a 10% of the total materials used for the cell fabrication [19], (Figure 3.2).

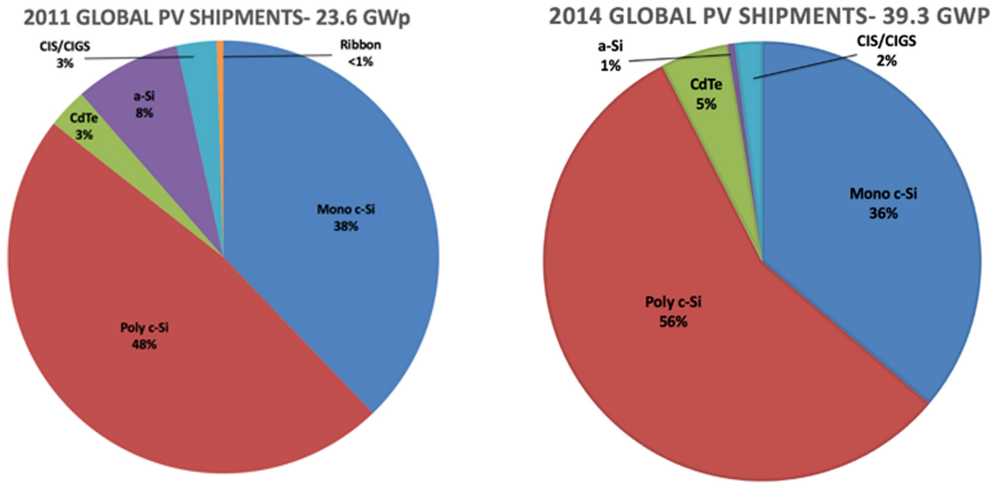

Figure 3.2: *Cell fabrication materials*

The way the use of these materials have been distributed and the tendency of the user along the time, depends basically on the utility and the cost of the material type:

- The monocrystalline silicon (Mono c-Si) is the most efficient material. Its wafer is made by single crystals with uniform properties and are obtained by a complicated and expensive procedure which make this material quite expensive.
- The polycrystalline silicon (Poly c-Si) has a structure that is less ideal than monocrystalline and therefore it has a relatively lower efficiency. Hence, its properties are a bit worse, however, its cost is not so expensive.
- The amorphous silicon (a-Si) is the easiest to manufacture but it has low efficiency.
- CIGS material has an efficiency quite close to the polycrystalline silicon and the manufacturing procedure is relatively cheap. Its principal problem is the toxicity and shortage of the material, and the cost of the main base material for its manufacturing, indium, which is by far less found in the earth and it's also used in other products and therefore much more demanded.
- CdTe is a relatively expensive material with a complicated manufacturing procedure. It has a quite high efficiency, but the technology handicap makes it unfeasible for a normal project. However, it can find good use in space projects where the cost is not the main factor.

Consequently, it is obvious the trend of this distribution, where Poly c-Si and Mono c-Si clearly win the rest of the materials and they tend to be more used. Anyway, it is important to consider high edge technology, since more and more this renewable energy is starting to be considered around the world and its components are more studied. Much more materials are currently being developed and at any moment a new one that overwhelms the characteristics of the rest in all aspects can be discovered. Even considering the inertia of the market, a brand-new technology would be able to displace the actual one in a few years.

3.2 Equivalent model circuits

The different ways to represent mathematically the solar cell model have, generally, and as it can be seen in all mathematical models, a clear trade-off between its complexity and the accuracy with respect to the real model. It this case, 3 parameters model up to 9 parameters model are compared. On the one hand, 3 parameters model is the easiest to implement but at the same time it is the worst given that it can not achieve an accurate representation of the real model, and on the other hand, 9 parameters model is the hardest to implement, but the best representation of reality model as the parameters used are well defined by the manufacturer.

That is, in fact, another point to be aware of. The more parameters contains the model, the bigger the quantity of variability and error will be. As it can be found in literature, the 5 parameters model is the most used, since it has a fair trade-off compared to the rest of the mathematical models [20] and, therefore, it will be used in the simulation. In the next section a more detailed explanation about the different models will be made, and the meaning of the diverse parameters will be analyzed.

In Table 3.1 a summary of the different models approach with their respective parameters can be seen.

Table 3.1: *Table caption*

Model	No. of parameters	Parameters
Ideal single-diode model	3	I_{ph}, I_{d1}, n_1
Single-diode R_S model	4	I_{ph}, I_{d1}, n_1, R_S
Single-diode R_{Sh} model	5	I_{ph}, I_{d1}, n_1, R_S, R_{Sh}
Two-diode model	7	I_{ph}, I_{d1}, I_{d2}, n_1, n_2, R_S, R_{Sh}
Three-diode model	9	I_{ph}, I_{d1}, I_{d2}, I_{d3}, n_1, n_2, n_3, R_S, R_{Sh}

In the 'Parameters' column, the parameters used in each model can be seen. Summarizing, I_{ph} is the photocurrent, I_{di} is the reverse current of each diode, n_i is the ideality factor of each diode, R_S is the lumped series resistance and R_{Sh} is the shunt resistance.

3.2.1 Ideal single-diode model

This model represents the ideal circuit model of a solar cell. It can be represented by a source current in parallel with a rectifier diode as in the figure (3.3).

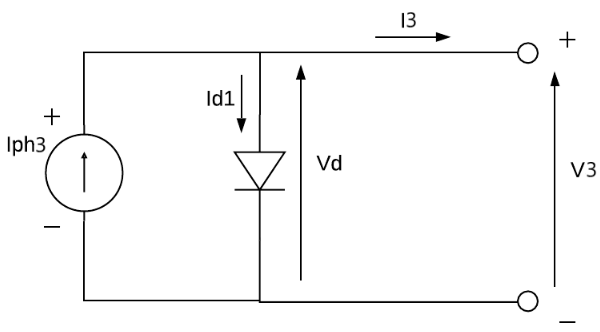

Figure 3.3: *Ideal single-diode model*

The model equations are 3.1 and 3.2,

$$I_3 = I_{ph3} - I_{d1} \tag{3.1}$$

$$I_{d1} = I_0 \left(e^{\left(\frac{V_d}{V_T n_1}\right)} - 1 \right) \tag{3.2}$$

where V_d, the diode voltage, is equal to V_3 in this case, V_T is the thermal voltage and n_1 is the diode ideality which gives information about how close is the diode to the ideal diode equation.

This 3 parameter model can be used to show an idea of the basic concept of PV cell but does not get a high performance simulating operating conditions. This is due to the limitations of the model. The series resistive losses, the shunt losses, the recombination at the space-charge region of solar cells and the non-ideality of the diffusion diode are not represented.

In this way, the model is insufficient to guarantee an accurate representation of the maximum power point in the PV cell emulation and, therefore, is rarely used to do this task.

3.2.2 Single-diode R_S model

This model represents the ideal circuit model of a solar cell, adding the effect of the current traveling through a semiconductor material and other contacts and wires which all contribute to the series resistivity losses. It can be represented by a source current in parallel with a rectifier diode and a series resistance as shown in figure (3.4).

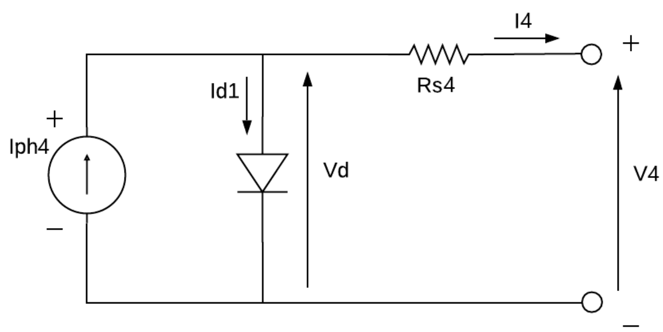

Figure 3.4: *Single-diode R_S model*

The model equations are 3.3, 3.4 and 3.5,

$$I_4 = I_{ph4} - I_{d1} \tag{3.3}$$

$$I_{d1} = I_0 \left(e^{\left(\frac{V_d}{V_T n_1}\right)} - 1 \right) \tag{3.4}$$

$$V_4 = V_d - I_4 R_{s4} \tag{3.5}$$

Now, there are 4 parameters counting the new series resistance, even though, it is already researched and proved that the fact of neglecting of the shunt resistance, provokes that the model doesn't perfectly fit the experimental I-V and P-V data, getting at some point some incongruent results in the new parameter, such as getting a negative value which has no physic sense.

3.2.3 Single-diode R_{Sh} model

This model represents the ideal circuit model of a solar cell, adding the series resistance and a shunt resistance between current generator terminals which represents shunt losses due to non-ideal isolation on the p-n junction construction. It can be represented by a source current in parallel with a rectifier diode, a series resistance and a shunt resistance as shown in figure (3.5).

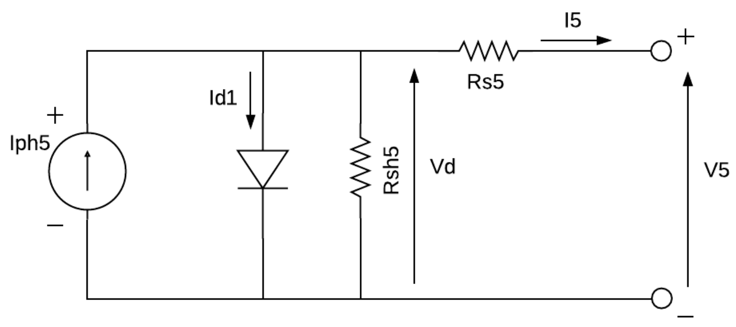

Figure 3.5: *Single-diode R_{Sh} model*

The model equations are 3.6, 3.7 and 3.8 ,

$$I_5 = I_{ph5} - I_{d1} - \frac{V_d}{R_{Sh5}} \tag{3.6}$$

$$I_{d1} = I_0 \left(e^{\left(\frac{V_d}{V_T n_1}\right)} - 1 \right) \tag{3.7}$$

$$V_5 = V_d - I_5 R_{s5} \tag{3.8}$$

This 5 parameters model is the most widely used and accepted in literature and researching, principally due to its fair trade-off between complexity and accuracy.

3.2.4 Two-diode model

This model adds a second diode, taking into consideration both, charge diffusion and recombination effects in the space-charge layer of the p-n junction. It can be represented by a source current in parallel with two rectifier diodes, series resistance and a shunt resistance as shown in figure (3.6).

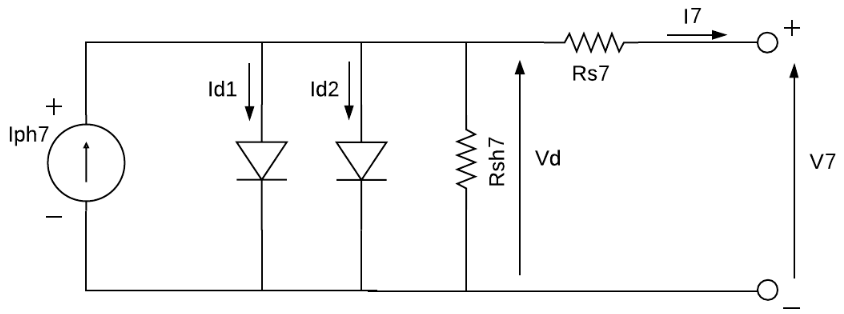

Figure 3.6: *Two-diode model*

The model equations are 3.9, 3.10, 3.11 and 3.12,

$$I_7 = I_{ph7} - I_{d1} - I_{d2} - \frac{V_d}{R_{Sh7}} \tag{3.9}$$

$$I_{d1} = I_{01}\left(e^{\left(\frac{V_d}{V_T n_1}\right)} - 1\right) \tag{3.10}$$

$$I_{d2} = I_{02}\left(e^{\left(\frac{V_d}{V_T n_2}\right)} - 1\right) \tag{3.11}$$

$$V_7 = V_d - I_7 R_{s7} \tag{3.12}$$

This model can be useful on low voltage systems and on any system that achieves a low irradiance ratio during a long time range since this situation involves a low voltage in the PV cell. However, in the most common case, the partial time at which the irradiance is low is short enough to consider insignificant its effect on the simulation accuracy. In consequence, 5 parameters model is more used.

It is also important to notice that this model can be simplified by assigning an ideality factor of 1 to one diode, representing it as an ideal diode, and the second one to 2. Although this consideration matches correctly with the Shockley-Read-Hall recombination in the junction space-charge layer approximation, it is not always valid in all cases.

3.2.5 Three-diode model

This model adds a third diode, taking into account also the grain boundaries and leakage current through peripheries effect. It can be represented by a source current in parallel with three rectifier diodes, series resistance and a shunt resistance as shown in figure (3.7).

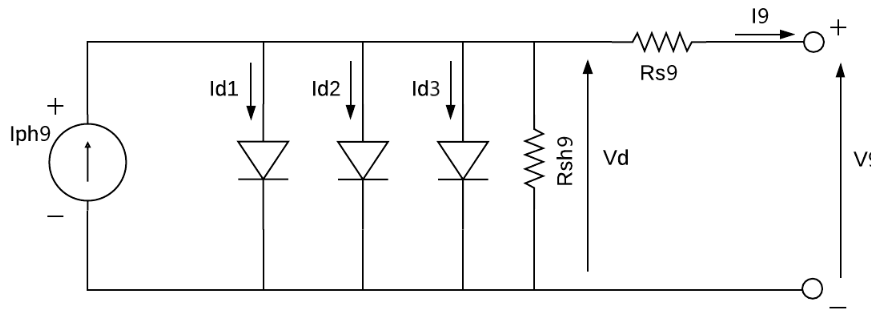

Figure 3.7: *Three-diode model*

The model equations are 3.13, 3.14, 3.15, 3.16 and 3.17,

$$I_9 = I_{ph9} - I_{d1} - I_{d2} - I_{d3} - \frac{V_d}{R_{Sh9}} \tag{3.13}$$

$$I_{d1} = I_{01}\left(e^{\left(\frac{V_d}{V_T n_1}\right)} - 1\right) \tag{3.14}$$

$$I_{d2} = I_{02}\left(e^{\left(\frac{V_d}{V_T n_2}\right)} - 1\right) \tag{3.15}$$

$$I_{d3} = I_{03}\left(e^{\left(\frac{V_d}{V_T n_3}\right)} - 1\right) \tag{3.16}$$

$$V_9 = V_d - I_9 R_{s9} \tag{3.17}$$

As the complexity has been considerably increased, a few parameters are usually ignored to reduce the overwhelming solution process. It is mostly used to consider in the model the properties of the multi-crystalline Silicon solar cells, but the use is quite limited due to the complexity of the parameter extraction process.

3.3 Matlab simulation on 5 parameters model

3.3.1 Model analysis

Even though the 5 parameter model, or Single-diode R_{Sh} model, seems quite simple and easy to represent mathematically within the three equations shown above, 3.6, 3.7 and 3.8, it is necessary to clarify that some of those parameters and other constants of the model, have a certain dependence with temperature and irradiation. Because of this, if a more accurate model is needed to make as faithful as possible to reality, it is necessary to treat them as variables that are dependent based on temperature, irradiation or both.

The dependence of this variables is remarked in the following equations 3.18, 3.19, 3.20, 3.21 and 3.22,

$$R_{sh} = R_{shRef}\frac{G_{Ref}}{G} \tag{3.18}$$

$$I_{ph} = \frac{G}{G_{Ref}}\left(I_{phRef}\left(1 + alfaT\left(T - 298\right)\right)\right) \tag{3.19}$$

$$I_o = I_{oRef}\left(\frac{T}{T_{Ref}}\right)^3 e^{\left(\left(\frac{E_{gRef}}{nk_2 T_{Ref}}\right)-\left(\frac{E_g}{nk_2 T}\right)\right)} \tag{3.20}$$

$$E_g = E_{gRef}\left(1 - 0,0002677\left(T - T_{ref}\right)\right) \tag{3.21}$$

$$V_t = \frac{k_1\left(T - 273\right)}{q} \tag{3.22}$$

- The constant T_{ref} is 25°C and G_{Ref} is 1000 W/m^2. Its respective variables, adopted from the external system conditions, are T and G.
- The constants measured in standard conditions and given by manufacturer are defined in table 3.2. This parameters are bound to the real application example used to create the model from the research [15].

Table 3.2: *Standard constant values*

Constant	Value	Definition
R_{shRef}	14,2Ω	STC shunt resistance
R_s model	$5,142 * 10^{-3}\Omega$	STC serie resistance
I_{phRef}	9,831 A	STC photocurrent
I_{oRef}	$1,871 * 10^{-9}$ A	STC saturation dark current
n	1,146	STC diode ideality factor
E_{gRef}	1,121 eV	STC Silicon bandgap
AlfaT	$4,6 * 10^{-4}\ \frac{1}{K}$	STC temperature coefficient

- Some other physic constants are defined in table 3.3.

Table 3.3: *Physic constant values*

Constant	Value	Definition
q	$1,602 * 10^{-19}\ \frac{J}{V}$	elementary electric charge
k_1	$1,381 * 10^{-23}\ \frac{J}{K}$	Boltzmann constant $\left(in\frac{J}{K}\right)$
k_2	$8,617 * 10^{-5}\ \frac{eV}{K}$	Boltzmann constant $\left(in\frac{eV}{K}\right)$

3.3.2 Model simulation

Once all equations, parameters, and constants are defined, the model is encoded on MatLab. The input range of the curve characteristic is set with a $V_d = -15$ V with a 0,01 V step until the I_5, in the I-V curve, reaches the first value that exceeds below -5 A.

The output values of interest are V_5 and I_5, obtained from 3.6 and 3.8, which finally shapes the I-V curve of the solar cell, shown in Figure (3.8).

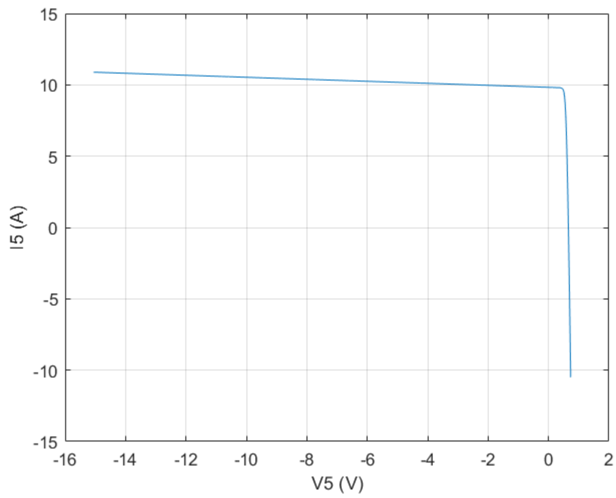

Figure 3.8: *Solar Cell I-V curve simulation plot*

Some deviation from the ideality is observed in the horizontal and vertical section of the I-V curve as it is seen in the literature figure (3.9).

Figure (3.10) shows the same I-V curve and adds the P-V curve, both fitted at 0 value in x-axis and y-axis. The series and shunt resistances effect on I-V curve are more notorious here, fading the graph away from the ideality of an ideal diode curve.

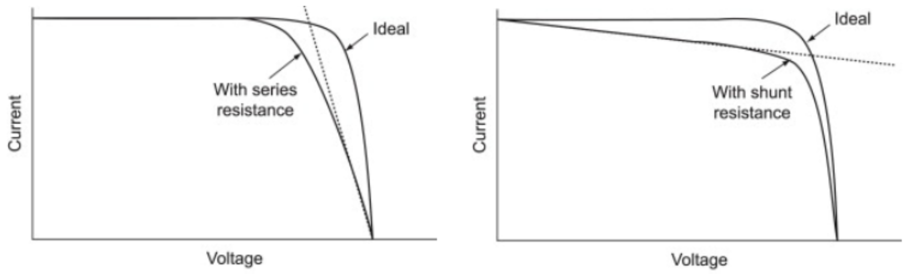

Figure 3.9: *Solar Cell graph: R_s and R_{sh} effects*

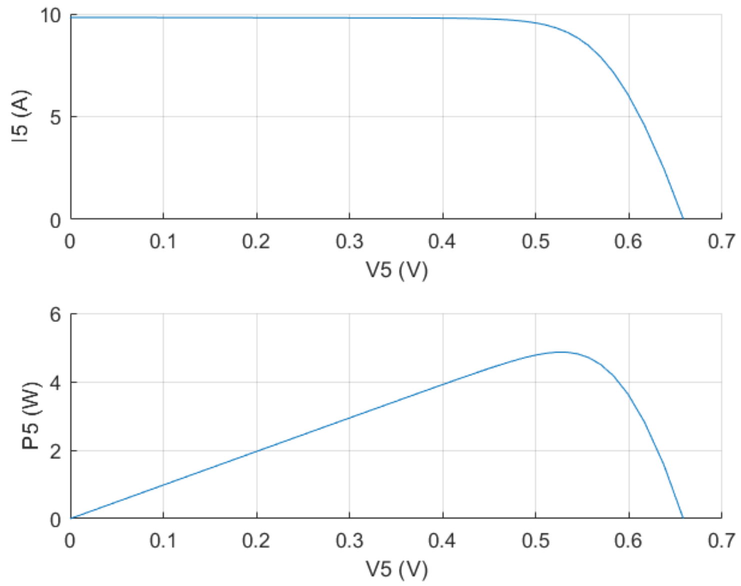

Figure 3.10: *Solar Cell I-V and P-V curve simulation plot*

3.4 Open circuit voltage, short circuit current and fill factor

As seen in the introduction, the physic mechanism that permits the transformation of energy is based on a technic used in diodes, the p-n junction. In this way, it is obvious that the curve model will be close to the diode one. It follows, then, the same shape, and it can be emulated just by the superposition principle, shifting the diode curve in the y-axis (Figure 3.11).

The principal characteristics that the cell curve model previously defined contains are presented in the next points.

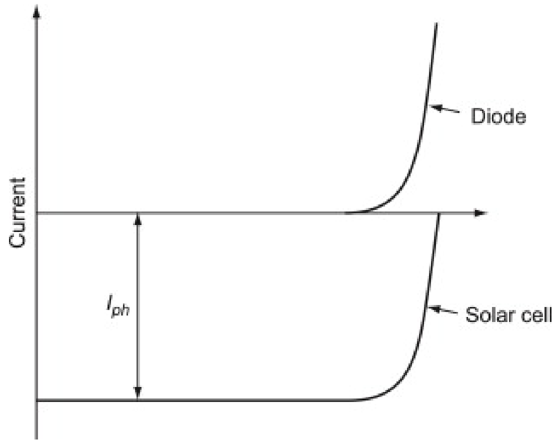

Figure 3.11: *Diode curve and I-V curve*

3.4.1 Open circuit voltage

V_{oc} is the voltage found crossing the x-axis, in the zero ordinate. It is a point where its respective power is zero and can be deducted by 3.23.

$$V_{oc} \approx \frac{AkT}{q} ln\left(\frac{I_L}{I_0} + 1\right) \quad (3.23)$$

3.4.2 Short circuit current

I_{sc} is the current found while crossing the y-axis, in the zero coordinate, at V = 0. In the same way, its respective power point is zero and from the main equation the short-circuit current can be computed(3.24):

$$I_{sc} \approx I_L \quad (3.24)$$

3.4.3 Fill factor

It is defined as the quality rate of the cell and can be represented by 3.25. It represents then, the ratio between the maximum power achievable and the one that would be found if tracing a straight line vertical and horizontal from the open-circuit voltage and the short-circuit current respectively.

$$FF = \frac{I_{MPP}V_{MPP}}{I_{SC}V_{OC}} \quad (3.25)$$

In figure 3.9 some effects of the resistances on the points defined above can be seen.

Regarding R_s, it has no effect on open-circuit voltage, but influences short-circuit current and, therefore, a decreasing effect in fill factor, getting far away from an ideal curve and, in consequence, making lower the maximum power achievable.

Modifying R_{sh} does not affect open-circuit voltage but short-circuit current and fill factor reduce as resistance increases.

That is a big reason to consider both resistances in the mathematical model since, as it was said before and can be observed right now, they have a huge effect on the determination of the MPP point.

3.5 Temperature and irradiation effect

The principal factors considered in this model, that are able to modify strongly the characteristic curve, are obviously irradiation and, in second term, temperature.

However, there could be included in the mathematical model other effects like humidity and wind, which also have some perturbations directly and indirectly into the model. The authors in [18] use some corrective factors taking into account the natural convection of wind, for instance, affecting the temperature model, and also applying some modification in I-V output based on humidity. Nevertheless, their conclusion is that the most important factor to consider is irradiation since it has a bigger impact on the system.

The fact that I-V curve can be strongly modified by these parameters is the reason why MPP trackers are quite necessary to "follow" this moving point, maintaining the maximum possible power efficiency in the system in real time.

In the next sections it is analysed how this factor can affect the I-V and P-V curve defined by the model presented in previous stages.

3.5.1 Temperature

In figure 3.12 it is shown the result obtained by the PV cell model defined in Matlab, and can be observed how the I-V and P-V curve is affected by changes in temperature from 25°C until 85°C in steps of 15°C.

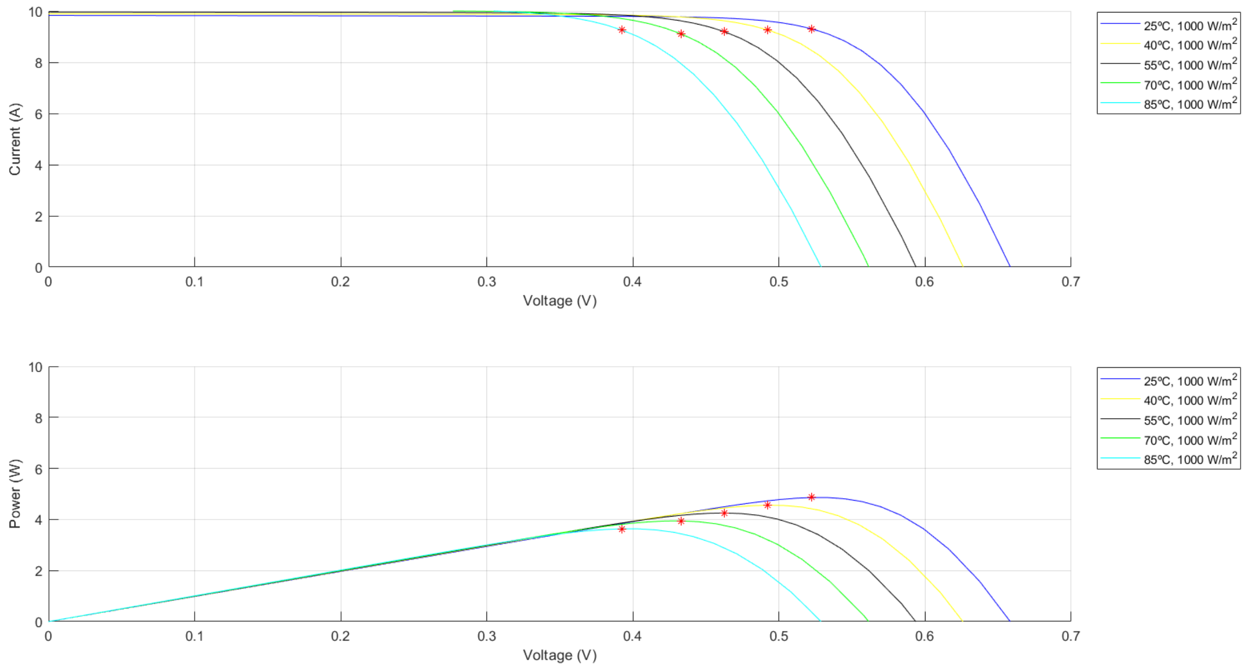

Figure 3.12: *I-V and P-V curve vs. temperature*

Just checking both curves it can be observed the unexpected fact that an increment of temperature implies a lower power, and also a decrement in the open-circuit voltage.

If equations 3.19, 3.20 and 3.21 are recalled, it is possible to deduct that actually temperature affects in a positive way the power curve due to the PV cell (3.19), if positive is understood as an increment of power, which is the logic point of view, but it is compensated (in equation 3.6) by the diode part (3.20 and 3.21).

The fact is that this final increment is practically unnoticed, due to the relatively small constants that are found in those equations (check table 3.2 and 3.3) and the compensation said before. Therefore, if compared to the effect in 3.22, that reduces drastically the output open-circuit voltage in comparison to the short-circuit perturbation, the power is finally reduced on average, which can be checked in P-V curve of the figure.

3.5.2 Irradiation

In figure 3.13 it can be observed how the I-V and P-V curve is affected by changes in irradiation from 1000 W/m^2 until 600 W/m^2 in steps of 100 W/m^2.

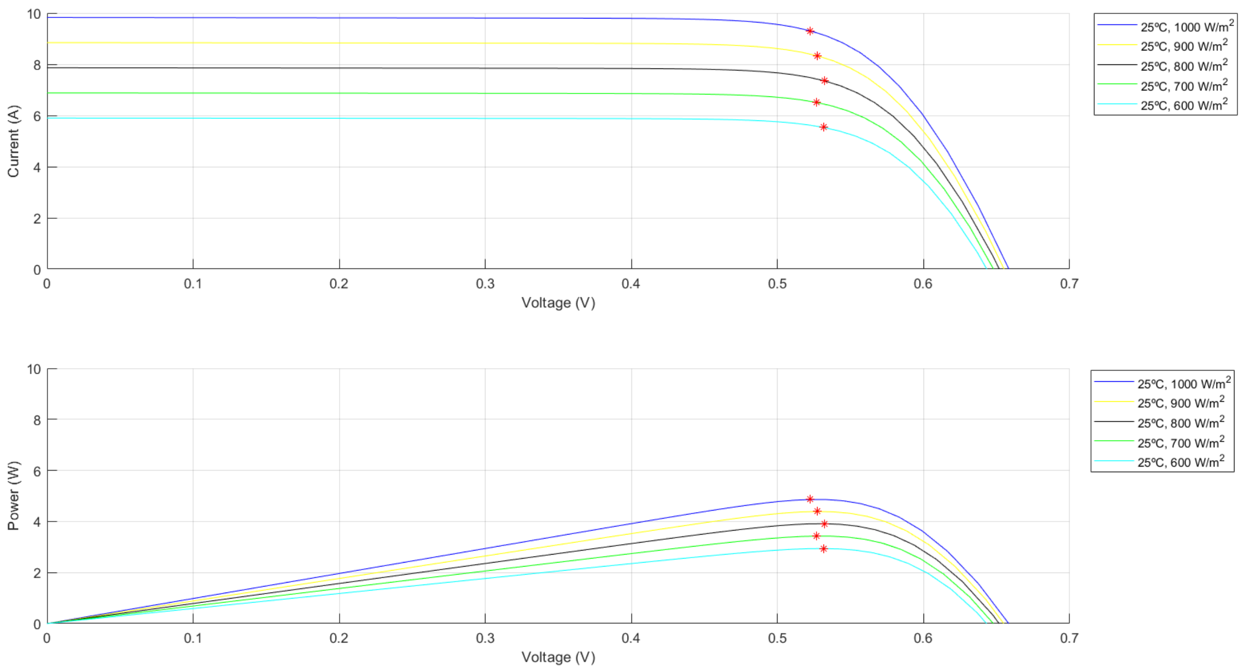

Figure 3.13: *I-V and P-V curve vs. irradiation*

By checking both curves, it is observed that an increment of irradiation implies more power, and a bigger short-circuit current, while the open-circuit voltage remains practically constants in comparison.

Now, recalling equations 3.18 and 3.19, the logic of the result above can be proved since shunt resistance is decreased and photocurrent increased. In this way, equation 3.6 gets a bigger current output from two different sides.

In conclusion, a higher irradiation and a lower temperature improve the performance of the system. That means that, if the P-V occupies a wider area, the work point found by the crossing of the P-V curve and the load curve applied will be situated in a point of a higher power.

CHAPTER 4

Photovoltaic module, array configuration and photovoltaic system

4.1 Introduction

A PV cell can provide a DC source of current and voltage, although it provides a quite humble quantity of power just by itself. Considering the definition of the power per area, it is found that, with an actual high level of irradiance (1000 W/m^2) and a high-efficiency energy transformation (20%), in a typical PV cell area size (6 in^2), it is obtained around 4 W of power.

Hence, it is necessary to combine a few quantities of them into a module to start having a considerable amount of power available. According to the PV system finality, several modules will also be combined to provide with an even more big quantity of power, in terms of a combination of high voltage or current.

There are some different approaches to define a PV system array configuration, like the minimum current or voltage threshold necessary in the application, which determines the series and parallel module array combination. That could be the type of system that is receiving the power, like a stand-alone system, a grid or both mixed.

The power converting technology available is usually focused on converting the DC into an AC power, since most of the receiving systems require an AC input power. However, it is also needed an interphase DC-DC in most of the cases. Then, it's important to take into account which kind of converter is required and available.

The economical stage is also a considerable important part in the design as well as as what kind of configuration uses more or fewer converters with its pros and cons, or which is the scale economy in the future (in terms of transformers) to be able to forecast a good and efficient design, in terms of rentability, in a long-term view. For example, in [21], the author states that an AC module type converter presents a tendency to be mass produced and, therefore, becomes more economical.

Finally, partial shading is also an important point to be aware of in the PV system design, since it strongly affects the amount of power that the whole system is producing. It can decide the array combination, its positioning or the number of bypass diodes necessary in PV modules, among other things.

4.2 PV module

4.2.1 Module configuration

The Photovoltaic Module is based on the real one that can be found in the SolarTech-Lab (found in Milano Bovisa, Politecnico di Milano). Its configuration is 60 PV cells in series where each set of 20 cells is connected in parallel with a bypass diode as in the figure 4.1.

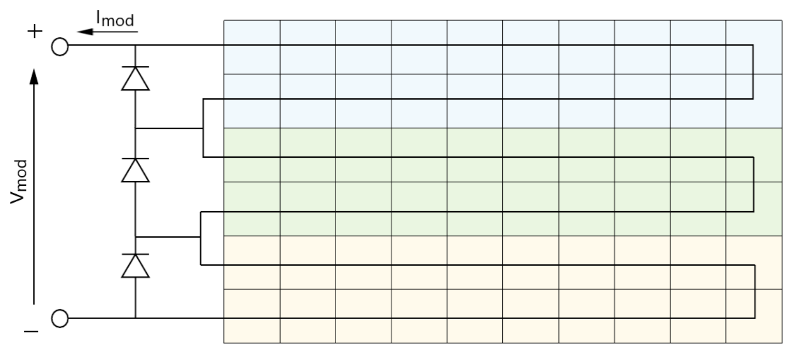

Figure 4.1: *PV module*

Hence, the total output voltage and current is a combination of the I-V curves from the 60 PV cells shown in the last chapter and three bypass diodes.

As seen in the figure, it is the typical configuration (also found with the 72 cells configuration) that is used these days due to its cost which has reduced considerably these last years, thanks to the scale production.

4.2.2 Simulation of the module configuration

The methodology to calculate the equivalent I-V curve of the total PV module is the next one:

- The characteristic curves of the cells separately and the diode itself have defined different limit values on their axis (based on their characteristics and also the parameters that can change in real time, like irradiation). Hence, it's important in this operation to define a superior and inferior limitation in the reference axis that shares the I-V curves that are to be summed.
- Since every cell in the module is in series, its equivalent voltage can be calculated as the sum of every single cell. In this way, the first 20 cells I-V curve is taken and once selected a reference point in the current axis, all voltage values of all I-V curves are interpolated to this reference. Then, they can be added, as in the figure 4.2, where a fixed current set of points is taken, and their respective values of voltage in each I-V curve are summed at these current reference points.

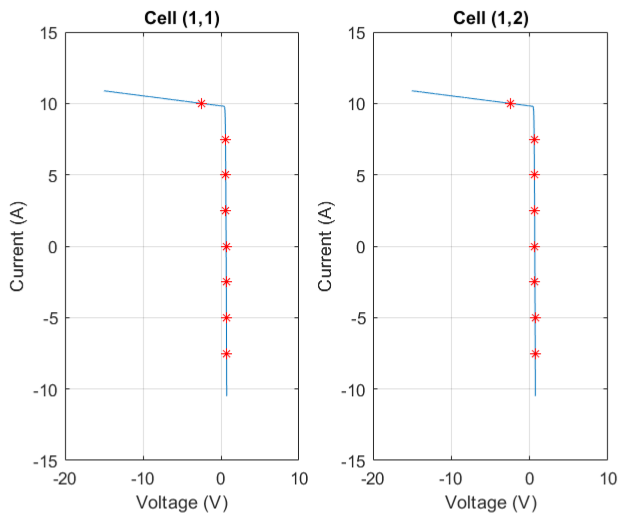

Figure 4.2: *Curve sum in series cells*

- Once the 20 cell I-V curve are added, the bypass diode characteristic must be summed too. In this case, they are in parallel with the 20 cells. Therefore, they share the same voltage and their current values must be summed. The same approach is realized where the reference voltage points are shared and the interpolated current values are summed as in figure 4.3. In this way, one-third of the module is characterized.

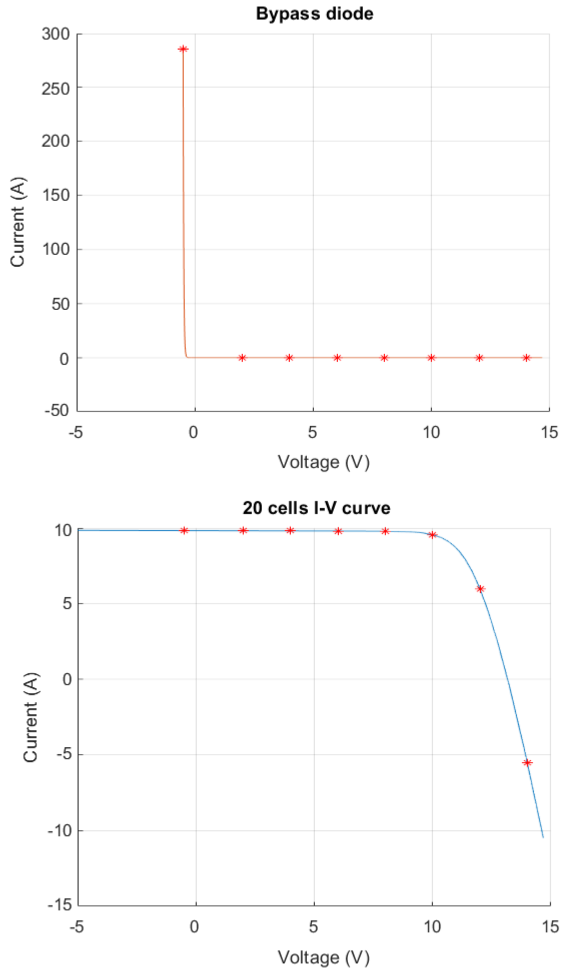

Figure 4.3: *Curve sum parallel diode and 20 cells curve*

- As for the series cells, the three I-V curves in the sections of 20 cells are added. In a similar way, they share the reference current points and the interpolated voltage values are added, forming the final module I-V curve as in figure 4.4. The first figure is the full characterized I-V curve and the second is the same one but defined only in the first quadrant (positive axis).

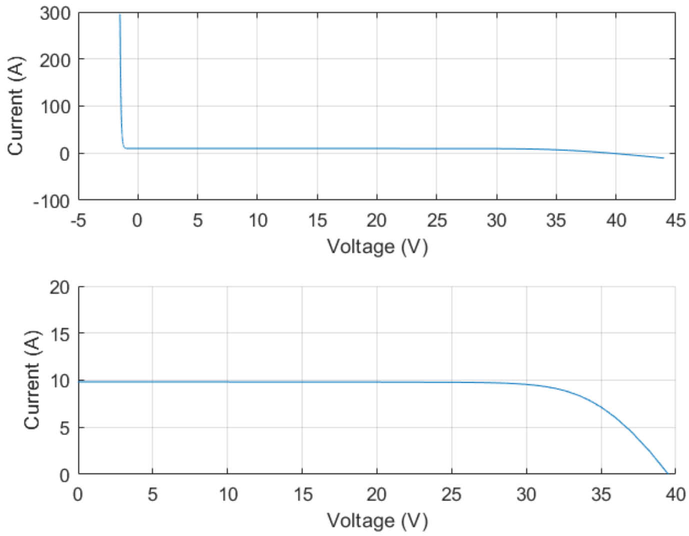

Figure 4.4: *PV module I-V curve*

4.3 Array configuration

4.3.1 Array configuration functionality

The MPP in the PV array configuration may change according to the topology used, such as the series, parallel, series-parallel or parallel-series combinations.
This gives the designer a wide range of possibilities, in terms of current and voltage outputs, and at the same time, a way to shape the I-V curve in the most interesting way, which can compensate in some cases the negative effects of the multiple local maxima, due to imperfections which create certain differences between the diverse PV modules, or in the case that affects strongly this issue, the partial shading, and more generally, an uneven irradiation pattern over the module configuration (which can be also induced by dust or other external causes).

The author in [22] makes an overview in different setup combinations, showing the MPP variance based on the topology used.

The author in [23] compares different setups and comments that parallel-series topologies are unused due to the bad performance in partial shading scenarios.

The author in [24] simulates some shadow patterns over diverse array configurations. There are series and parallel combinations called Total-Cross-Tied, Bridge-Linked, Honey-Comb, a Hybrid between TCT and BL, and the series-parallel (figure 4.5). Then, it is compared how much is power affected in each configuration, in the different shadow pattern conditions.

It turns out that there is an obvious trade-off between their performance regarding the shading conditions and the extra cost of adding more ties to the configuration. However, it is shown that a Hybrid configuration can result, at least in the patterns designed by the author, in a better performance than TCT, with fewer ties, which implies an improvement not only in the total performance of the system, but also a reduction in its cost. The different setups used in the simulation are presented in the next sub-

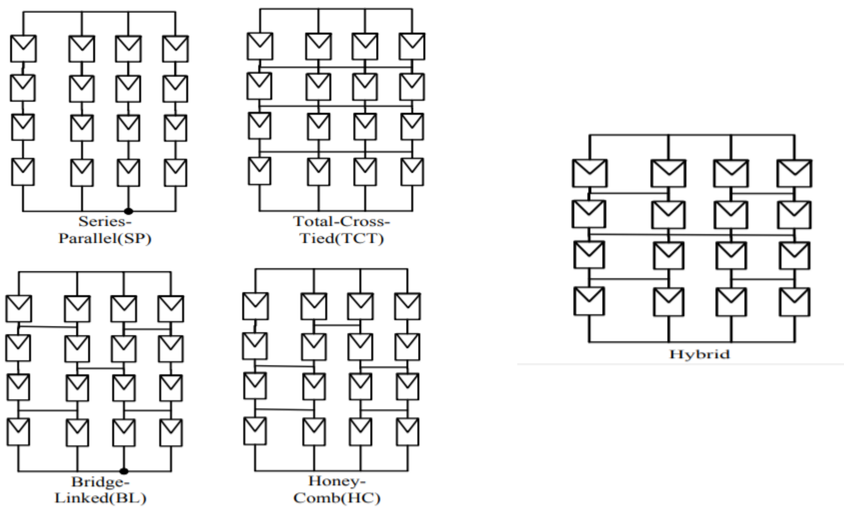

Figure 4.5: *Array configurations*

section, which consists basically in series and series-parallel topologies which are also more susceptible to present higher problems with partial shading and, in consequence, a good setup configuration to compare MPP tracking algorithms performance.

4.3.2 Simulation of the array configuration

Three different array configurations are defined in this work. First of all, a $3x5$ array setup, where modules can be connected all in series (figure 4.6), 5 rows in series and 3 columns in parallel (figure 4.7) and 3 rows in series and 5 columns in parallel (figure 4.8) are considered.

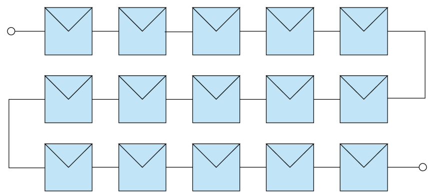

Figure 4.6: *Setup 1*

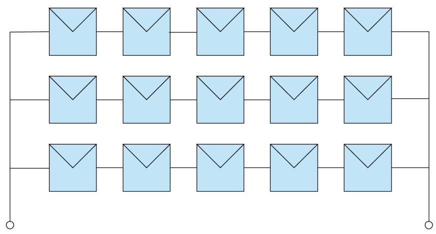

Figure 4.7: *Setup 2*

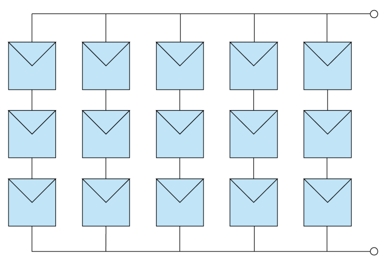

Figure 4.8: *Setup 3*

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Block diode selection

It is crucial to implement a blocking diode at the end of the series array that converges on a parallel connection with other series arrays. If this configuration is found under partial shading condition, it could experiment some points with more potential than others (the full irradiated arrays in relation to the shaded ones) and, therefore, miss operating the full system. Blocking diode avoids the wrong pathing of the current.

There are some points to take into account at the moment to choose the blocking diode used in the series array:

- Avoid as much as possible the oversizing of its characteristics since the oversize increments proportionally the final cost.

- Take into consideration the worst case possible in the two setups that use the blocking diode and, in consequence, try to choose it for both cases. This point takes into account that the manufacturer establishes, as usual, a different stock price based on the quantity demanded. It is, then, necessary analysing whether the use of a diode a bit oversized for one setup (a bit more expensive) is compensated with the fact that an extra number of bought units reduces its average cost and, therefore, the absolute system cost (economy of scale).

- In this case, the maximum reverse voltage is found in setup 2, ($197.5V$), and the maximum working current is common to all series arrays where the diode is placed. The chosen diode can be found in [25].

- To find out the I-V curve characteristic is necessary to deduct it from the curves that the manufacturer provides (Figure 4.9). Once some reference points from the curves are taken, the MATLAB tool, nftool, is used to approximate its parameters. The diode equation is found then and will be used in the model of setup 2 and 3, adding at the end of each series array the blocking diode modelized (Figure 4.10).

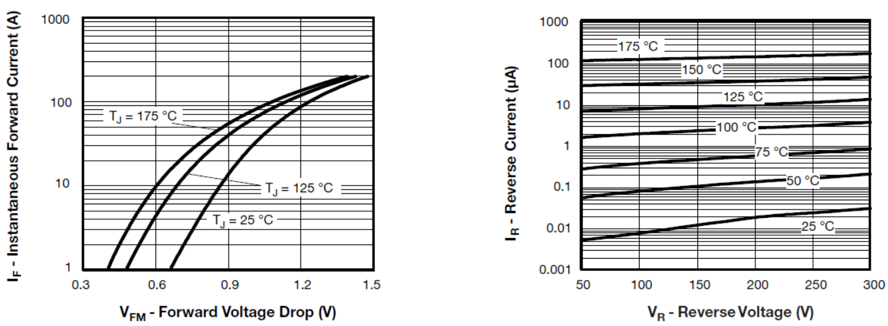

Figure 4.9: *Manufacturer diode I-V curves*

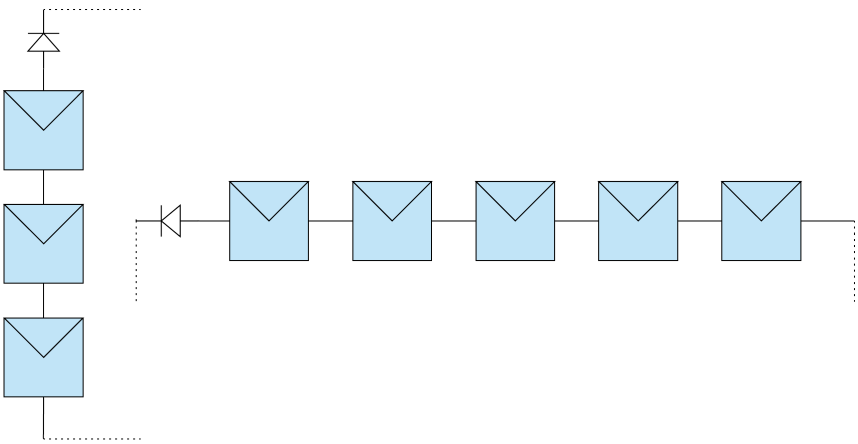

Figure 4.10: *Blocking diode in series arrays*

Setup simulation

The configuration module is determined in a similar way as in the PV module deduction from the cells that compose it.

- The first setup is a full series module configuration without blocking diode since it is not necessary for a unique series array. Hence, the equivalent I-V curve is found adding the voltages of each one of the 15 I-V modules curves from its respective reference step current (figure 4.11).

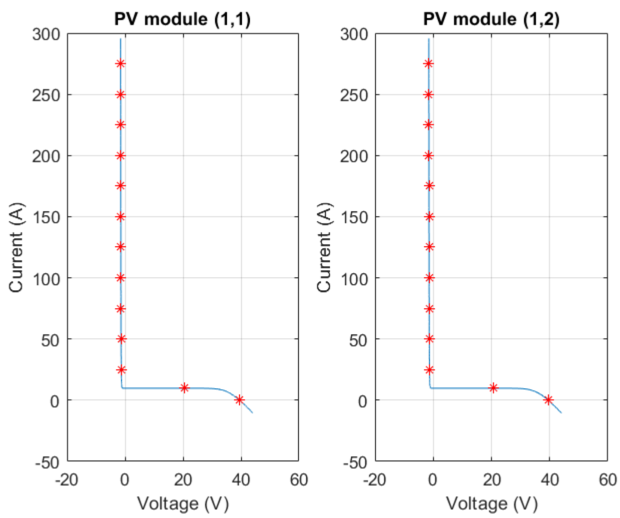

Figure 4.11: *Series, setup 1: Series sum*

- For the second and third setup, both series-parallel, it is necessary a two-stage curve adding. First, the voltage sum for the 5 or 3 rows in series, plus the blocking diode, and then, the current sum from the 3 or 5 columns in parallel, bound to the setups 2 and 3 respectively. This procedure is plotted in a visual way in figures 4.12 and 4.13, in the setup 3 case.

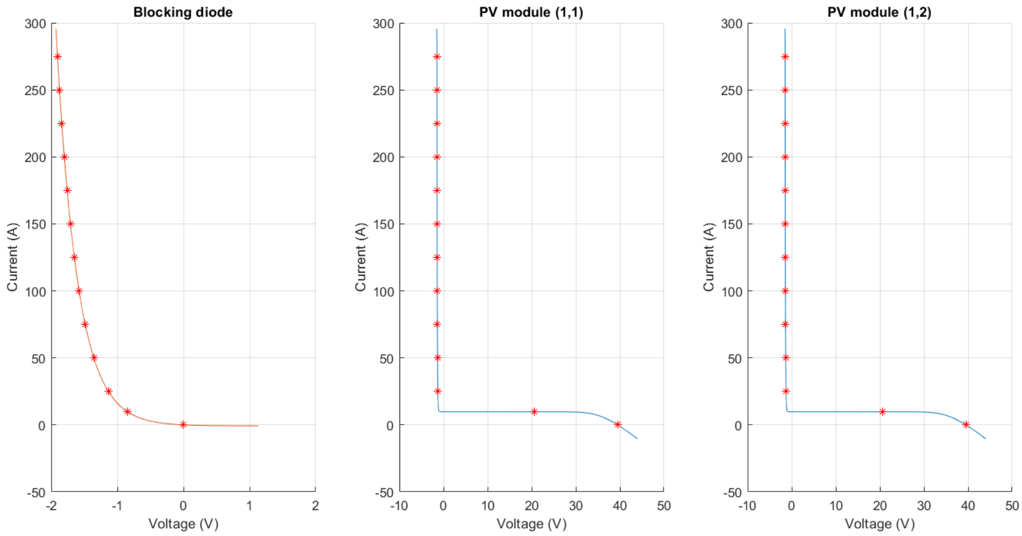

Figure 4.12: *Series-parallel, setup 3; Series sum*

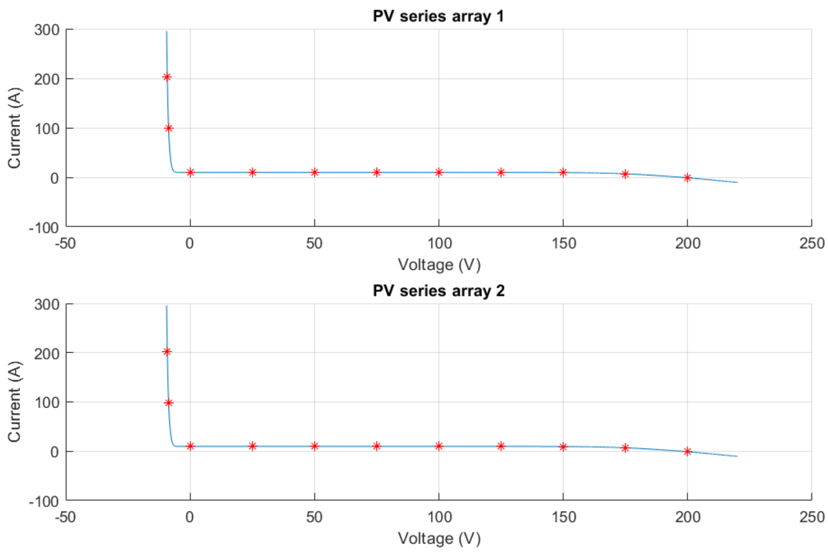

Figure 4.13: *Series-parallel, setup 3: Parallel sum*

Once every setup configuration is defined, the I-V and P-V curve of the three cases are characterized. In figure 4.14 are plotted overlapped, in order to be able to compare between their energy output possibilities, the three I-V and P-V curves from the different configurations (at 25°C and 1000 W/m^2).

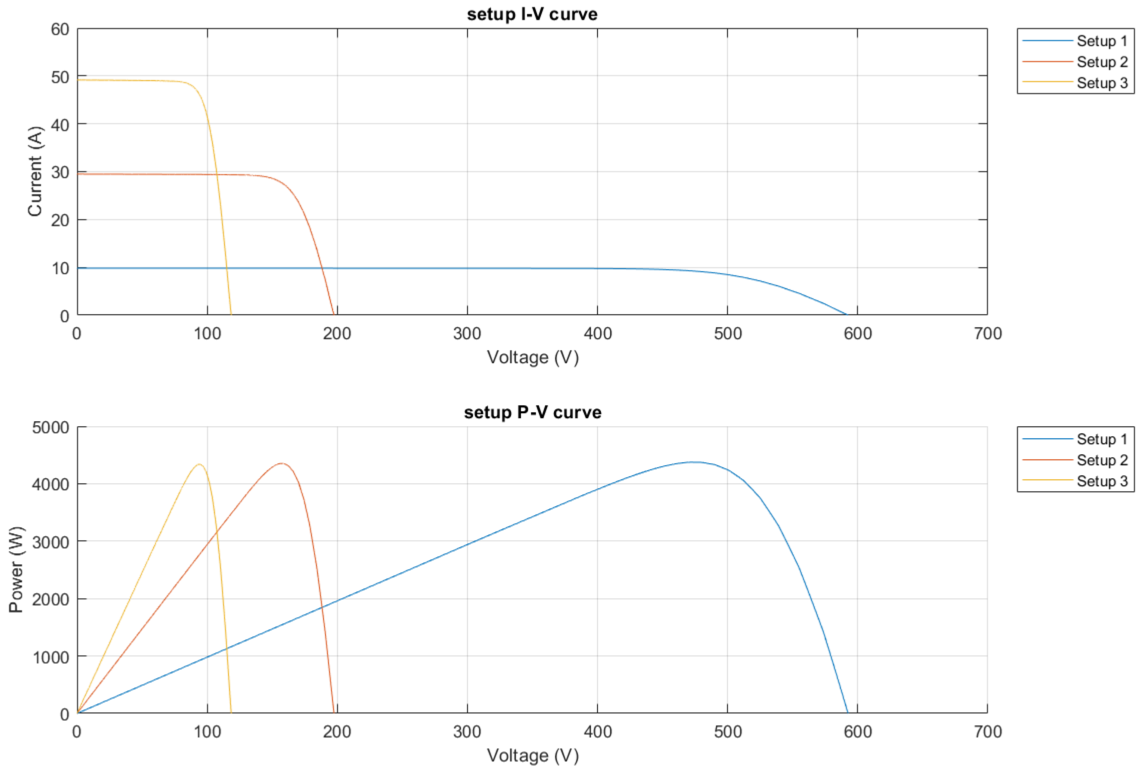

Figure 4.14: *Series-parallel, setup 3; Series sum*

Some important parameters are summarized in the next table (4.1).

Table 4.1: *Physic constant values*

Setup	$V_{oc}(V)$	$I_{sc}(A)$	**MPP (W)**
1	592.5039	9.8317	$4.3741 \cdot 10^3$
2	197.5014	29.4944	$4.3510 \cdot 10^3$
3	118.5008	49.1564	$4.3357 \cdot 10^3$

As it is logic, V_{oc} and I_{sc} between the three different setups, follow a ratio of 1:3, 3:5 and 1:5 depending on the setup comparison. On the power it is observed a decreasing in setup 2 and a slightly bigger decrease in setup 3. This is due to the extra condition of the blocking diode, which contributes to an additional power loss for the system. In case of no blocking diode, the power would be equal in the three setup configurations.

4.4 PV system

The next stage consists of analysing which kind of power converter is necessary to extract the energy generated by the PV setup configuration. In any case, the following subsection starts with an overall review of the types of configurations that can be used in a PV system.

4.4.1 Typical converter configuration

The PV energy conversion system requires diverse power converter configurations to extract the maximum power and depends on the receiving system (stand-alone or grid integration). In summary, power electronics in the system-receiver interconnection consists of two basic designs:

- A DC-DC converter with the MPPT controller integrated, and a DC-AC converter, integrating the grid interface control functionality, that sets the output frequency to the needed one.
- A DC-AC where both are integrated, the MPPT controller and the frequency controller, to allow the grid-matching power controller.

The basic technologies used up to now are seen in figure 4.15, from the paper [21], where the author defines the main characteristics of the use of one or another type of converter.

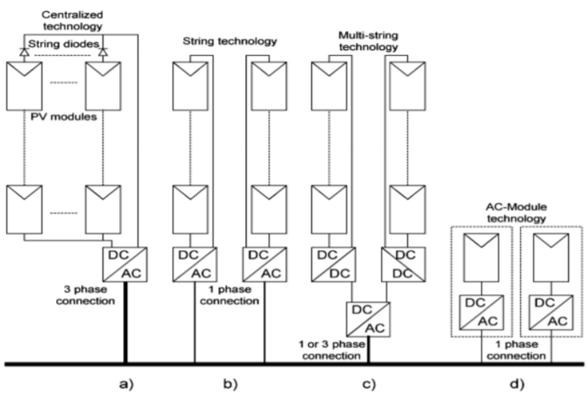

Figure 4.15: *Power converters scheme*

- The first one on the left shows the most antique type of configuration, which uses a centralized inverter that interfaces a large number of PV modules into the grid.

Normally, this large amount of PV modules provides with a sufficient amount of voltage so that it is not required a midterm DC-DC boost converter in order to amplify the voltage at a correct level for the system-grid interconnection.
Even though normally it is not necessary to implement this extra converter, which supposes a smaller economical charge, it is badly compensated with its performance towards partial shading, which reduces its overall generated power (and the extra joule losses due to the bigger current after the parallel junction).

Considering the main topic of study in this thesis, MPPT can be used to palliate this pernicious effect, adding a DC-DC converter in the midway in order to modify the output voltage and, therefore, moving the equivalent load that crosses the I-V curve until finding the MPP.

- The second one is a more versatile configuration, called string inverter, which can reach the adequate voltage to be interconnected directly into the grid and at the same time, has the benefit of the mass production (scale production) if compared with the centralized configuration and, therefore, the price is also lower.
- The third one is the next step of the string inverter, the multi-string inverter, which has a DC-DC interface before a common DC-AC converter. It can enhance the centralized configuration in the sense that each string is controlled individually, being able to palliate in an efficient way the partial shading issues.
- The last one is called AC-module, which consists of a AC-DC converter integrated into a PV module in order to be mass produced in this setup. Its configuration can minimize the mismatch losses between the PV modules due to the partial shading. This configuration is, with the string configuration one, the easiest for applying an enlarging of the PV energy system, which makes them a versatile choice from the point of view of the design.

Apart from the inverter configurations shown above, author [23] adds the DC-DC optimizer configuration which is quite close to the AC-module type in the sense that all PV modules have its own DC-DC converter, and then are centralized into a DC-AC converter. In this paper the analysis of partial shading effects on the different converter's configuration is made, also considering diverse bypass diodes configuration on PV modules.

An interesting point of view regarding the power converter type is done in [26], where the author analyses the reliability of the system according to the configuration used,

reaching the conclusion that high voltage applications, central and string inverters have a similar mean time to failure, while that AC-module has a considerably higher reliability, overcoming more than 10 times the mean time to failure found in the other cases.
It is also commented that in low voltage applications there is a bigger difference between central and string inverters reliability, being the second one a better choice.

4.4.2 Simulation of the converter configuration and load characterization

As seen before, a central configuration setup has been defined. A typical representation of the full system that is going to be simulated is the one seen in figure 4.16.

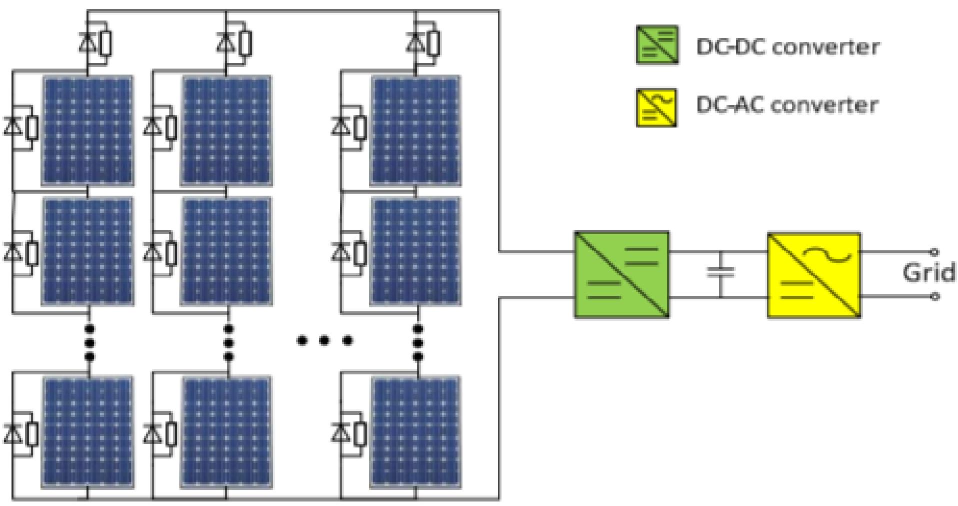

Figure 4.16: *PV system and converter*

In the actual case of study, the converter side is simplified into a constant load. The equivalent load in the PV system side will be modified based on the duty cycle of the DC-DC converter and will move the load curve modifying the working point in the I-V curve of the PV system. The final system is defined as in figure 4.17.

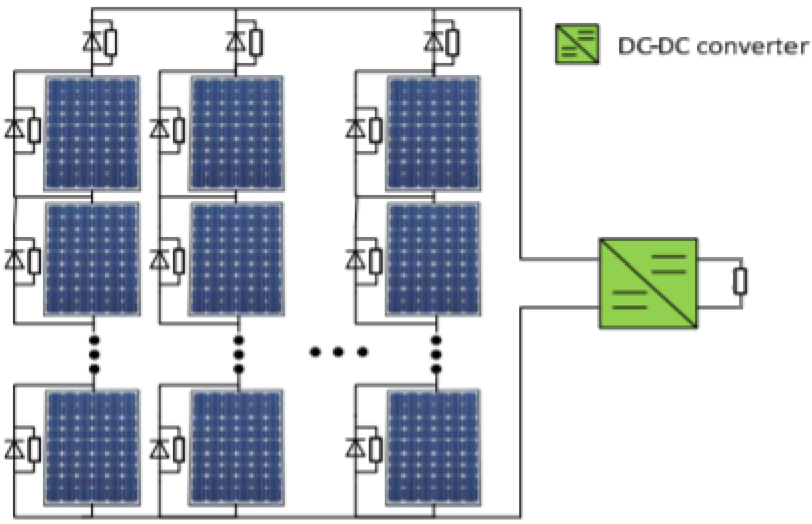

Figure 4.17: *PV system, converter and load*

As a final note, the load will be defined as the one that is seen at each different setup when the full PV system is full irradiated and the DC-DC (considered a buck-boost converter) is working at a 0.5 duty cycle or, in other words, when the load is the same in both sides of the DC-DC converter. The final values of the loads are in table 4.2.

Table 4.2: *Load values*

Setup	**R** (Ω)
1	50.7728
2	5.6278
3	2.0224

4.5 The partial shading issue

4.5.1 Effects on system efficiency

In previous sections the effect of the solar irradiance and the ambient temperature in the I-V and P-V curve shape of the PV system has been discussed. The MPP position modification demands certain control to counter the loss of the power system efficiency.

An extra issue, quite bigger, appears when partial shading is present. It is common and sometimes unavoidable, since it can be induced by daily causers like nearby trees, chimneys or clouds. In this way, and due to the non-linear characteristic seen on the I-V and P-V curve, if partial shading is originated, the different adding curves have mismatching shapes which in the total sum create a P-V shape with not only one maximum, but also local maximum or maxima.

These different shapes are a direct consequence of the bypass diodes that are used to grant another path to the power, through the regions that are less irradiated, and avoid the 'hot spot' effect [27], deteriorating those shaded cells that are absorbing power of the rest of the system. Hence, instead of losing a full branch of power, there are different curve shapes, as said before, that will originate multiple maxima as it can be seen in figure 4.18.

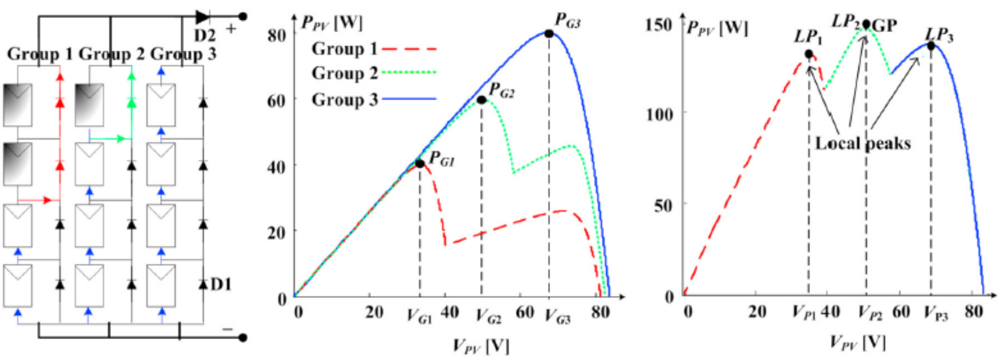

Figure 4.18: *Partial shading effect*

In case of even irradiation and temperature changes, there are some trackers that can do a fair job: the deterministic based methods. However, in case of multiples peaks, these kinds of trackers have a chance to found out a wrong maximum, needing, in this case, some alternative to overpass these local peaks and find the global one.

4.5.2 Simulation under a complete shadow transient

Below is shown the setup and shadow configuration for the next simulation stage (figure 4.19), using an image tool from MATLAB over the matrix that represents the experimental field region.

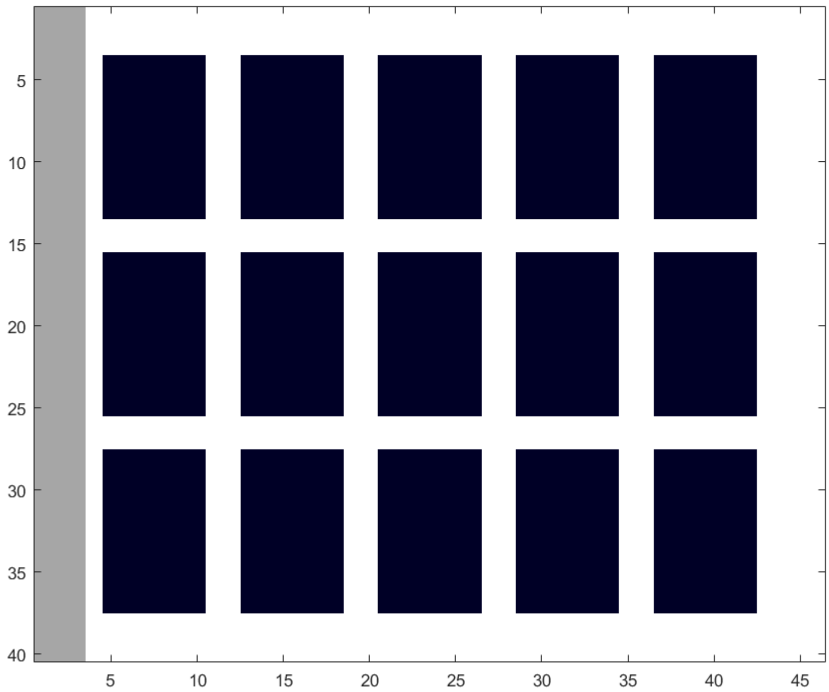

Figure 4.19: *Full shadow transient*

The navy blue rectangles represent the PV modules in the matrix, the grey region is the shadow that will extend over the full matrix, covering all the PV modules at the end, whereas the white coloured region is just an empty zone between modules.

Each unit is about the size of one solar cell side longitude. The speed of the field covering will be fast enough to surpass almost one PV cell per time step (10 $cm/(timestep)$). That is because the intention of this simulation is to analyse the P-V curve evolution while it is getting covered. Therefore, in order not to saturate the plot, it is defined as a high-speed step.

The P-V curves of the three setups are shown in figure 4.20.

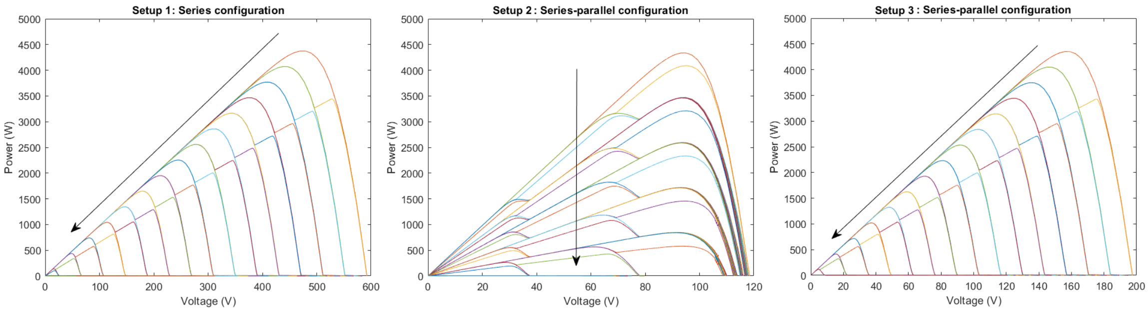

Figure 4.20: *P-V curves in shadow transient*

Setup 1 and 3 show no difference in its behaviour. Configurations seen in figures 4.6, 4.7 and 4.8 give a more visual explanation. Basically, the shadow falls in the same direction in setup 1 and 3, while setup 2 has its array configuration perpendicular to the shadow advance border. That can be observed in the second figure, as its P-V curve decreases in a different direction.

On the other hand it is important to observe the maximum local power point generated during its shading. Due to this P-V shape, some MPPT fail in their task to track the MPP. Especially, the deterministic MPPT have some difficulties in that case, and they lose their reliability as a control algorithm.

4.6 Algorithm convergence in constant shading

An initial test over some algorithms has been done. The chosen algorithms (which will be explained in more detail in the next chapter) are Perturb and Observe (fixed perturbation step), Short-Circuit Current method, Particle Swarm Optimization (with 3 particles) and Genetic Algorithm.

In the next figure (4.21) the two scenarios and their respective power shapes are shown.

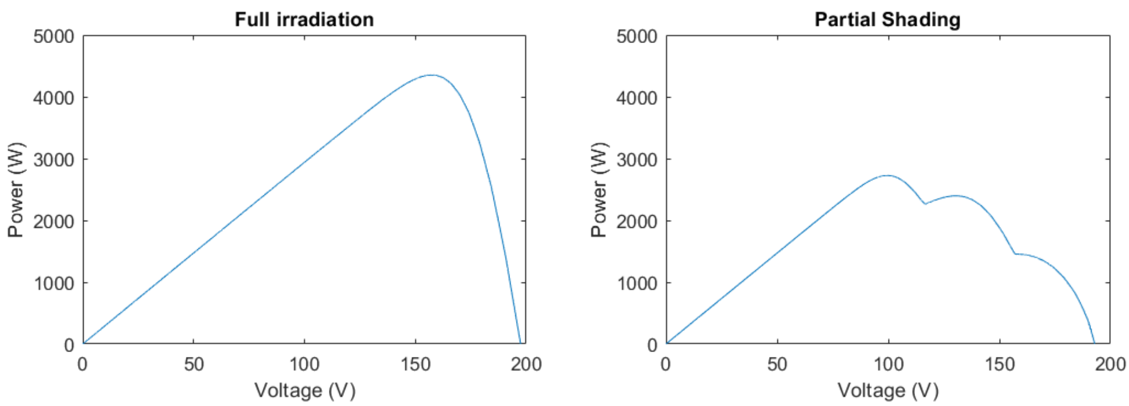

Figure 4.21: *Full irradiation and partial shading scenarios*

4.6.1 Convergence in full irradiation

In the next figure (4.22) the convergence of the 4 algorithms named in the last section is shown. It can be seen how the deterministic methods are able to reach and follow in an accurate way the maximum power of the system. Their pathing until this maximum point is smooth and it shapes a continuous curve.

In the case of short-circuit current, discontinuity can be seen every 20-time steps, that is, the moment when the code is searching the reference value that will be used to set the direction of the duty step change. Since it is a 20 Hz sampling frequency, this searching is done each 20-time steps, which involves an interruption each one second.

On the other hand, stochastic algorithms are also able to follow the maximum power reference. Their tracking is quite random and do not follow a smooth pathing until the maxima. Once reached this point, they remain in the maxima until they experiment a perturbation strong enough.

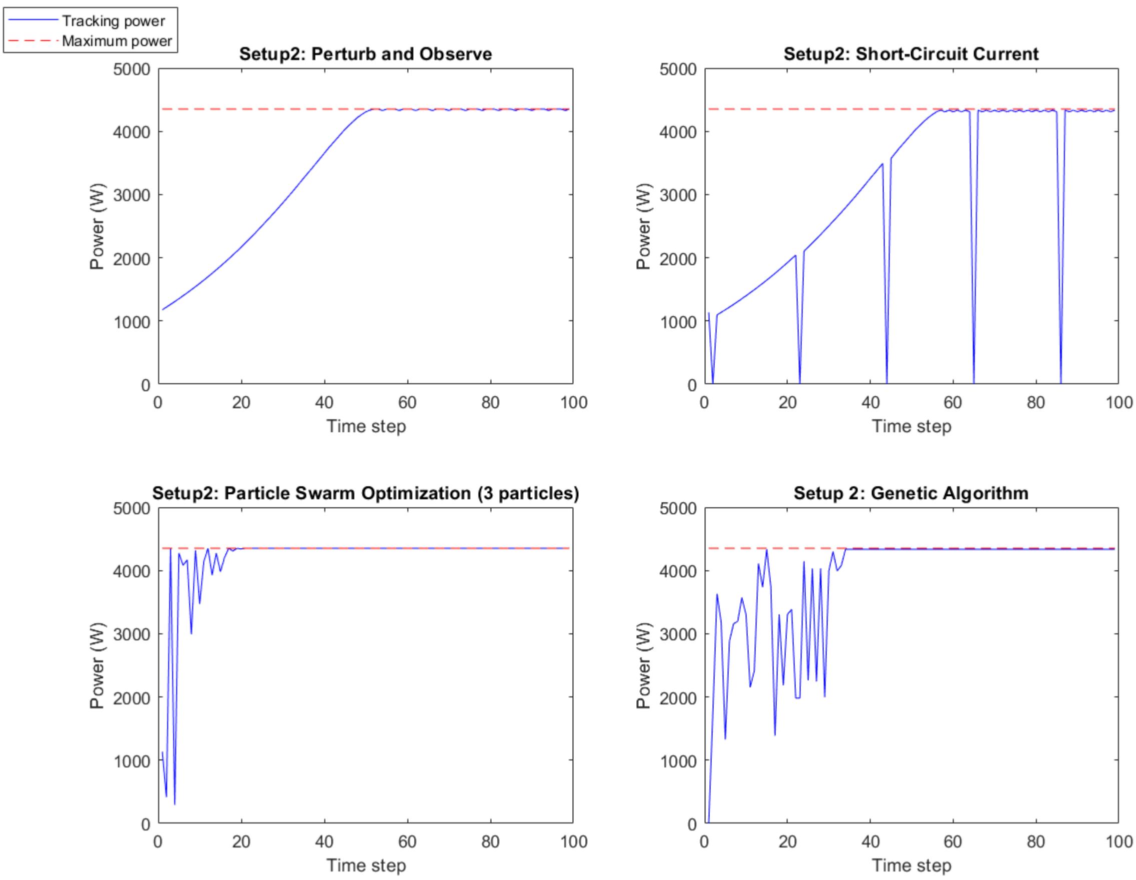

Figure 4.22: *Full irradiation scenario*

4.6.2 Convergence in partial shading

In the next figure (4.23) the convergence of the 4 algorithms is shown once again, this time considering a partial shading over the PV configuration scenario. This partial shading scenario induces a second local maxima in the curve shape, seen as the black discontinuous line in the four graphs.

In the Perturb and Observe graph it can be observed how the algorithm gets stuck in the wrong maxima. The short-circuit current, follows the reference found in the searching point each second and does not depend on how many local maxima are in the curve shape.

The stochastic algorithms are successful on finding the correct maxima and follow their reference accurately once they have found it.

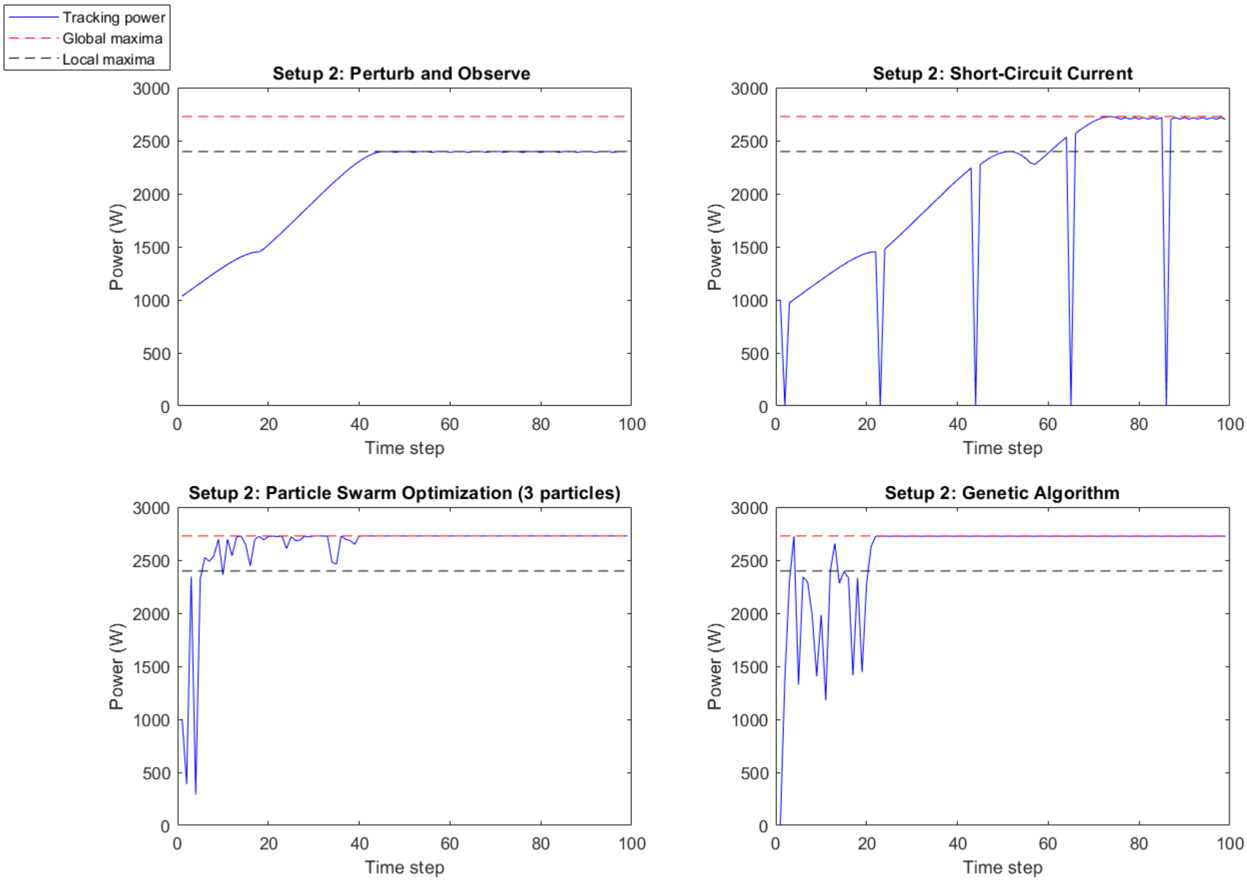

Figure 4.23: *Partial shading scenario*

4.6.3 Scenario comparison

There are some previous points to consider with respect to the algorithm differentiation in the diverse scenarios.

- The dynamic shading scenario used to modify time step by time step the P-V curve shape of the system. That is, the performance of the stochastic and deterministic algorithm will be different from the one in a static curve shape searching. Generally, stochastic algorithm are worse in dynamic objective function tracking, and get even worse the faster the dynamic condition is.

  The aim of this study, is to find out how the efficiency is affected according to the algorithm used, in a wide range of dynamic scenarios, trying to highlight when stochastic algorithms start to become worthless in this PV array configuration.

- It has been seen that deterministic algorithm can get stuck into a local maximum, losing a high percentage of efficiency in consequence. However, it is important to remember that stochastic algorithm is also, just by probabilistic, susceptible to fall inside a local maximum. The point is that this stochastic algorithm presents an enhancement towards the deterministic ones in this case, but it does not imply that they can avoid one hundred percent of the problem presented by partial shading.

- Deterministic algorithms that follow a quite constant reference, such as short-circuit current, open-circuit voltage and constant voltage, do not have the same problem as perturbing methods, but shading conditions strongly affects their performance. In this case, the geometry of the shading shape is the most important point to consider.

4.7 The array reconfiguration

This last section is centred in the array configuration, regarding the mitigation of the issues that are generated due to the partial shading.

This type of control uses a completely different methodology with respecto to the MPPT algorithm, since it works on the physical array configuration (like the configurations seen in figure 4.5). Some authors like [28] and [29] propose an array reconfiguration from the Total-Cross-Tied in order to reshape the P-V curve and generate the new power curve with a higher MPP.

The last author cited uses this simulation shadow patterns (figure 4.24) to analyse the different MPP found based on the PV array reconfiguration. It is found that the physical relocation of modules with a fixed electrical connection (PRM-FEC) grants a bigger MPP point with respect to the normal TCT in big shape shadow patterns.

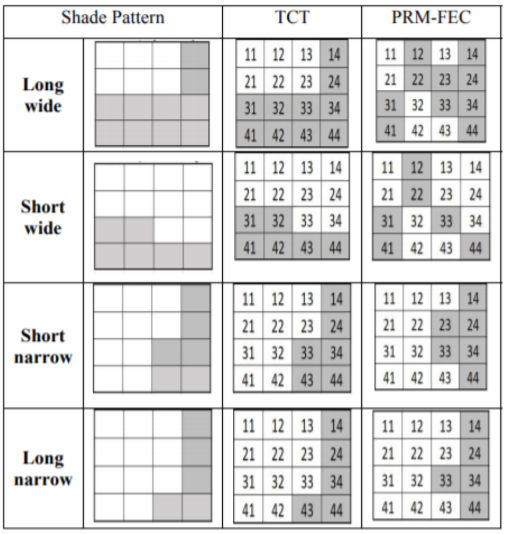

Figure 4.24: *Shadow patterns*

This method is not directly related to the MPPT control, but it is still interesting and another way to approach to the PV system control problems.

CHAPTER 5

Simulation scheme

5.1 General scheme

The aim of this simulation is to analyse and compare the diverse MPPT algorithms' efficiency at diverse shading speed dynamics, in 3 different array configurations and with 3 different groups of shadow shapes.

The whole set of code stages that conform the main core of the simulation, taking only into account the main analysis and tracking of the maximum power efficiency, can be basically summarized in the next points:

- PV field and shadow creation: A set up of $3x5$ PV modules and the shadows that pass over it.
- The power curve characteristic of the full configuration, calculated each time step basis on the module area that is irradiated.
- Tracking of the system maximum power working point, through the different algorithms.
- Average efficiency during the power transient generated by the shading condition.

5.1.1 MPPT techniques

The MPPT techniques chosen are typically found in literature and described in the literature review chapter 2. Their core code is based on the one used in [15] and is seen in the next sub-section flowcharts, which show the logic functionality of all the MPPT techniques used to track in the diverse scenarios.

Perturb and Observe, fixed perturbation step

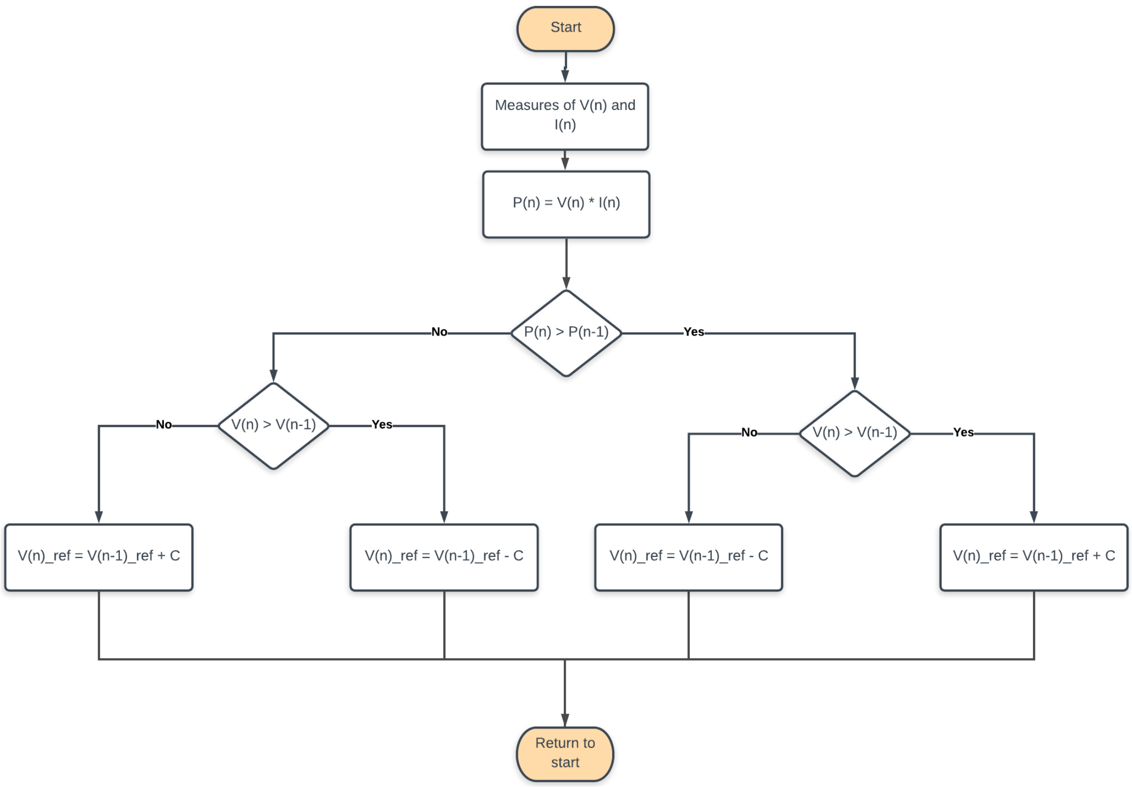

Figure 5.1: *Flowchart: P&O Algorithm*

The simple Perturb and Observe operation is shown above. An important annotation is that the reference parameter modification can be in voltage reference but also in the duty cycle reference, being both of them interrelated. The chosen parameter to be modified in the whole set of algorithms will be the duty cycle from now on.

Perturb and Observe, variable perturbation step

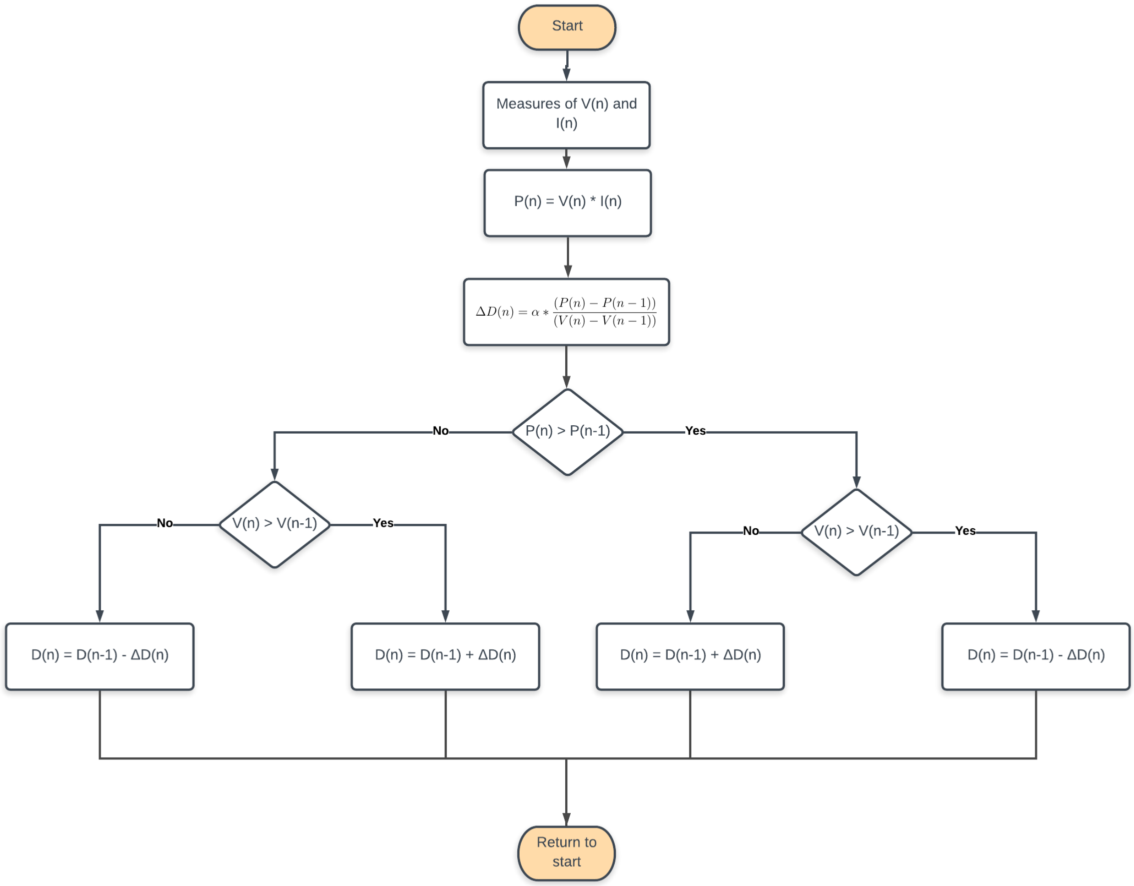

Figure 5.2: *Flowchart: P&O with adaptative perturbation step algorithm*

Variable step algorithm is a small variation of the previous method that demands an extra calculation for the acceleration term, which will affect the duty cycle increasing or decreasing its value.

Perturb and Observe, three weight points

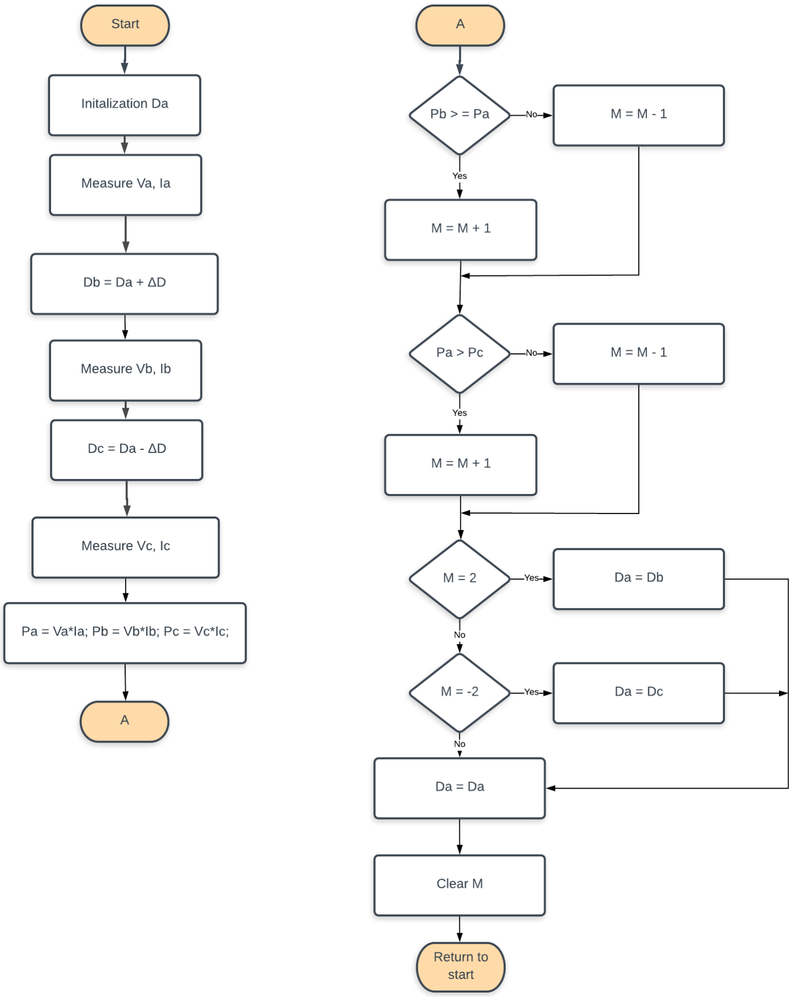

Figure 5.3: *Flowchart: Three weight point comparison algorithm*

As it can be seen in three weight point flowchart, this Perturb and Observe technique demands more time (3 measuring cycles) and also more variables storage. It firstly has an early measuring stage where the first measuring point depends on the results of the calculation stage, and the two sequential measuring points are bound to the first one.

Incremental Conductance

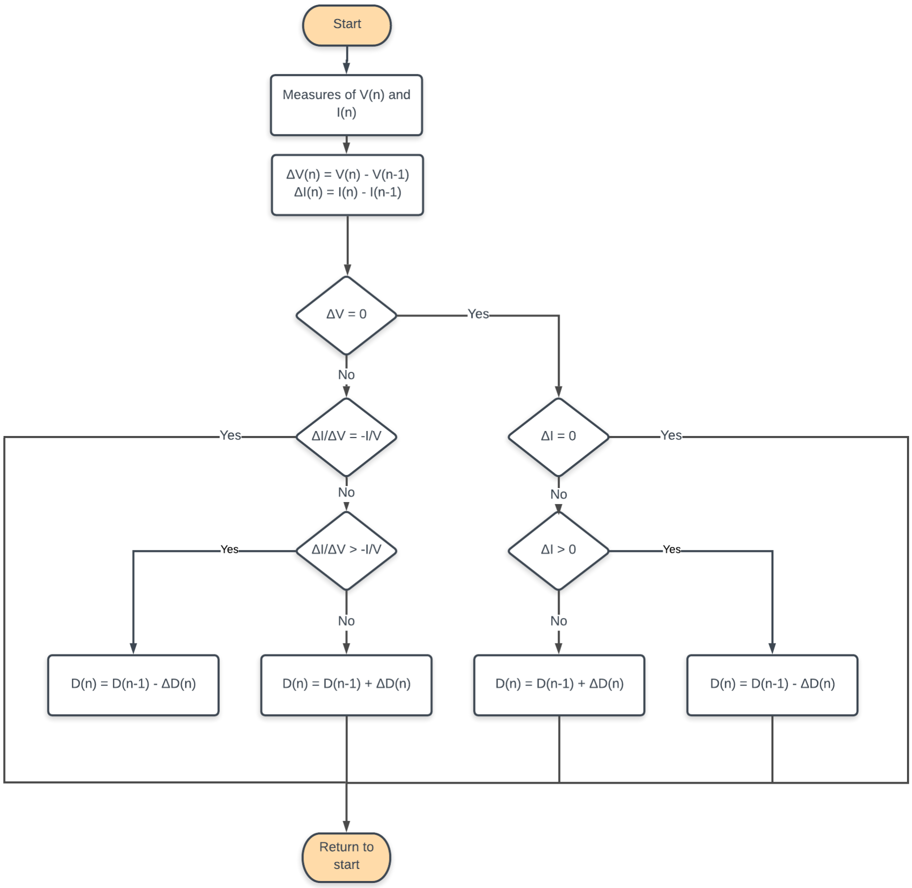

Figure 5.4: *Flowchart: Incremental Conductance algorithm*

This method has a fixed step perturbation on the duty cycle as in the first Perturb and Observe method. Its particularity is that the required sensors are bound to the voltage and current values of the system.

Initial PVI values

In the last four algorithm schemes an initial value is used to compare with the next cycle step. It is a trivial point, but it differentiates them once they have to be designed and encoded.

Nevertheless, in the end they only require an extra condition loop dedicated for this four cases, shown in figure 5.5.

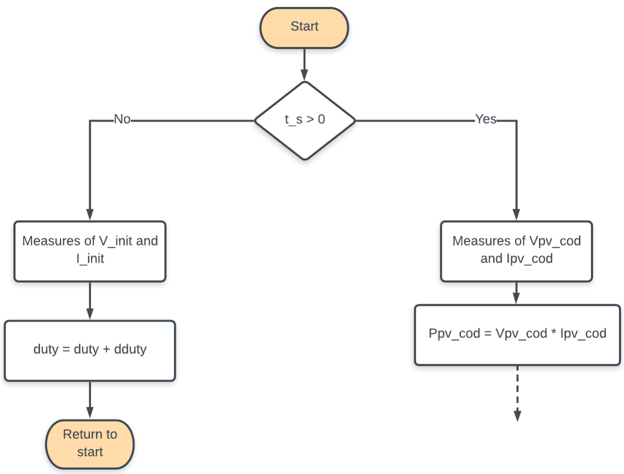

Figure 5.5: *PVI values initialization*

Fractional Short-Circuit Current

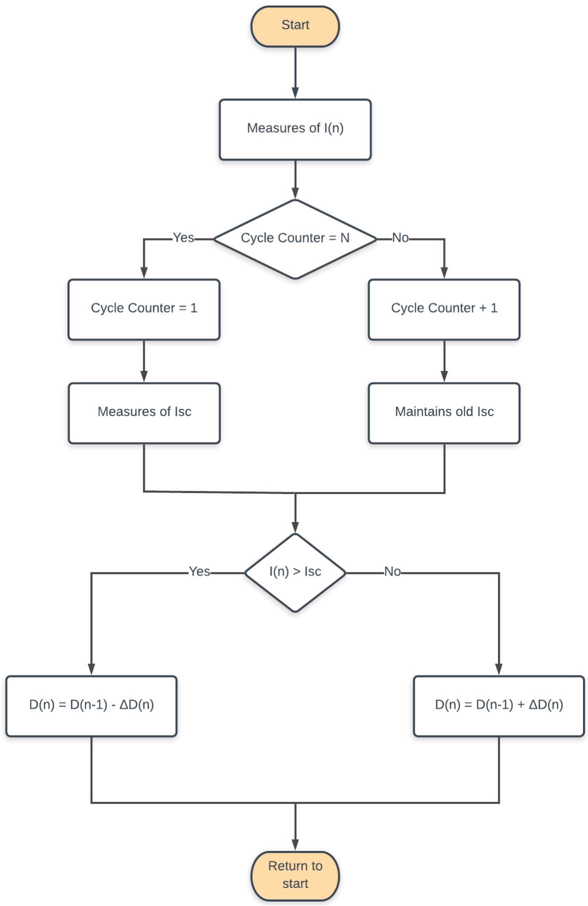

Figure 5.6: *Flowchart: Short-Circuit current algorithm*

This technique uses a cycle counter that is reinitialized each second, calculating and refreshing the reference value that is used to define the next duty cycle variation. A positive point of this method is the only need of a unique sensor, bound to the current of the system measuring.

Fractional Open-Circuit Voltage

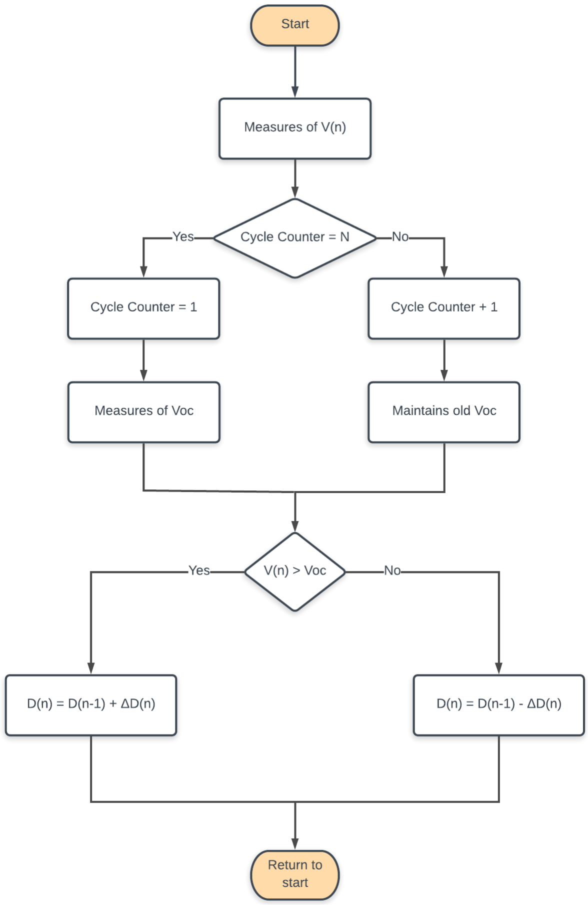

Figure 5.7: *Flowchart: Open-Circuit voltage algorithm*

In the same way as in the Short-Circuit current algorithm, this one uses a one second counter to reinitialize and refresh the reference voltage value. A sensor for measuring the voltage of the system is also needed.

Constant voltage reference

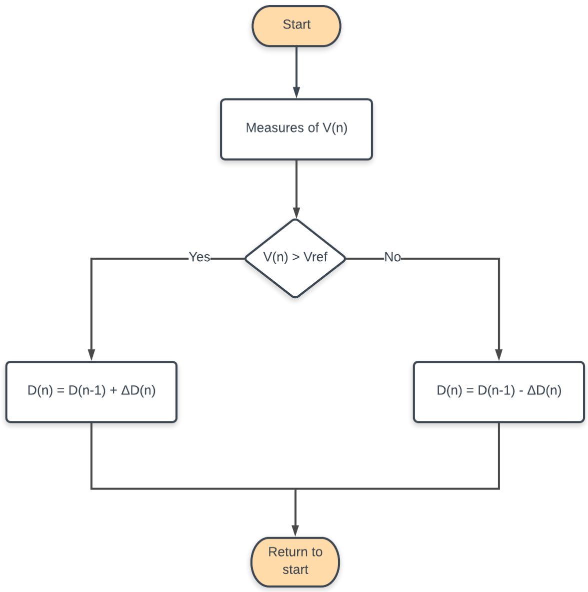

Figure 5.8: *Flowchart: constant voltage algorithm*

The flowchart shows the simplicity of this last conventional method. There is a constant reference value that is compared to the voltage measure of the system.

Particle Swarm Optimization

As it was described in chapter 2, Particle Swarm Optimization algorithms are based on the natural group behaviour, that share information to find their best response to the external stimuli and therefore guarantee the best survival capacity.

Particle Swarm Optimization algorithms purpose is to find the best possible solution to a problem, or in other words, the minima or maxima of an objective function (in this case, the PV curve). Each particle (with its own defined position and being a potential solution of the objective function of the problem) knows both, the position of the best solution ever found by the swarm and by itself. These particles do not go in a straight way to the best position, but they move towards it, travelling through their own paths, with their defined inertia and speed.

The idea of this 'travelling' is to explore the regions instead of directly choosing the best position. The inertia term refers to their own resistance to modify their speed towards the best position. This parameter is important, since its tuning can significantly change its response and solution convergence depending on the problem scenario. The relative position of the single particle respect its best position ever found by itself and the relative position of the single particle respect the best position ever found by the group also modifies its speed towards the best position. The inertia term works in the same way, given that it can be tuned based on the objective function related to the problem that is meant to be solved. These terms are also weighted by acceleration terms c_1 and c_2 with some random variability added by the random terms r_1 and r_2.

The complete equation that relates the speed of the particle to the best position of the system can be seen in equation (5.1) and equation (5.2).

$$v_i^{k+1} = w \cdot v_i^k + c_1 \cdot r_1 \cdot \left(p_{best,i} - x_i^k\right) + c_2 \cdot r_2 \cdot \left(g_{best} - x_i^k\right) \tag{5.1}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{5.2}$$

Each particle speed is refreshed each cycle, that consists in a set of time step related to the number of particles used (5.1), updating the position of the group of particles at the end of the last time step (5.2) and computing a new family set of positions that will be used in the next cycle once again in (5.1).

Generic flowchart

The last equations are used in an iterative way until the pre-defined criteria reaches the convergence point. The full flowchart of the generic Particle Swarm Optimization algorithm application is shown in figure (5.9).

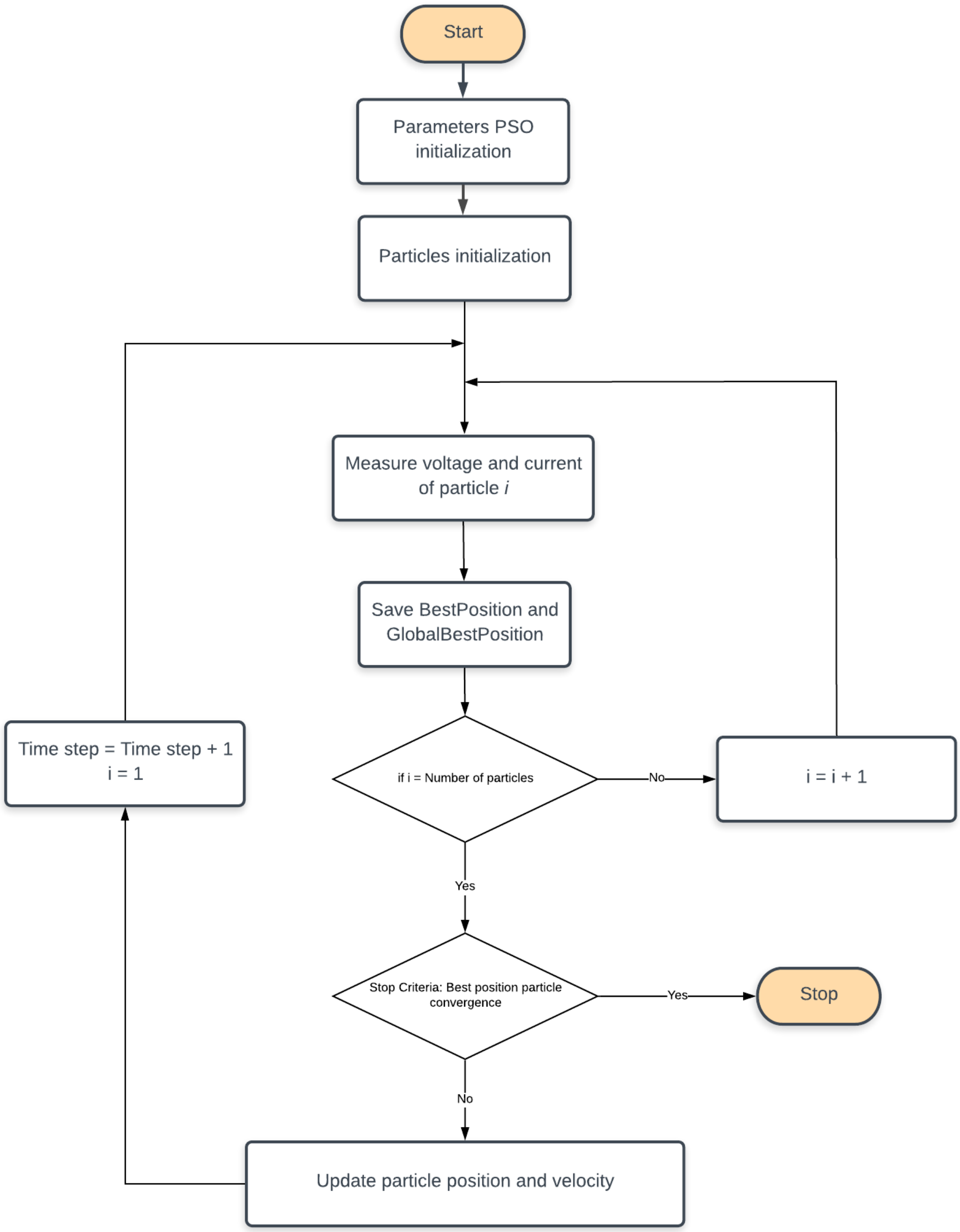

Figure 5.9: *Flowchart: Particle Swarm Optimization algorithm*

Stop criteria, check and reset

Once the particles' position converges into a sufficient small region or a singular point, the algorithm shall stop its iteration, since the global maxima is supposed to be found. However, that singular case is considering a completely static scenario where the objective function, the PV curve of the array configuration, does not vary along the time. In the real world, and so in this scenario simulated, the PV curve will be normally modified due to the shadow transient that crosses over the PV field.

Then, it is necessary using an extra algorithm condition, not only to find the convergence point of the objective function, but also to be able to feel the significative changes on the PV curve after a convergence (even in the same particle position or duty cycle).

Finally, the full process done by the algorithm can be summarized in the next points:

- Particle Swarm Optimization tracking: Iteration process until the best position remains constant during 4 sets of particle families iteration (then it reaches the 'stop' in (5.9)). However, if the convergence does not arrive in the 15th family iteration the process is restarted, returning to 'start' in (5.9)). During all the process, the best position (and power value bound to it) is saved, and refreshed if it is surpassed.

- Check MPP: Checking the actual power extraction of the system and comparing it with the MPP saved during the iteration process. Overcoming an error threshold resets the iteration process (returns to 'start' in (5.9)), otherwise the duty cycle that corresponds to the MPP power is saved and the code is redirected to the control of power changes.

- Check power changes: During the duty steady state condition, power changes must be controlled, comparing the actual power extracted with the MPP power saved in the last steps. Overcoming an error threshold between those two values resets the iteration process (returns to 'start' in (5.9), otherwise duty cycle remains unvaried until new significant perturbation.

In this way, it is implemented a stochastic algorithm, capable to look for the MPP extraction of the system and at the same time notice the environment changes due to the shadow transient.

Genetic Algorithm

The characteristics of a living being are represented in its DNA codification as a chain of information. When the animal has better conditions to survive and reproduce, its information will be passed to their offspring and so on. This is emulated in the Genetic Algorithm, with a gene codification which is evaluated in a function which is supposed to be tracked in an optimization problem. This value of this gene is called chromosome in this nomenclature.

The stochastic part of the method in found in the gene crossover and in the possible mutation of the future gene combination. The steps to follow are the next:

- A family set of values is initialized (4 values in this concrete case) between a given threshold range of duty cycles. These values are transformed into a binary code of 10 digits (gene) and evaluated in the objective function (the PV curve), returning the value of it (chromosome).

- Then, the 4 values are compared, assigning a value between 0 and 1 (their relative weight). This weight will be the point to consider in the moment of selecting the best genes to conform the next family set of values (offspring). If the weighting value surpasses a threshold value, the gene priority will make it reproduce twice. If it surpasses another threshold value, three times, and so on. Depending on the number of genes, this aspect can be used if the algorithm convergence is working correctly.

- The selected genes conform a new family of 4 genes in binary form. Then, are randomlye mixed (crossover). For example, if the binary number is of 10 digits, the first 3 binary digits of the first gene can be mixed with the 7 lasts digits of the second gene, and vice versa.

- When the new family of 4 genes is already generated, a function is used to generate a random number. If it surpasses a threshold that will imply the mutation of one gene (that is, swapping the 0 or 1 in the binary code). This is done iteratively for each gene of the family.

- The new family of genes will be evaluated and all the process is done once again, until the convergence criteria is reached.

Generic flowchart

The steps mentioned before are represented in the next figure (5.10), which shows the iterative process of the stochastic algorithm.

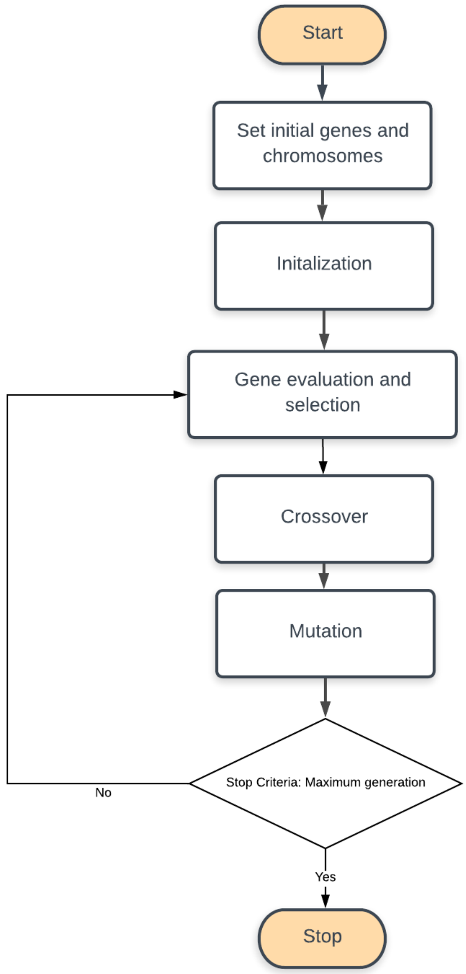

Figure 5.10: *Flowchart: Genetic algorithm*

Genetic Algorithm enhanced: Survival

The main core of the code is shown in figure (5.10) and it works basically as in the typical GA model explained before, but there are some aspects to comment about this modified algorithm. The parameters that are tuned to modify the response and behaviour of the algorithm are in the Table 5.1

Table 5.1: *Table caption*

Parameters	Range of values	Meaning
Step	[0,1023]	Creates a narrower range of initial values (duty cycle)
Perturbation	[0,1023]	Survival gene perturbation
R code crossover	[0,10]	Selects the bit position where the genes are mixed
Gene priority 1	[1,1.5]	Threshold which determines the importance of a gene
Gene priority 2	[2,2.5]	Threshold which determines the importance of a gene
R code mutation	[0,10]	Selects the bit position where the code is muted

These parameters are the ones chosen to be tuned to achieve a good performance of the algorithm:
- The first one, 'step', can be used to close the initial guess of the duty cycle value family. That can be useful when the objective functions are not totally unknown.
- 'R code crossover' has shown that does not affect the convergence unless the values were on the extremes.
- 'Gene priority' 1 and 2, are the most important parameters to be tuned. If the number is close to 1 or 2, the threshold of the gene to reach the selectivity phase is much lower. Therefore, in general a low value shows a fast convergence, but also a poor chance of reaching the correct optimal point.
- 'R code mutation' selects which binary digit is mutated in case of mutation. The closest to 1 the strongest is the effect of mutation and vice versa. Then, a high value will difficult the convergence of the algorithm while a low value gives a fast convergence but a poor chance of reaching the correct optimal point as in the 'Gene priority' parameter. That can be compared to the explorer aspect of the nature-based algorithm. This 'exploring' side is the one that gives some extra information to the group to be able to find better options. This stochastic part is the main point to use this type of algorithms that can overcome the local maxima and find out where the global maxima are.

The last parameter to comment affects the enhanced part of the Genetic Algorithm ('Perturbation'). This parameter sets up the range that the survival gene 'explores' when one iteration process is over.
The survival gene plays the role of the strongest gene that does not disappear, even if the mutation plays against it. That is, the gene family has a collective 'memory' of which genetic code is more beneficial for the group and if the exploring part of the algorithm (mutation) makes a bad step and destroys a good gene, the worst gene of the family is replaced with the best gene ever grown in it.

This implementation can be used for 1 or more genes, depending on how many genes are conforming the family set of values. On the other hand, this new condition allows to tune the exploring part of the algorithm in a more aggressive way, since there is a strong convergence condition due to the survival gene.

Stop criteria, check and reset

As in the PSO algorithm, when Genetic Algorithm reaches a point of converge into a sufficient small region or a singular point, the algorithm stops its iteration. In the same way, this algorithm shall be able to notice the external modifying conditions (the PV curve is modified during the shadow transient).

The stopping criteria is summarized in the next points:

- Genetic Algorithm convergence: Iteration process until the best position remains constant during 4 sets of particle families iteration (then it reaches the 'stop' in (5.10)). However, if the convergence does not arrive in the 15th family iteration the process is restarted, returning to 'start' in (5.10)). During all the process, the best position (and power value bound to it) is saved and refreshed if it is surpassed.

- Check MPP: Checking the actual power extraction of the system and comparing it with the MPP saved during the iteration process. Overcoming an error threshold resets the iteration process (returns to 'start' in (5.10)), otherwise the duty cycle that corresponds to the MPP power is saved and the code is redirected to the control of power changes.

- Check power changes: During the duty steady state condition, power changes must be controlled, comparing the actual power extracted with the MPP power saved in the last steps. Overcoming an error threshold between that two values resets the iteration process (returns to 'start' in (5.10), otherwise duty cycle remains unvaried until new significant perturbation.

A stochastic algorithm capable to look for the MPP extraction of the system and at the same time notice the environment changes due to the shadow transient is implemented.

Combinations and flowchart

The combinations used in this MPPT algorithms are:

- Particle swarm optimization (4 particles) / Perturb and Observe (fixed perturbation step)
- Particle swarm optimization (4 particles) / Incremental Conductance
- Genetic algorithm (4 genes) / Perturb and Observe (fixed perturbation step)
- Genetic algorithm (4 genes) / Incremental Conductance

The method that follows this combined control algorithm is shown in the figure (5.11).

Threshold definition and example application

The criteria used to jump from one algorithm type to another depends on many factors, such as the array configuration, which determines the maximum power that the system is available to provide, the external conditions, which can be more or less aggressive in relation to the P-V curve shape and the type of algorithms used to track the maximum power (also the parameter tuning of the stochastic algorithms).

In this code a threshold of 500 W seems to be a fair limit between the using of one or the other algorithm. On the one hand, it is a bit more than a 10% of the maximum power developed by the PV setup configuration defined in the simulation program, and the different types of shadows that will affect it too has been taken into account, that is, there will be scenarios where the shadow will be enough to trigger the swapping algorithm criteria and other cases where it is not sufficient. In this way, in this point of view the performance of the combined algorithm can be also compared.

A combined algorithm made of a GA and Perturb and Observe union is shown in figure (5.12).

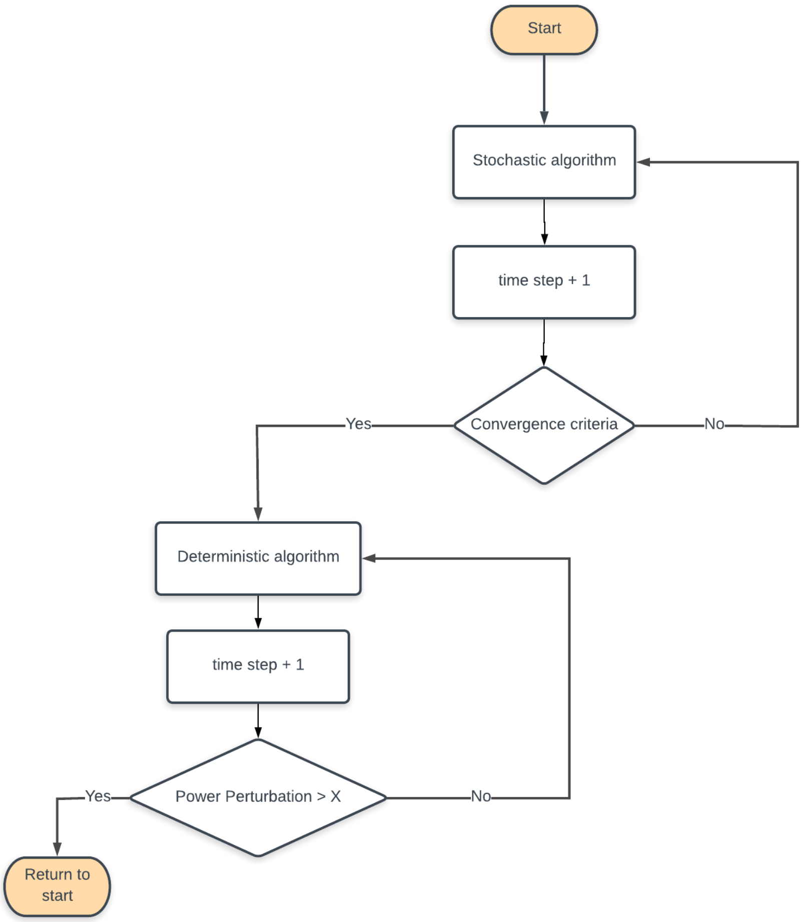

Figure 5.11: *Flowchart: Combined algorithm*

While in the first perturbation the shading condition, and therefore the irradiation over the PV configuration, is small enough to set the maximum power in a difference less than 500 Watts, in the second the variation is higher than 1000 Watts.

First of all, the algorithm uses the Genetic Algorithm, the stochastic method, to find the MPP in full irradiation condition and at that moment swaps into the deterministic algorithm.

Then, a small shading condition is applied into the system. However the algorithm stays in the deterministic algorithm since it is not enough to trigger the swapping condition.

Only once the second perturbation overcomes the threshold of 500 Watts, the algorithm redirects once again into the stochastic algorithm until finding the new MPP,

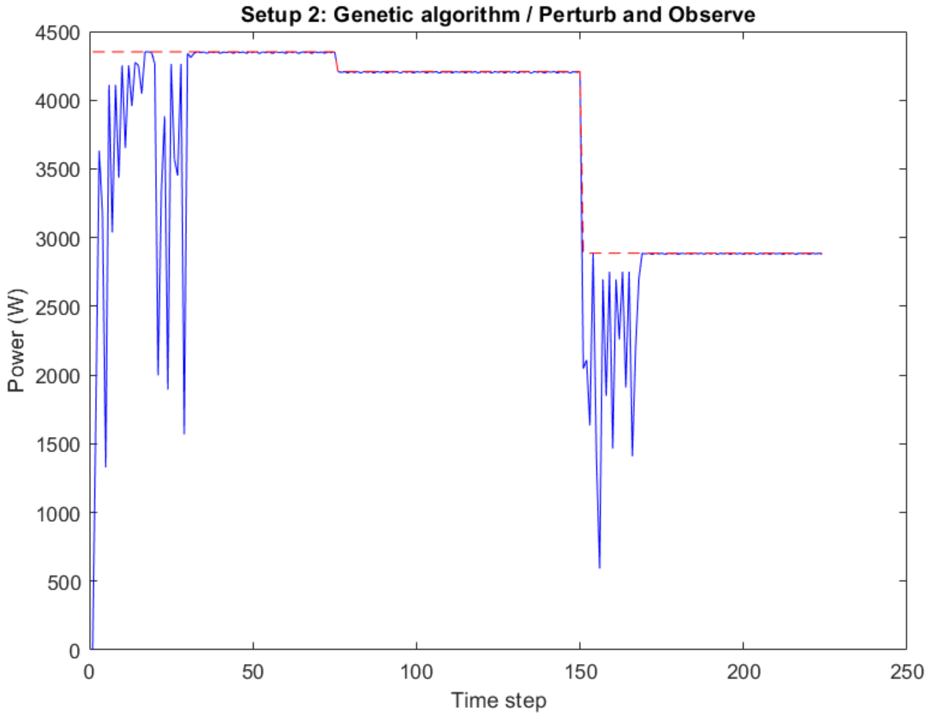

Figure 5.12: *Combined algorithm under two perturbations*

changing finally again into the deterministic Perturb and Observe method.

5.2 Code stages

5.2.1 PV array configuration field

The array configuration is defined as a $5x3$ PV panel matrix. Each PV module is conformed, as seen in chapter 3, by 60 PV cells connected in series and by-passed each group of 20 cells. Each cell has 15 cm of length and width and it conforms the unity value of the first stage matrix in the MATLAB codification.

The whole configuration is organized as a $5x3$ field where there are 2 units of distance between all PV modules. This is shown in figure (5.13). As it can be seen, the variable is a two-dimension matrix where each unit corresponds to one cell.

The distance between the edges of the matrix and the PV modules can be modified by a ratio, so when creating the shadow, it can be bigger or smaller to fit it correctly.

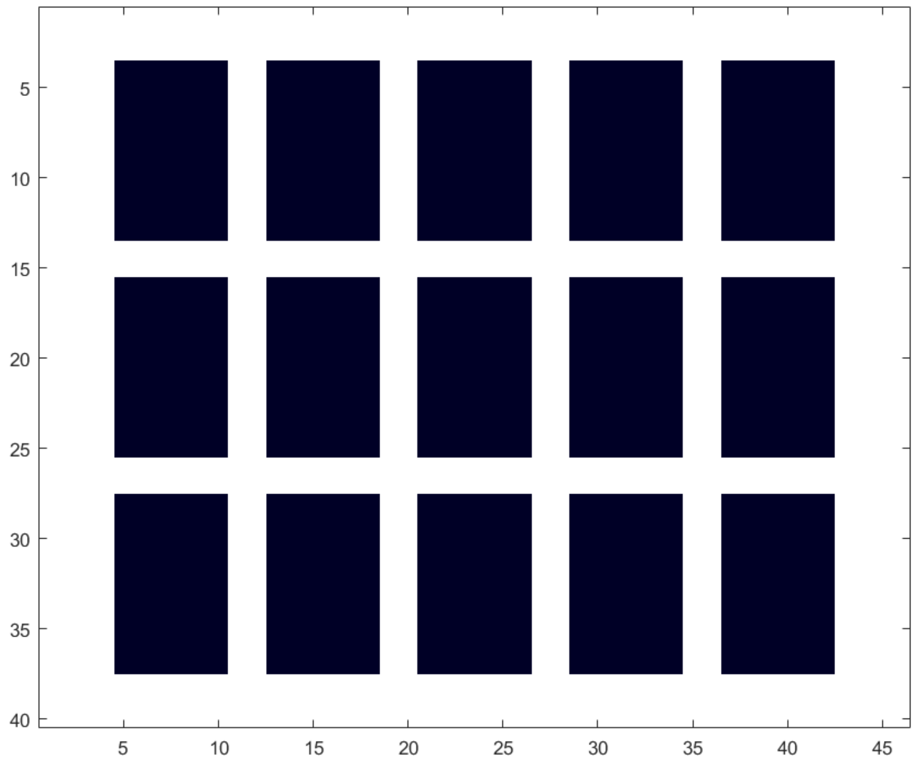

Figure 5.13: *PV module configuration*

5.2.2 Shadow definition

The shadow is defined in the same variable of the PV module configuration, but in a third dimension. In this way, 3 more fields are used (two-dimensional fields) with the PV module configuration size, to define the shadow per se and its horizontal and its vertical position.

There are three different types of shadows defined in three subgroups:

- Vertical group: Compound by 4 similar shadows. These shadows cover from 1 to 4 column arrays. That is, $3x1$, $3x2$, $3x3$ and $3x4$ panel size. The vertical group will move through the field from left to right in a straight direction.
- Horizontal group: Compound by 3 similar shadows. These shadows have these shapes: $1x3$, $2x4$ and $3x5$ panel size. This group will move in $45°$ (same speed in left-right and up-down direction).
- Multi-peak group: Compound by 3 diverse vertical shadows. These shadows are

defined to create a 3, 4 and 5 peak P-V curve when they are full covering the PV module configuration. They follow the same direction as in the vertical group.

They are more detailed in the next chapter.

The figure (5.14) shows graphically the first shape of vertical and horitzontal group and their speed direction.

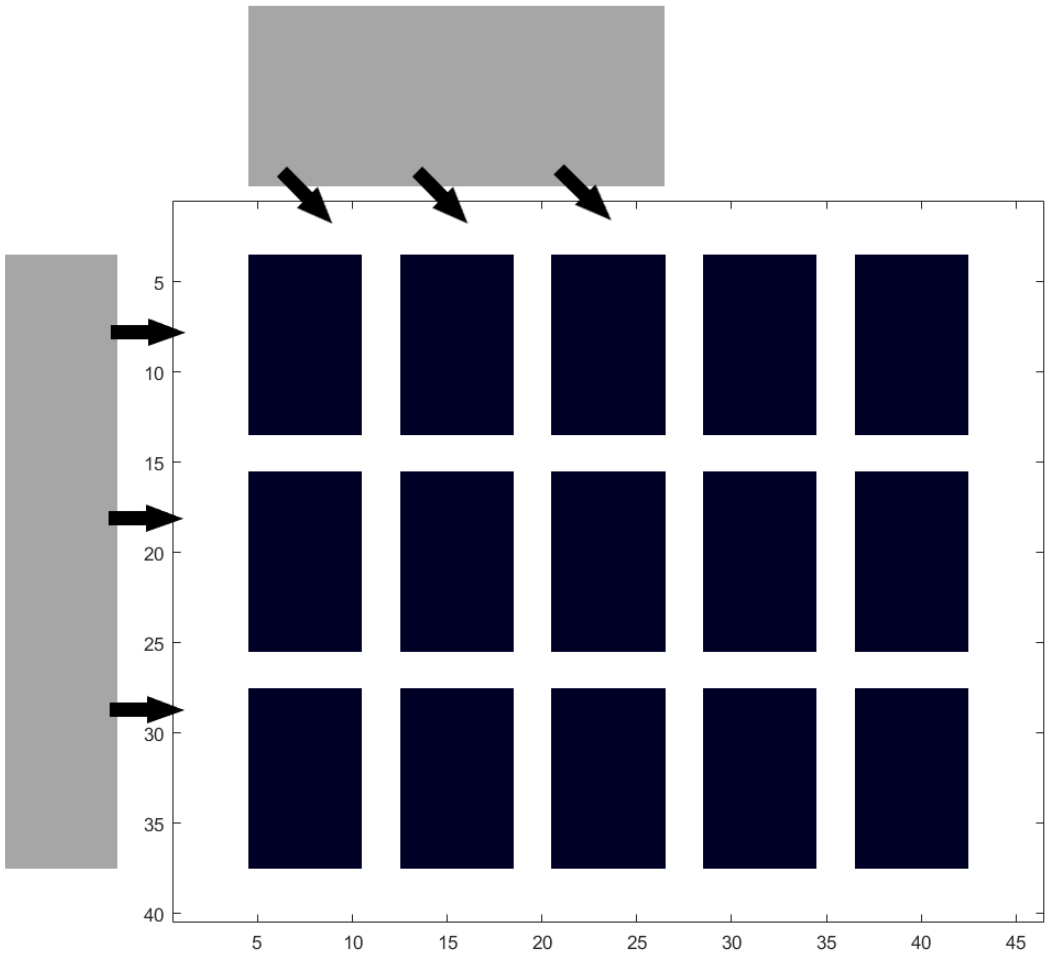

Figure 5.14: *PV module and shadow configuration*

5.2.3 Irradiation and P-V curve calculation

Irradiation is calculated at each time step, 0.05 seconds, according to the ratio between the full PV module covered by the shadow and the PV module total area.

Then this value is used to calculate the I-V cell, I-V module and I-V array configuration outputs successively and therefore, the P-V characteristic curve from all of them (following the procedure of chapters 3 and 4).

In the last stage, I-V array configuration outputs calculation, there will be 3 possibilities, as it was defined in early chapters: the full series array, the $3x5$ series-parallel array configuration and the $5x3$ series-parallel array configuration with their respective P-V curves.

5.2.4 Tracking algorithm

Once each PV array configuration curve is calculated, it is time to track the maximum power through a MPPT algorithm.

A DC-DC boost-buck converter is defined with an external constant load (resistance). The algorithm must evaluate the I-V and output power characteristics (based on the algorithm used) and modify the duty cycle of the DC converter, which will change the resistance observed by the PV configuration side and, therefore, the load curve will be modified, changing the working point (crossing point between P-V curve and load curve) and creating a new I-V and output power characteristic.

If the MPPT works according to its function, it will pursue the highest power extraction through the power converter duty cycle modification.

5.2.5 Efficiency calculation

The efficiency calculation is done with the ratio of the tracked power split by the maximum power point which can be extracted from the system at each time step. The efficiency equation can be seen in (5.3).

$$\eta_{MPPT} = \frac{\sum_{t_1}^{t_2} p_{DC}(t)\Delta t}{\sum_{t_1}^{t_2} p_{MPP}(t)\Delta t} \tag{5.3}$$

5.3 Simulation flowchart

5.3.1 Start-End condition

The shadow is defined just next to the PV module array configuration. A 'transient' variable with a value of 75 is set up with a decremental counter. That is, while the variable is still up, the speed of the shadow remains zero. That gives a minimum time to stochastic algorithms to reach the convergence in the initial characteristic curve and, therefore, all different algorithms will start with the same initial condition: the MPP position under full irradiation condition.

Once the transient time step is over, the shadow acquires the speed and it moves through the field at each time step until it gets out of the PV module field. At this point, another counter is initialized with the same number of steps as in the 'transient' variable. Finally, when it runs to zero, the simulation ends.

5.3.2 Core simulation

The speed range is spread from $1cm/s$ until $10m/s$, in a logarithmic interval. It starts from $1cm/s$ and at the end of the core simulation it increases according to the last speed used until it reaches the last one, $10m/s$.

In the next subsections two flowcharts that represent the main functionality of the simulation seen in figure (5.15) and figure (5.16) are presented.

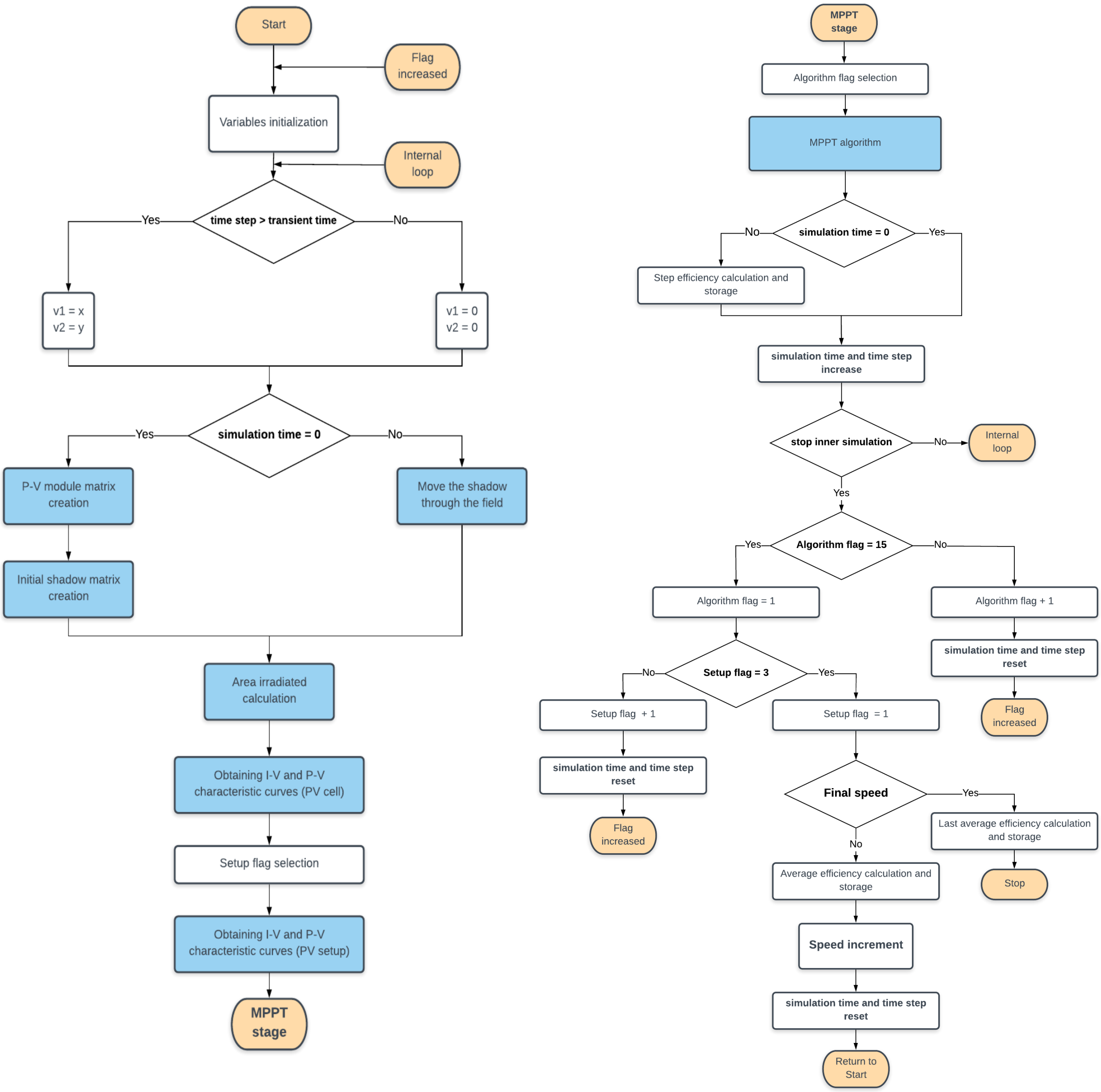

Figure 5.15: *Flowchart: Series simulation*

5.3.3 Comparison and MATLAB Cloud application

The series case simulation is the first design and the most versatile because just one MPPT algorithm can be chosen to be simulated separately. The parallel one is more complicated to use since it requires much more time to set it in an individual MPPT operation. However, it solves the time-consuming issue, improving almost 35 times

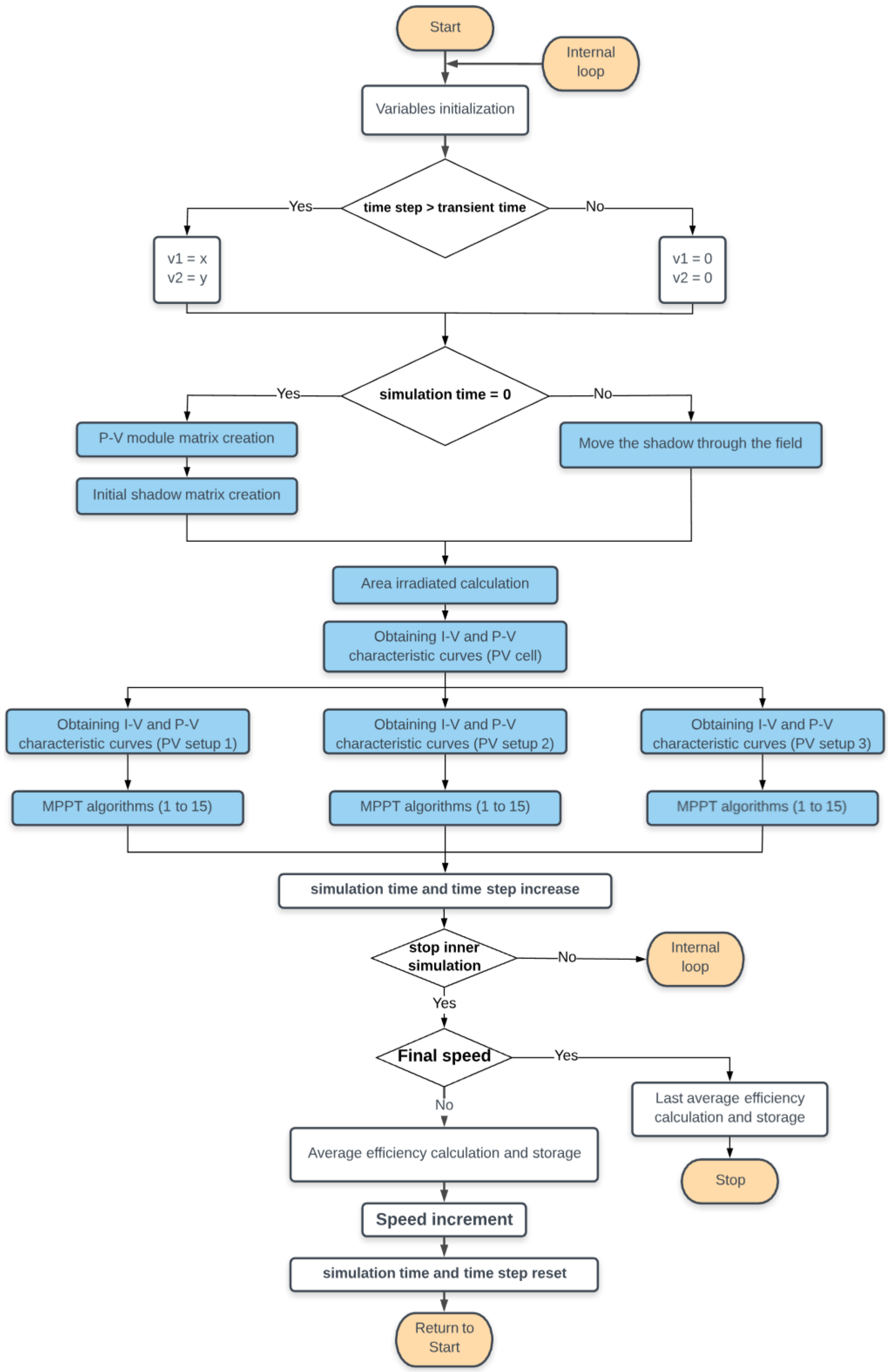

Figure 5.16: *Flowchart: Parallel simulation*

the series one, without incrementing the CPU charge (extra variables do not overcharge the processing, but increase slightly and practically in an insignificant way the memory charge).

Therefore, the multi-speed simulation is done in a parallel simulation configuration, which requires less time.

MATLAB Cloud

In case of needing an extra speed boost, if the simulation requires a high CPU charge or it is extremely time consuming, there are some applications, provided by the same MATLAB creators, or some other providers like Amazon Web Services (AWS) or Microsoft Azure, to virtually parallelize a processing setup to increase the simulation speed and to store and share data.

5.4 Data analysed

5.4.1 Power tracking curves

For each shadow speed test, the maximum power point of the system and the tracking power of the algorithm are stored at real time, which is the sampling time of the microprocessor, 20 Hz. Therefore, 45 power tracking curves are obtained, due to the 15th algorithm and the 3 different setup configurations.

Even though an efficiency number is not obtained yet, these graphs can give interesting information that just an average number can not do, such as if the algorithm has a bad performance because it got stuck in a local maximum. In this case, it will be observed that the tracking power traces a path that seems coherent but not next to the maxima path.

Another example could be the case of constant reference algorithm, such as short-circuit current or open-circuit voltage, that strongly depend on the disposition of the array configuration towards the geometry shape of the shadow. In that specific analysis, the different setups can be compared in a graphical way to understand which algorithm is less affected by the shadow scenario.

In a general point of view, this information can show which setups are better or worse for the different scenarios of shading in a more visual way that just a set of values.

Another example of power tracking curves is shown in figure (5.17), where two combined stochastic algorithms track the MPP when a vertical shadow is passing through the PV array configuration at $1m/s$. Another advantage of plotting this tracking power

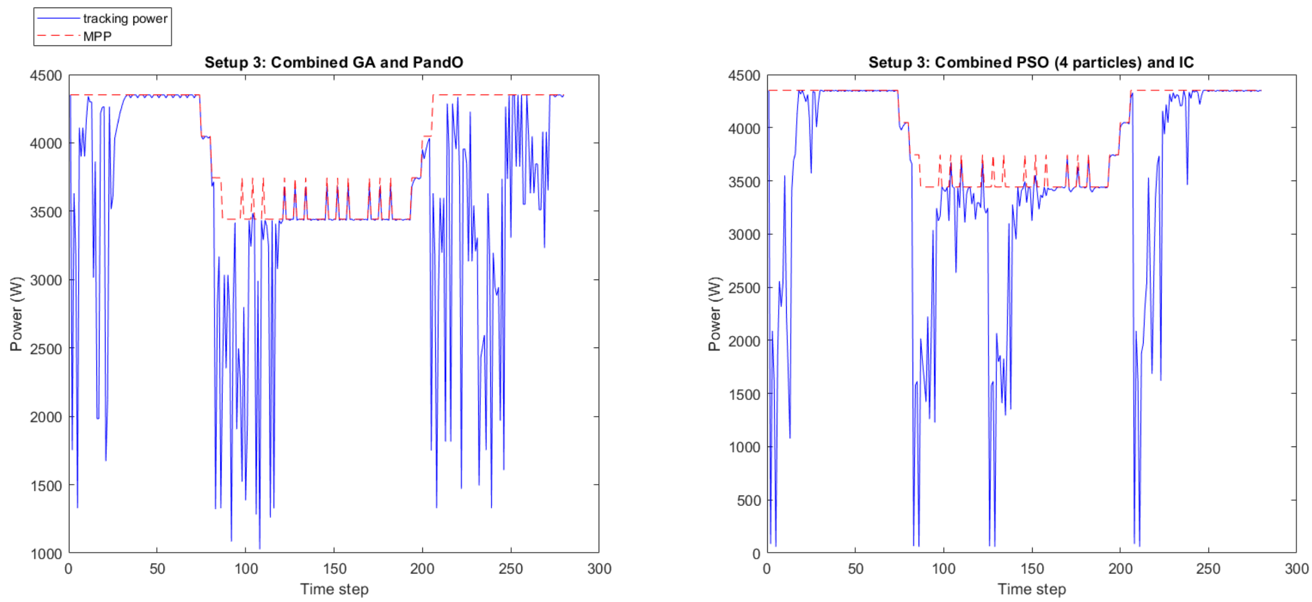

Figure 5.17: *Power tracking graphs*

graphs is to be able to compare the algorithm effectiveness between different speed dynamics. Furthermore, in case of stochastic, it can also give some important feedback during the designing stage and tune their parameters, while it can be checked which convergence speed is reached, if the convergence is robust and accurate, and also how much is triggered the resetting part of the algorithm code, and in consequence tune its sensibility.

5.4.2 Algorithms efficiency

There are three possibilities to extract the average efficiency: from the start of the simulation until the end (region 1, 2 and 3), the first time the shadow passes over the PV module of the array configuration until it completely leaves it (region 2), and from the first time the shadow passes over the PV module of the array configuration until the end of simulation (region 2 and 3). In figure (5.17) the different considered regions are shown. The basis to choose which region is going to be considered to compare between algorithms depends on the initial parameters definitions in the whole code.

Deterministic algorithms start on the best duty position when the PV module is full irradiated, that is why it has no transient to find the maxima before the shadow path

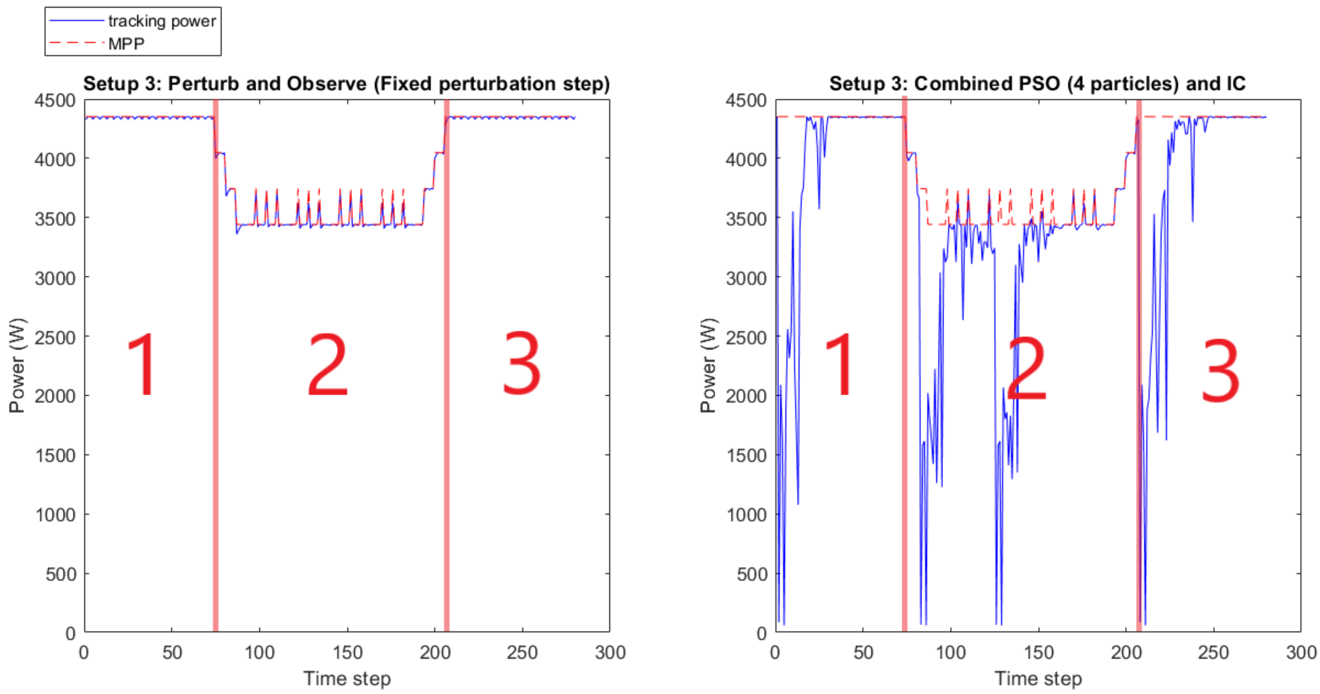

Figure 5.18: *Efficiency regions*

starts.

On the other hand, stochastic algorithms start with the reset part of the code where they take a constant family of values between the duty cycle range pre-defined. Therefore, region 1 is not a fair way to compare between deterministic and stochastic algorithms, and it must be dismissed. Region 3 doesn't present that problem since both types, stochastic and deterministic, come from a shadow transient stage. However, that region belongs again to a full irradiated condition and the study is mainly centred in the partial shading transient. Hence is taken uniquely the region 2 range to calculate the efficiency average of the MPPT techniques.

CHAPTER 6

Algorithms efficiency comparison

6.1 Introduction

The whole algorithm set has been distributed into 4 groups, to guarantee an easier view and analysis in the MATLAB plot graphs. The deterministic perturbing step type (1 to 4), the constant reference type (5 to 7), the stochastic algorithms (8 to 11) and the combined algorithms (12 to 15). The named algorithms are sorted in this order:

- Perturb and Observe, fixed perturbation step
- Perturb and Observe, variable perturbation step
- Perturb and Observe, three weight points
- Incremental Conductance
- Fractional Open-Circuit Current
- Fractional Open-Circuit Voltage
- Constant voltage reference
- Particle Swarm Optimization, 3 particles

- Particle Swarm Optimization, 4 particles
- Particle Swarm Optimization, 5 particles
- Genetic Algorithm
- Combined algorithm: Particle Swarm Optimization (4 particles) and Perturb and Observe (fixed perturbation step)
- Combined algorithm: Particle Swarm Optimization (4 particles) and Incremental Conductance
- Combined algorithm: Genetic Algorithm and Perturb and Observe (fixed perturbation step)
- Combined algorithm: Genetic Algorithm and Incremental Conductance

The analysis will be focused on the algorithm efficiency comparison at different shadow speeds, with diverse shadow shapes and array configuration scenarios. The different sets of results come up to 45 efficiency plots (efficiency percentage versus the shadow speed step).

A several group of charts and data will be analysed, comparing the trend of the groups in the range from $1cm/s$ to $10m/s$.

6.2 Sampling frequency

Before starting with the efficiency analysing, the global sampling frequency must be defined.

First of all, it is necessary to consider the shadow speed advance and the microprocessor sampling frequency because the maximum power point curve resolution will vary according to those two variables (where the MPP curve resolution is referred to the MPP curve sampled by the sensors with the microprocessor frequency).

If there is a high shadow speed, the MPP curve will change the irradiation condition of the setup array configuration and the PV curve in a strong fast way and, therefore, the maximum power curve will vary quickly. This means that to maintain the resolution of the curve, the sampling frequency of the microprocessor must be higher at faster speeds. Then, higher dynamics requires a greater investment in a better control system for the PV array extraction power system.

In a hypothetical case, if a high edge technology microprocessor with an almost infinite sampling frequency capacity is available for the control system, it can not be used at the highest resolution rate because the whole system is composed by a closed control loop where the duty cycle of the power converter must be changed with the electrical transient time that it entails.

Therefore, there is an another time limitation to the system. In a simple way, there is a maximum shadow speed, or power curve changing, that can be correctly sampled and tracked, depending on the transient ratio of the power system (depending on their inductance, capacitance and resistance). However, the electrical transient is usually much lower than the time step used in this analysis (0.05 s).

In the next figure (6.1) the power curve that is drawn through a constant microprocessor sampling frequency at different shadow speeds ($1cm/s$, $10cm/s$, $90cm/s$ and $10m/s$) is shown.

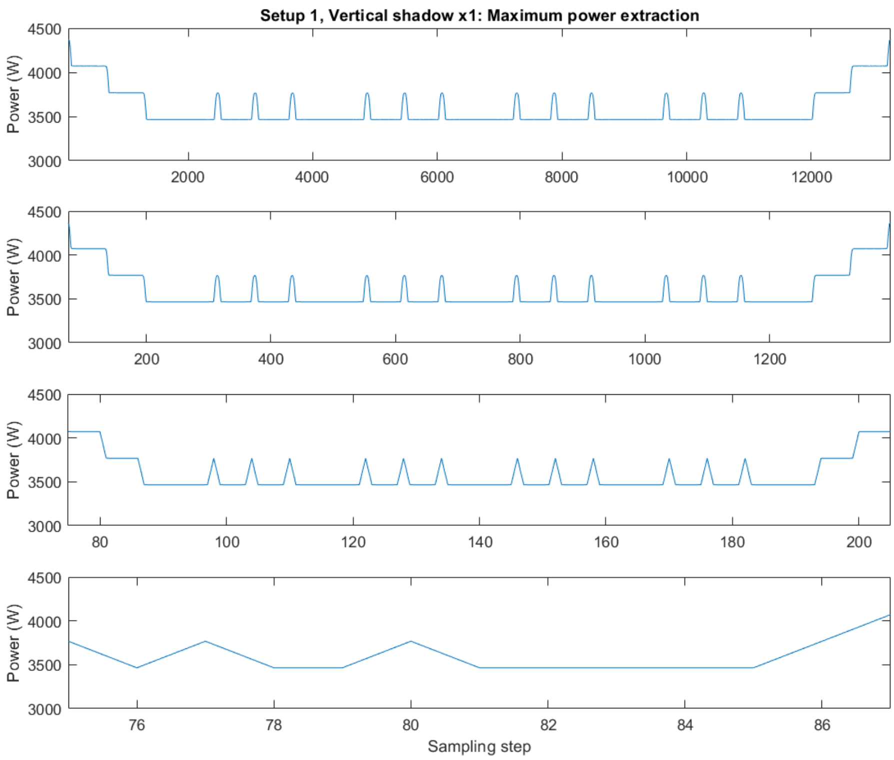

Figure 6.1: *Maximum power curves: Sampling frequency*

The main point of this graph is showing how the shape of the maximum power curve is affected based on the sampling frequency versus the shadow speed advance. The MPP curve is the hypothetical maximum power that could be extracted if the MPPT reached the 100% of effectiveness at each step of time.

The sampling frequency is constant in all cases, $20Hz$. This means that the faster the shadow is, the faster the characteristic curve is modified and, therefore, the MPP. When the PV characteristic curve changes much faster, the sampling rate is not enough to capture a correct MPP varying. If figure (6.1) is observed, a high resolution curve can be seen in the first plot. In this case, the shadow advances $1/300$ the length of the unit PV solar cell (which is $15cm$ length) per each time sample. The PV array characteristic is slightly modified during this sampling period and the final power curve at the end has a high resolution.

Moving through this graph, the second plot is done under a $10cm/s$ travelling shadow. Its definition is practically the same as in the first case. In the third plot it can be seen how the resolution of the curve is far lower, but somehow the MPP point follows the trend of the past plots and, therefore, the MPP can still be found through a searcher algorithm. However, in the last plot, it can be seen how the lower sampling frequency induces a poor definition of the MPP curve (compared to the real one).

Actually, there is an extra consideration with respect to the last curve. It is shown as a continuous function, but the real graph should be a set of points or, at least, one defined point that goes on the same value until the next step sampling time, being a horizontal line. In the highest resolution sampling cases the curve would remain visually unchanged.

Returning to the curve analysis, the first MPP curve is the closest one to the reality that can be obtained (with $20Hz$ and the lowest shadow speed). In the other cases, the real MPP curve is always as in the first case, but with 'infinite' resolution. Therefore, in the fourth one the sampled values extracted from the real curve are so limited that the MPP curve generated differs considerably with respect to the real one. That is, the system will maintain one value of duty cycle during a period when it should clearly vary, but it can not perceive this change because the sampling frequency is too low. Hence, even if the reference is generated in the hypothetical MPP in one sampling step, it will have a high error since it will give a fixed reference value during a large period of time. In consequence, in this scenario it is irrelevant which kind of algorithm is used, because the tracking part generates too much error and then its use is meaningless.

At this point, the correct tracking will depend more on the knowledge of the PV setup array configuration and the external characteristics to set a more or less correct (optimal) duty cycle which corresponds to a close MPP, since there is no physic time to track and to modify fast enough the duty cycle to relocate the working point to the MPP due to the high dynamics. Actually, the incorrect tracking can induce to more losses if it sets a wrong MPP, such as in the stochastic algorithms case, where the changing of the MPP curve characteristic during the obtaining of a family set of values can make it fail completely, since it gives diverse reference values to a method that is supposed to find a global maxima of a unique objective function and it is finding or trying to find out where is the global maxima of an objective function inside a transient modification. That is why in these cases, a correct data analysis of the PV setup MPP curve may produce a better behaviour of the system than MPPT algorithms.

6.2.1 Shadow speed threshold

As seen in the last section, there must be a point where the sampled MPP curve starts differing too much with respect to the real one to be considered as an accurate reference to be used by MPPT algorithms. In this section, it is explained how the condition of constant sampling frequency and varying shadow speed affects to the whole set of cases.

The table (6.1) shows the thresholds where the curve reference becomes a bad sampled representation of reality. When the shadow overpasses these thresholds, the power

Table 6.1: *Shadow speed thresholds*

	Vertical shadow	**Horitzontal shadow**	**Partial shadow**
Setup 1	60 cm/s	80 cm/s	70 cm/s
Setup 2	100 cm/s	80 cm/s	100 cm/s
Setup 3	60 cm/s	80 cm/s	70 cm/s

curve bound to the MPP starts to differ from reality, inducing the obtain wrong reference values for the control system during a large period. Once the values of speed reach and go above $1m/s$, the shape is visually wrong in most of the path, with respect to the real power curve shape. At this point using the reference taken from this sampling rate (for the stochastic MPPT algorithms) may be a worse idea than not using them.

6.3 Shadow scenario chart: MPP shape

The MPP curve related to the shadow scenario differs mostly between all the setups, depending on the shadow shape and the array configuration that conform the solar panels. In the next figure the MATLAB graph that includes all the setup charts in the three different shadow shape scenario is shown.

The first and the second shadow scenario could be bound to a homogeneous cloud that covers uniformly the PV array region (or a building near to the PV array, if the speed was lower), whereas the third shadow scenario could be a set of small clouds that passes close but separated over the PV array.

In this way, a stronger variability in the change of power is expected in the third case.

The figures (6.2), (6.3) and (6.4) show the MPP curves in the whole set of cases.

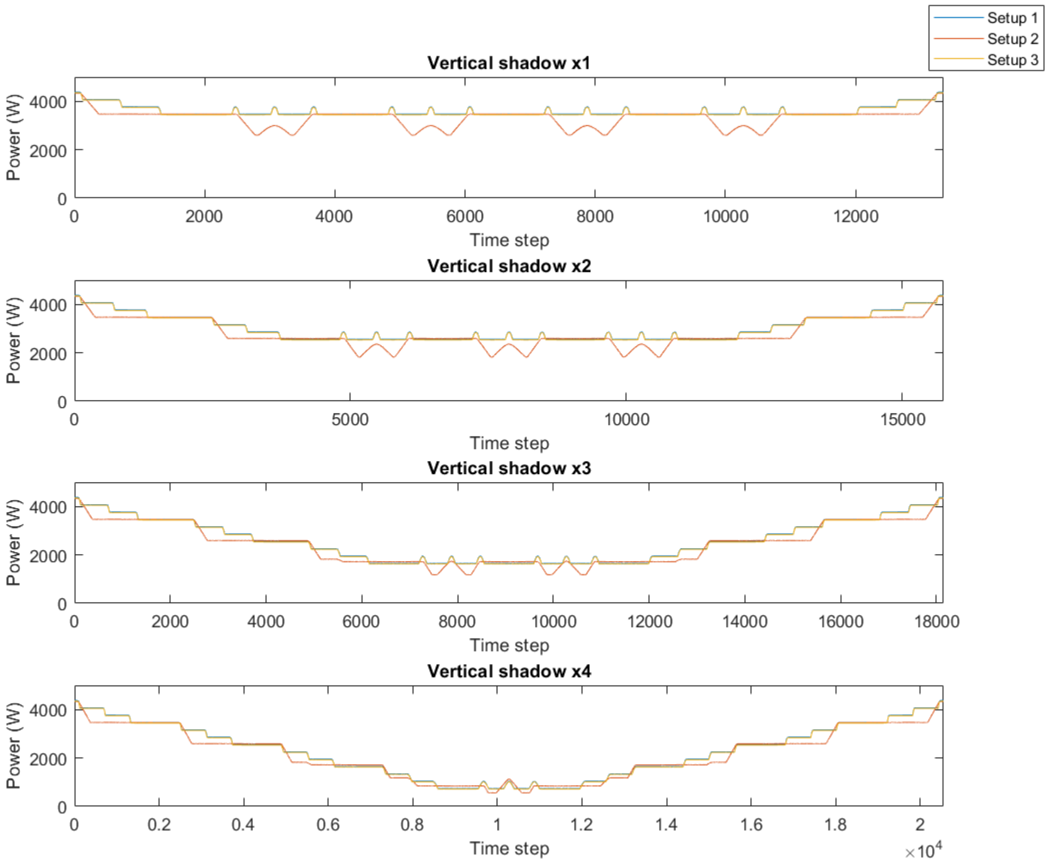

Figure 6.2: *Maximum power curves: Vertical shadow*

The shape of the vertical shadow plus the array configuration of the setup 1 and setup 3 causes these two setups to share the same MPP curve since the incidence of the shadow over the panels is equivalent in both cases, so the blue and orange lines are overlapping. The table (6.2) defines the shadow shape parameters.

Table 6.2: *Shadow sizes*

	Vertical shadow x1	**Vertical shadow x2**	**Vertical shadow x3**	**Vertical shadow x4**
Vertical lenght	510 cm	510 cm	510 cm	510 cm
Horizontal lenght	90 cm	210 cm	330 cm	540 cm

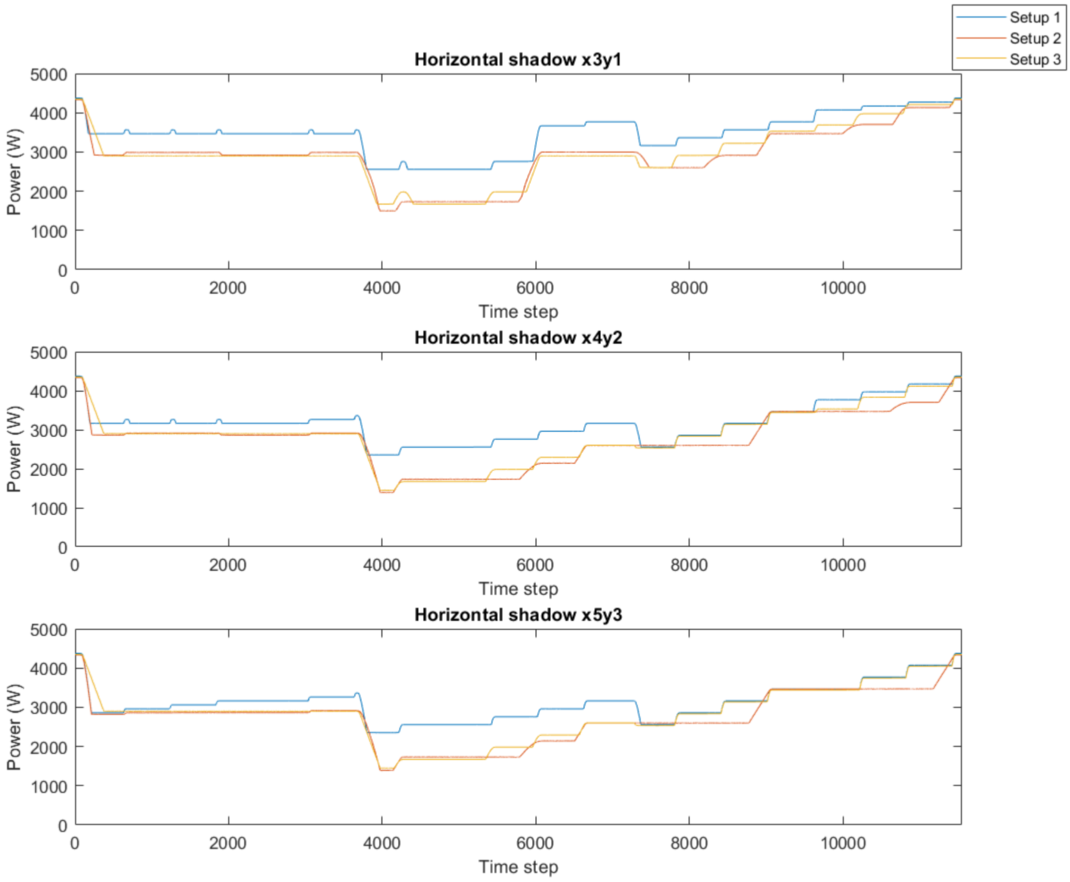

Figure 6.3: *Maximum power curves: Horizontal shadow*

In this case it is observed that all setups differ given that the diagonal advance of the shadow will affect to the power shape in a different way in each scenario. The table (6.3) defines the shadow shape parameters.

Table 6.3: *Shadow sizes*

	Horizontal shadow x3y1	**Horizontal shadow x4y2**	**Horizontal shadow x5y3**
Vertical lenght	150 cm	330 cm	510 cm
Horizontal lenght	90 cm	210 cm	330 cm

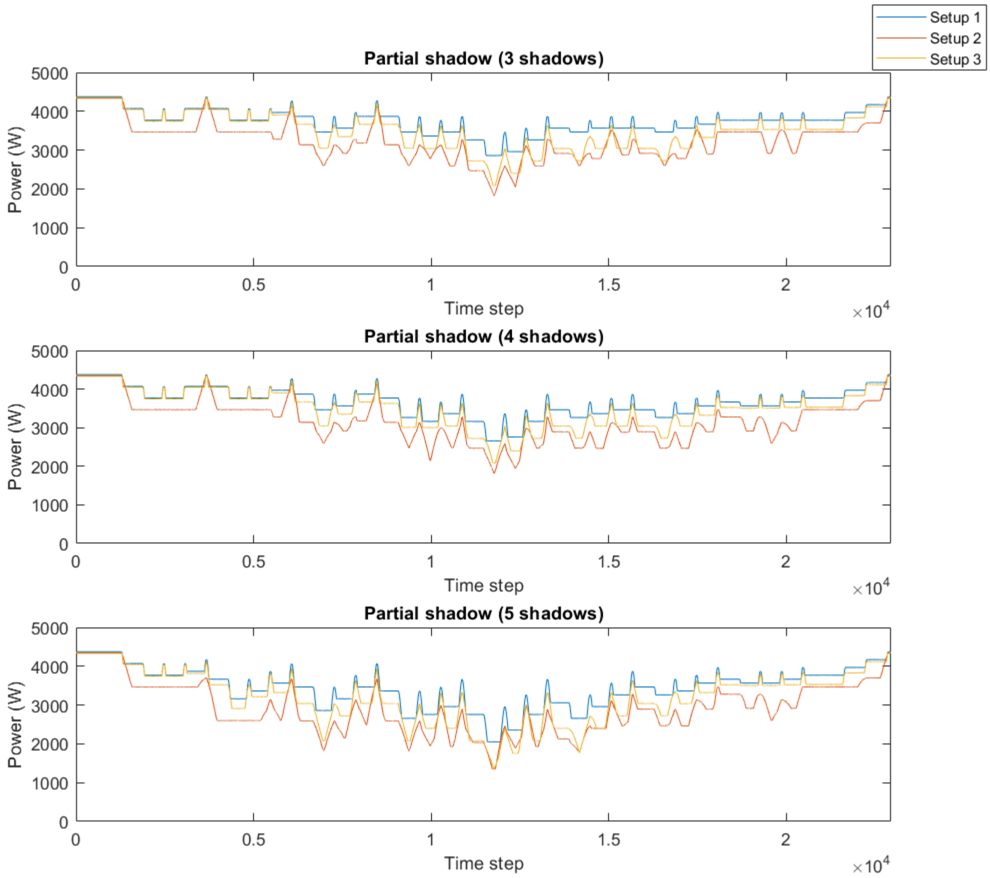

Figure 6.4: *Maximum power curves: Partial shadow*

The multiple shadows over the panel array are observed in the chaotic shape that present this last scenario. In a first approach, setup 1 (blue colour) seems to be the less affected in all cases since the MPP curve covers a bigger area than in the other two cases. The table (6.4) defines the shadow shape parameters.

Table 6.4: *Shadow sizes*

	Shadow 1	**Shadow 2**	**Shadow 3**	**Shadow 4**	**Shadow 5**
Partial shadow (x3) Vertical lenght	330 cm	150 cm	510 cm	-	-
Partial shadow (x3) Horizontal lenght	90 cm	60 cm	30 cm	-	-
Partial shadow (x4) Vertical lenght	330 cm	150 cm	510 cm	150 cm	-
Partial shadow (x4) Horizontal lenght	90 cm	60 cm	30 cm	30 cm	-
Partial shadow (x5) Vertical lenght	330 cm	150 cm	510 cm	150 cm	330 cm
Partial shadow (x5) Horizontal lenght	90 cm	60 cm	30 cm	30 cm	60 cm

6.4 Efficiency tendency

There are two principal manners to analyse the MPPT efficiency through the different scenarios, using the MPP curve versus the tracked power curve and the average efficiency charts, that sums up the efficiency obtained along the range of the defined shadow speed.

MPP curves show the trend of the tracker during the whole simulation, although the biggest backdraw is the amount of information that contains and the difficulty to analyse it, since there are 45 curves for each MPPT technique and for each speed scenario. Considering this point and that there is no direct numerical result, it is not the best way to compare efficiently the MPPT techniques. However, it is a good visual tool to understand what happens in each simulation. In case of finding a strange result that moves away from the logic expected, it can be used to help and clarify the issue.

Therefore, the average efficiency calculated from these graphs is used to understand the trend of the MPPT techniques along the speed range defined.

6.4.1 Average efficiency data

The next figure 6.5 shows the efficiency trend in the setup 1 during the partial shading due to the vertical shadow shape (first case). The horizonal axis refers to the range of speeds at which the shadow travels (from $1cm/s$ up to $10m/s$) and the vertical axis is defined as the average efficiency (from 0 to 1).

In figure 6.6 the efficiency data shown in the charts and summarized in a table can be seen. The whole set of MPPT techniques data is collected there and the best and the worst solution found for each speed is highlighted. The best and the worst solution are assigned into a subgroup, where A is bound to the Perturb and Observe algorithms, B to the constant reference algorithms, C to the stochastic algorithms and D to the combined algorithms.

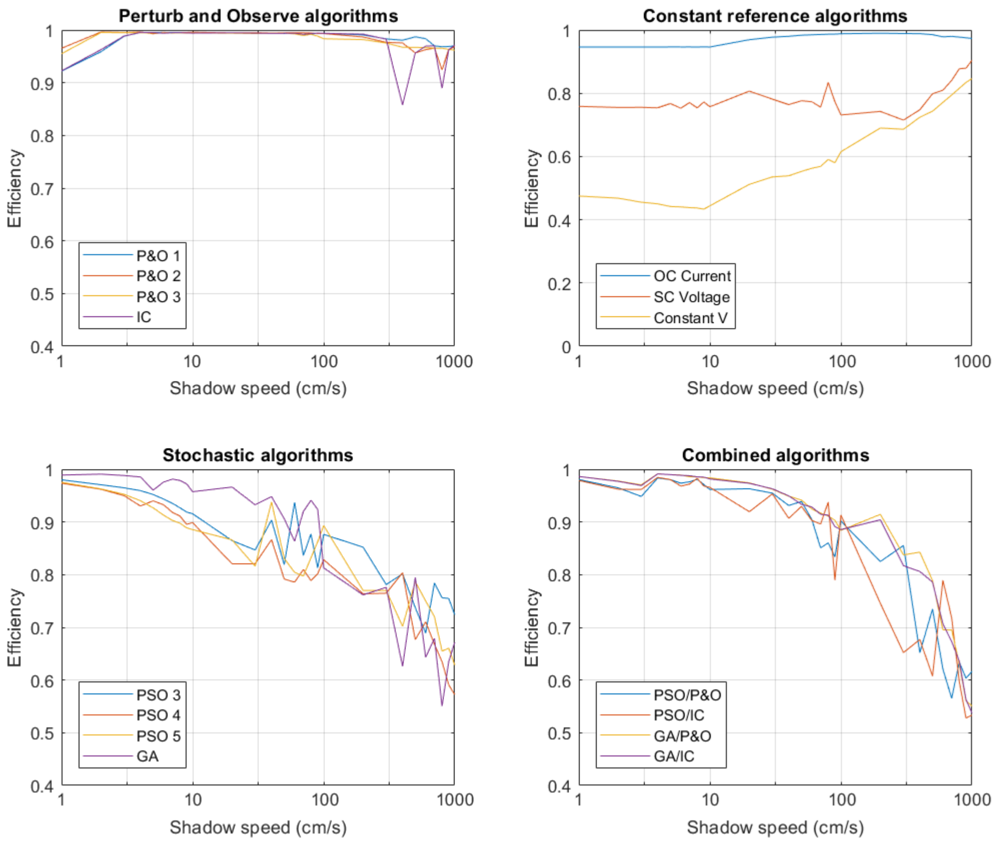

Figure 6.5: *Average efficiency chart: Vertical shadow 1x (setup 1)*

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,922	0,959	0,988	0,995	0,995	0,995	0,995	0,995	0,995	0,995	0,995	0,994	0,994	0,993	0,994	0,992	0,992	0,994	0,994	0,991	0,983	0,981	0,987	0,984	0,970	0,968	0,969	0,970
P&O 2	0,965	0,996	0,995	0,996	0,993	0,995	0,995	0,995	0,995	0,996	0,995	0,995	0,994	0,995	0,995	0,995	0,994	0,993	0,993	0,987	0,977	0,975	0,957	0,963	0,966	0,925	0,963	0,968
P&O 3	0,955	0,995	0,995	0,995	0,994	0,995	0,994	0,995	0,994	0,995	0,994	0,993	0,994	0,994	0,993	0,990	0,992	0,988	0,983	0,982	0,975	0,967	0,967	0,966	0,966	0,965	0,963	0,962
IC	0,922	0,963	0,989	0,995	0,995	0,994	0,995	0,995	0,995	0,994	0,995	0,994	0,994	0,994	0,994	0,992	0,993	0,994	0,994	0,992	0,983	0,858	0,956	0,970	0,970	0,890	0,963	0,971
SC Current	0,946	0,946	0,946	0,946	0,946	0,946	0,946	0,946	0,947	0,946	0,969	0,977	0,980	0,984	0,985	0,986	0,987	0,987	0,988	0,990	0,989	0,989	0,985	0,978	0,980	0,978	0,975	0,973
OC Voltage	0,759	0,755	0,755	0,754	0,767	0,753	0,771	0,754	0,773	0,757	0,807	0,781	0,764	0,776	0,773	0,756	0,834	0,773	0,731	0,743	0,715	0,748	0,798	0,810	0,841	0,877	0,879	0,904
Const. Voltage	0,475	0,468	0,455	0,450	0,442	0,441	0,438	0,437	0,433	0,444	0,512	0,535	0,539	0,553	0,563	0,569	0,591	0,580	0,615	0,690	0,686	0,724	0,743	0,771	0,794	0,816	0,834	0,847
PSO 3	0,980	0,971	0,965	0,960	0,952	0,943	0,936	0,927	0,919	0,916	0,865	0,847	0,903	0,819	0,937	0,836	0,877	0,813	0,877	0,852	0,781	0,802	0,737	0,689	0,784	0,756	0,755	0,724
PSO 4	0,974	0,962	0,950	0,930	0,940	0,933	0,918	0,911	0,895	0,899	0,821	0,821	0,867	0,792	0,786	0,810	0,789	0,802	0,828	0,764	0,765	0,804	0,677	0,710	0,668	0,635	0,591	0,572
PSO 5	0,975	0,963	0,952	0,940	0,927	0,913	0,903	0,898	0,889	0,885	0,866	0,816	0,938	0,831	0,804	0,797	0,832	0,862	0,893	0,770	0,770	0,702	0,787	0,750	0,720	0,655	0,660	0,629
GA	0,989	0,991	0,988	0,985	0,960	0,976	0,981	0,979	0,972	0,957	0,966	0,933	0,948	0,906	0,863	0,920	0,941	0,924	0,813	0,762	0,776	0,626	0,795	0,643	0,679	0,551	0,635	0,672
PSO/P&O	0,981	0,965	0,948	0,983	0,980	0,974	0,976	0,981	0,971	0,962	0,963	0,955	0,931	0,939	0,905	0,851	0,860	0,834	0,902	0,825	0,855	0,652	0,735	0,621	0,565	0,634	0,603	0,616
PSO/IC	0,979	0,962	0,962	0,985	0,980	0,968	0,972	0,983	0,968	0,966	0,920	0,953	0,907	0,930	0,903	0,896	0,938	0,789	0,913	0,746	0,652	0,677	0,608	0,789	0,718	0,597	0,528	0,534
GA/P&O	0,986	0,978	0,970	0,991	0,990	0,989	0,986	0,986	0,984	0,984	0,974	0,962	0,949	0,942	0,924	0,917	0,911	0,903	0,884	0,914	0,838	0,843	0,789	0,695	0,695	0,631	0,561	0,550
GA/IC	0,986	0,977	0,969	0,991	0,990	0,989	0,988	0,986	0,985	0,982	0,973	0,963	0,949	0,934	0,928	0,915	0,913	0,891	0,886	0,904	0,817	0,806	0,786	0,707	0,673	0,636	0,563	0,537
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	D	C	D	D	D	C	D	D
Setup 1	C	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	A	A	B	B	B	B

Figure 6.6: *Average efficiency table: Vertical shadow 1x (setup 1)*

The whole set of efficiency results can be found in the appendix A, which contains the charts of the 10 shading scenarios and the 3 setups configuration, and the appendix B contains the respective data tables bound to the efficiency charts.

6.4.2 Subgroup trend

In the next sections it is presented which MPPT techniques are developing a good and a bad performance in the whole set of scenarios. Firstly, a general approach is done, considering the full range of shadow speed, to check if there is a significant difference between MPPT technique groups.

It is important to remember that the conditions of this simulation are defined for a range of speeds considering a constant sampling frequency of $20Hz$, that is, the equivalent distance that the shadow advances at each sampling time step is defined as the shadow speed divided by 20.

Even though the shadow has the same advance ratio in all scenarios, the maximum PV panel area affected differs in each case.

Therefore, it is important to bear in mind that MPPT will work in scenarios where the maximum shading area ratio per time step differs strongly (and it may affect or not the MPPT behaviour), being the partial shadow scenario the one that has most variability in the area shaded per time step.

MPPT groups representation

As a first approach it is summarized which type of algorithm has the best and the worst behaviour in the defined scenarios at every speed point (in $\%$ of representation). The grouping statement is the same named before, dividing the MPPT techniques as in the chart plotting in appendix A.

The tables (6.5) and (6.6) collect all the data shown in appendix B, selecting the MPPT group with the biggest and the smallest efficiency at each speed point and assigning them into one of the MPPT groups.

Table 6.5: *Best MPPT behaviour group (in %)*

	Gr. A1	Gr. B1	Gr. C1	Gr. D1	Gr. A2	Gr. B2	Gr. C2	Gr. D2	Gr. A3	Gr. B3	Gr. C3	Gr. D3
Vertical shadow (x1)	75.0	21.4	3.6	0	7.1	92.9	0	0	75.0	21.4	0	3.6
Vertical shadow (x2)	64.3	32.1	3.6	0	17.9	82.1	0	0	67.8	28.6	0	3.6
Vertical shadow (x3)	64.3	32.1	0	3.6	28.5	64.3	3.6	3.6	64.3	32.1	0	3.6
Vertical shadow (x4)	75.0	21.4	0	3.6	28.6	71.4	0	0	71.4	25.0	0	3.6
Horizontal shadow (x3y1)	82.1	17.9	0	0	82.1	3.6	0	14.3	60.8	25.0	7.1	7.1
Horizontal shadow (x4y2)	71.4	25.0	0	3.6	39.3	39.3	10.7	10.7	7.1	25.0	60.8	7.1
Horizontal shadow (x5y3)	71.4	25.0	0	3.6	39.3	42.8	3.6	14.3	28.6	50.0	0	7.1
Partial shadow (3 shadows)	67.9	28.6	0	3.6	96.4	0	0	3.6	82.1	14.3	0	3.6
Partial shadow (4 shadows)	64.3	32.1	0	3.6	1	0	0	0	82.1	17.9	0	0
Partial shadow (5 shadows)	64.3	32.1	0	3.6	1	0	0	0	85.7	10.7	0	3.6

Table 6.6: *Worst MPPT behaviour group (in %)*

	Gr. A1	Gr. B1	Gr. C1	Gr. D1	Gr. A2	Gr. B2	Gr. C2	Gr. D2	Gr. A3	Gr. B3	Gr. C3	Gr. D3
Vertical shadow (x1)	0	71.4	7.1	21.4	0	64.3	32.1	3.6	0	75.0	21.4	3.6
Vertical shadow (x2)	0	78.6	14.3	7.1	0	42.9	53.6	3.6	0	78.6	17.9	3.6
Vertical shadow (x3)	0	82.1	14.3	3.6	0	42.9	57.1	0	0	85.7	14.3	0
Vertical shadow (x4)	0	82.1	14.3	3.6	0	42.9	57.1	0	0	82.1	14.3	3.6
Horizontal shadow (x3y1)	0	71.4	3.6	25.0	0	32.1	57.1	10.8	0	39.3	35.7	25.0
Horizontal shadow (x4y2)	0	75.0	7.1	17.9	0	39.3	53.6	7.1	0	67.9	10.6	21.4
Horizontal shadow (x5y3)	0	82.4	7.1	10.7	0	39.3	50.0	10.7	0	67.9	14.3	17.9
Partial shadow (3 shadows)	0	71.4	10.7	17.9	0	35.7	64.3	0	0	64.3	10.7	25.0
Partial shadow (4 shadows)	0	71.4	14.3	14.3	0	32.1	67.9	0	0	75.0	14.3	10.7
Partial shadow (5 shadows)	0	75.0	14.3	10.7	0	32.1	67.9	0	0	75.0	3.6	17.9

When comparing the 4 groups of MPPT there is a clear winner, at least at this range of shadow speed. Group A, that corresponds to the Perturb and Observe algorithms, has the biggest representation in the best behaviour response in the whole set of scenarios except for some punctual cases inside the horizontal shadow scenario.

Group B is highly represented in both tables, that is, it has some of the best results and it monopolizes the table (6.6). Recalling the MPPT with constant reference type, they depend on the power curve shape that may vary according to the setup configuration (I_{sc} and V_{oc}) and the shadow shape (power curve shape and constants once again). Considering that the vertical and partial shadow scenario sets a shadow that moves in the horizontal axis towards a PV array configuration that stands parallel (setup 2) or perpendicular (setup 1 and 3) to this direction, then the V_{oc} parameter will be highly affected while I_{sc} is not in setup 1 and 3, and vice versa in setup 2. Since open-circuit voltage and short-circuit current methods depend on these parameters, they are highly affected in some of the cases, and they hit a good MPP reference in others. It can be checked how depending are these results in the orientation.

To prove this, appendix A can be checked in the constant reference algorithm graph region. There it can be seen how there is always one of the MPPT techniques that is performing correctly, alternating between open-circuit voltage and short-circuit current method.

In reference to the stochastic and combined techniques, they have very little representation in the best behaviour table, and in the worst behaviour table it can be seen at first sight, that stochastic techniques have a bit more representation in worse results in the vertical shadow scenario, while in the rest they are more or less getting the same representation.

After this overview, another comparison will be done. In this case, deleting the group B, since its representation in both tables shade the rest of MPPT techniques comparison.

Table 6.7: *Best MPPT behaviour group A, C and D (in %)*

	Gr. A1	Gr. C1	Gr. D1	Gr. A2	Gr. C2	Gr. D2	Gr. A3	Gr. C3	Gr. D3
Vertical shadow (x1)	96.4	0	3.6	1	0	0	96.4	0	3.6
Vertical shadow (x2)	96.4	0	3.6	1	0	0	96.4	0	3.6
Vertical shadow (x3)	96.4	0	3.6	92.9	3.6	3.6	96.4	0	3.6
Vertical shadow (x4)	96.4	0	3.6	1	0	0	96.4	0	3.6
Horizontal shadow (x3y1)	1	0	0	85.7	0	14.3	85.8	7.1	7.1
Horizontal shadow (x4y2)	96.4	0	3.6	71.4	14.3	14.3	32.1	60.8	7.1
Horizontal shadow (x5y3)	96.4	0	3.6	71.4	3.6	25.0	42.9	50.0	7.1
Partial shadow (3 shadows)	96.4	0	3.6	96.4	0	3.6	96.4	0	3.6
Partial shadow (4 shadows)	96.4	0	3.6	1	0	0	1	0	0
Partial shadow (5 shadows)	96.4	0	3.6	1	0	0	96.4	0	3.6

After comparing A, C and D groups it is totally clear the overwhelming superiority of group A among the other groups. The group C is also clearly worse than D.

However, there are still some regions in the speed range graphs in appendix A that can be analysed and must be checked. It will also be checked the most important point of this MPPT comparison, if there is a homogeneous trend in all speed range or if some regions where some MPPT techniques overcome the rest exist.

Table 6.8: *Worst MPPT behaviour group A, C and D (in %)*

	Gr. A1	Gr. C1	Gr. D1	Gr. A2	Gr. C2	Gr. D2	Gr. A3	Gr. C3	Gr. D3
Vertical shadow (x1)	7.1	60.7	32.1	0	96.4	3.6	3.6	92.9	3.6
Vertical shadow (x2)	7.1	75.0	17.9	0	96.4	3.6	7.1	82.1	10.7
Vertical shadow (x3)	3.6	67.9	28.6	0	1	0	3.6	78.6	17.9
Vertical shadow (x4)	3.6	71.4	25.0	0	1	0	3.6	78.6	17.9
Horizontal shadow (x3y1)	3.6	46.4	50.0	3.6	85.7	10.7	7.1	53.6	39.3
Horizontal shadow (x4y2)	0	57.1	42.9	14.3	64.3	21.4	28.6	50.0	21.4
Horizontal shadow (x5y3)	0	64.3	35.7	3.6	82.1	14.3	25.0	57.1	17.9
Partial shadow (3 shadows)	3.6	57.1	39.3	0	1	0	0	67.9	32.1
Partial shadow (4 shadows)	7.1	78.6	14.3	0	1	0	3.6	75.0	21.4
Partial shadow (5 shadows)	7.1	78.6	14.3	0	1	0	7.1	64.3	28.6

6.4.3 MPPT behaviour along speed dynamics

In this section the efficiency evolution towards the speed range is taken into account, using both, the graphs shown in appendix A and the data collected in appendix B.

Firstly, the values from the appendix B tables have been taken doing an average of the efficiency in groups A, C and D and annotating the speed point at which they lose efficiency in steps of -5% until -30%.

This is reflected in 3 tables, one for each setup configuration, and has the aim of finding out and differentiating the speed region where the groups of MPPT techniques win or lose effectiveness with respect to the others. This table is shown in 6.7.

Setup 1	Group A						Group C						Group D					
Shading scenario	-5%	-10%	-15%	-20%	-25%	-30%	-5%	-10%	-15%	-20%	-25%	-30%	-5%	-10%	-15%	-20%	-25%	-30%
Vertical shadow (x1)	*	*	*	*	*	*	5	20	50	200	400	600	40	70	200	300	400	600
Vertical shadow (x2)	200	400	800	*	*	*	6	20	50	200	500	600	20	50	100	200	300	700
Vertical shadow (x3)	200	300	600	*	*	*	5	10	40	90	300	500	10	30	60	90	200	300
Vertical shadow (x4)	90	200	300	400	700	*	5	9	30	80	200	500	9	20	40	100	200	300
Horizontal shadow (x3y1)	400	*	*	*	*	*	7	30	80	200	500	700	10	50	100	400	500	700
Horizontal shadow (x4y2)	300	400	*	*	*	*	6	20	80	200	600	700	10	40	60	90	300	500
Horizontal shadow (x5y3)	100	300	*	*	*	*	6	20	50	200	400	700	10	30	60	90	300	500
Partial shadow (3 shadows)	400	500	*	*	*	*	4	10	80	300	500	600	10	50	70	200	400	500
Partial shadow (4 shadows)	300	400	*	*	*	*	4	10	90	200	500	600	10	40	70	200	300	500
Partial shadow (5 shadows)	300	400	400	*	*	*	5	30	60	200	400	500	5	30	60	200	400	600

Setup 2	Group A						Group C						Group D					
Shading scenario	-5%	-10%	-15%	-20%	-25%	-30%	-5%	-10%	-15%	-20%	-25%	-30%	-5%	-10%	-15%	-20%	-25%	-30%
Vertical shadow (x1)	60	*	*	*	*	*	2	3	9	20	30	40	5	10	20	30	40	200
Vertical shadow (x2)	60	400	*	*	*	*	<1	3	10	20	30	40	5	10	30	40	60	90
Vertical shadow (x3)	50	200	400	*	*	*	<1	6	10	20	40	40	9	20	30	40	50	60
Vertical shadow (x4)	20	100	200	900	*	*	1	5	9	10	30	40	7	10	20	40	60	70
Horizontal shadow (x3y1)	9	70	*	*	*	*	1	6	10	20	30	50	4	10	20	30	60	100
Horizontal shadow (x4y2)	3	20	30	50	*	*	<1	9	20	30	40	60	1	9	20	40	90	200
Horizontal shadow (x5y3)	4	10	30	40	80	*	<1	8	20	30	40	50	5	20	30	40	60	90
Partial shadow (3 shadows)	20	*	*	*	*	*	<1	1	4	9	20	40	3	10	20	50	80	500
Partial shadow (4 shadows)	20	200	*	*	*	*	<1	1	3	8	20	30	3	10	30	40	70	200
Partial shadow (5 shadows)	10	30	200	*	*	*	<1	1	3	9	20	40	2	9	20	30	60	200

Setup 3	Group A						Group C						Group D					
Shading scenario	-5%	-10%	-15%	-20%	-25%	-30%	-5%	-10%	-15%	-20%	-25%	-30%	-5%	-10%	-15%	-20%	-25%	-30%
Vertical shadow (x1)	*	*	*	*	*	*	5	20	90	300	400	800	30	80	200	500	600	700
Vertical shadow (x2)	200	400	*	*	*	*	5	20	70	200	300	500	20	40	100	200	200	400
Vertical shadow (x3)	100	200	300	600	*	*	5	20	60	100	200	500	9	20	40	100	200	300
Vertical shadow (x4)	90	200	300	400	800	*	5	10	30	40	80	200	10	20	40	80	200	400
Horizontal shadow (x3y1)	10	60	100	500	*	*	5	20	50	100	300	400	9	20	50	80	100	300
Horizontal shadow (x4y2)	<1	10	30	60	200	*	<1	9	50	100	200	800	<1	9	30	80	90	100
Horizontal shadow (x5y3)	<1	10	30	50	200	*	<1	7	60	100	200	300	<1	20	30	50	200	300
Partial shadow (3 shadows)	90	*	*	*	*	*	2	10	60	400	600	900	4	20	50	80	400	800
Partial shadow (4 shadows)	70	200	*	*	*	*	2	10	60	90	500	900	6	30	60	100	400	700
Partial shadow (5 shadows)	20	100	400	*	*	*	1	9	70	300	400	700	3	20	50	90	400	500

Figure 6.7: *Effefctiveness over the speed range*

In the case of stochastic and combined algorithms (groups B and C), it is observed that stochastic efficiency falls in earlier speeds than combined. In setup 1 and 3, the horizontal shadow advance, group B clearly falls before group C, but this last group catches the first one up later. This means that stochastic has a worse behaviour in the short-range high speed but it does not fall so fast in the long-range high speed as in combined. In setup 2 they are more even.

Another important point that must be noticed is that in the whole set of the simulation scenarios, the stochastic component in groups B and C shows homogeneity in the results towards the increasing speed regardless of how much area the defined shadow occupies. On the other hand, the orientation does not affects the falling of the efficiency attribute either. However, the setup configuration does affect that falling ratio, being setups 1, 2 and 3 significantly different in that aspect.

Group A, which had presented the best results has, as in the groups B and C, a different behaviour according to the setup, being the setup 1 the less affected (this can also be observed in the MPP shape plots shown in 6.3 section where setup 1 clearly covers more area, which involves less loss of power due to the shading).

There is an interesting point in group A with respect to the groups B and C. While B and C are not clearly affected by the quantity of shading area, group A shows a deterioration of the effectiveness directly proportional to the shading area that is used in the simulation. In other words, the more shadow is applied, the earlier thresholds appear in the falling of efficiency, while stochastic and combined algorithms seem to not be affected, at least not at that level.

Among all these considerations, group A has a unique functioning with respect to the stochastic and combined algorithms.In vertical and partial shadow scenarios it presents an increasing in very short-range speed and long-range speed. This point is going to be analysed in next sections.

6.4.4 MPPT efficiency under 1cm/s and high speed

High speed efficiency

If appendix A plot is checked, a constant observed in every single graph can be found in group A and B algorithms. There is a point where the efficiency starts growing no matter the shadow speed, which could seem illogical. This is due to the starting condition of the simulation and the type of algorithm used.

The early condition of full irradiation plus the exact duty cycle reference where the MPP is found as a starting condition are the cause by which the step perturbation methods start getting higher efficiency in high speed in this simulation. The reason is that the more speed has the shadow, the less time passes over the PV panel region, so there is also less time to execute the algorithm and to modify the duty cycle. This perturbation algorithm demands some time to follow the reference step by step, and when the time is so little, they have less time to get away from the starting condition. Even if the reference is totally wrong, they have no way to follow it and this is represented as a higher weighting of the full irradiating condition, resulting as an increment of the efficiency. That's a real result since it's found by the definition of the simulation, but that trend wouldn't be observed in a simulation of which its time tends to infinite.

Regarding this observation, it is seen, according to the average efficiency of the MPPT, that the start point of the positive slope is found between $50cm/s$ until $5m/s$. The low cap is actually found in the minimum threshold that was defined in section 6.2.1.

It is important to consider this concept because is related to another phenomena that occurs in the early speed track in some of the shading scenarios and it is related to this 'inertia' from the MPPT algorithm part.

MPPT efficiency under 1cm/s

An early increasing of the efficiency in the group A algorithms, mainly in the setup 1 and 3 scenarios, is observed, while it can not be observed in the rest of the algorithms groups.

The difference between group A and the rest is that group A algorithms have the possibility to find out a local maxima and stay around it instead of tracking the correct global maxima. Knowing that this could be the reason of this early low efficiency in group A MPPT type, a slower simulation in a specific scenario is run to observe the power tracking of one MPPT, figure (6.8). There is a minimum cap where the efficiency stops decreasing whose trend can be seen in figure (6.9).

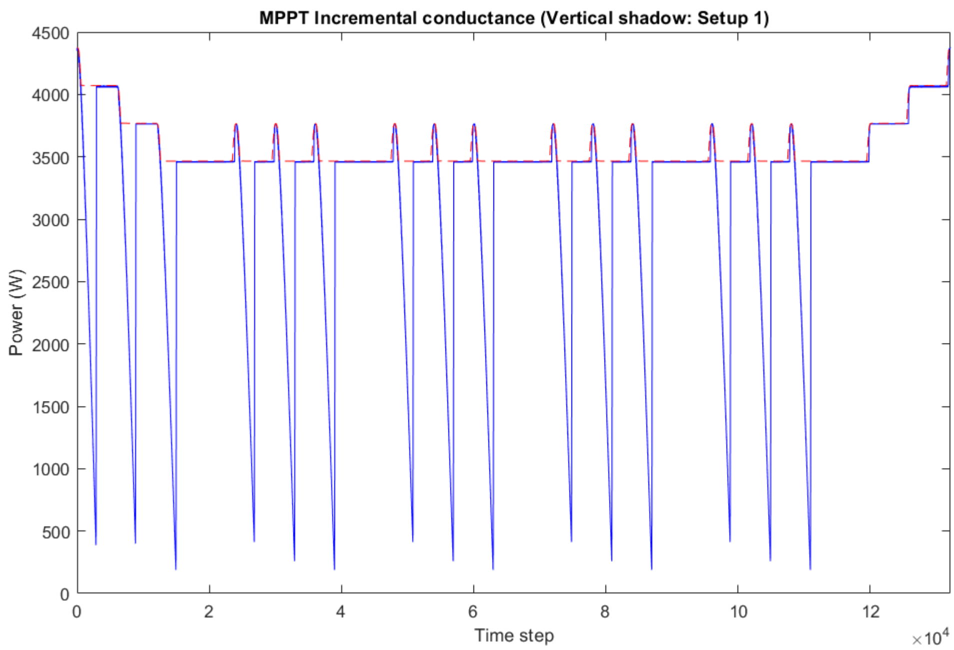

Figure 6.8: *Vertical shadow x1: Speed 0.1 cm/s*

Speed (cm/s)	0.1	0.2	0.4	0.6	0.8	1	2	3	4	5
IC	0,882	0,882	0,891	0,897	0,903	0,922	0,963	0,989	0,995	0,995

Figure 6.9: *Incremental conductance slow range speed*

This plot shows, a priori, a sharp decreasing power slope in several points. It seems, at first sight, that the smaller shadow transient should not drop at this rate the power tracking curve. However, reminding the transient curve of chapter 4, there was a near example that showed how the power curve was affected towards a full shadow transient with the same direction as in the vertical and partial shadow transient.

Figure (6.10) shows how the power curve is affected while the shadow with horizontal advance covers the PV region.

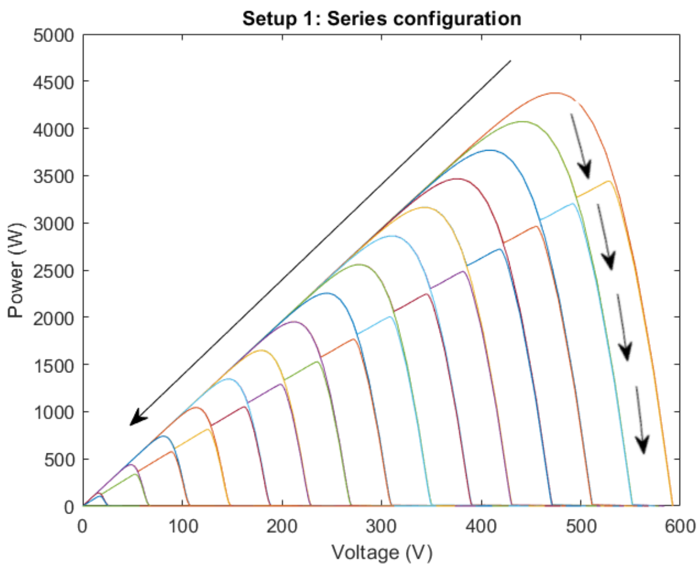

Figure 6.10: *Power curve*

The local maxima peak on the right starts decreasing until it disappears. Then, the full curve presents only one maximum displaced to the left, and once again another local maxima starts appearing in the right side, and decreasing one more time in the same way until it remains only one global maximum.

Here, the 'inertia' from the MPPT algorithm plays a fundamental part. This 'inertia', to follow the global or local maxima, depends on the microprocessor sampling frequency and the shadow speed (that involves the power changing ratio). Hence, a slow shadow speed or a big resolution in the sampling frequency involves that the MPPT is following the very small modifications in the power curve. In this way, in the early speed efficiency track ($0.1cm/s$) the group A of MPPT algorithms generally falls in following this local maximum. There is the same $20Hz$ resolution, but the shadow speed is slow enough to be able to track the wrong local maxima (low inertia which allows following the local maxima fast), following its transient modification, that is, going after this decreasing peak. This means that the MPPT is not only tracking a bad local maxima, but is also following a local maxima that is constantly decreasing, and that can be seen in (6.8), where it gets really low values of power.

Then, if the equivalent sampling resolution is low enough, the MPPT 'skips' this local maxima and it starts getting better results in the efficiency, as in the figure (6.11), where in region 2 the MPPT is skipping the local maxima due to the low equivalent resolution. Meanwhile in 1 it is able to follow the transient of the local maxima (wrong maximum).

Some abrupt regions also exists, as in region 3, that decrease in a sharp way. This can be also seen in the stochastic and combined MPPT algorithms plots (groups B and C), since they still have the possibility to converge in a local maxima, which is the cause of this abrupt and sudden fall of efficiency in the chart.

This last observation implies that a good knowledge of the PV system can save an important part of the inversion, because if a lower equivalent resolution is needed, a worse microprocessor can be used (less resolution, less cost) and, at the same time, the group A of MPPT algorithms can be used too, which is bound to a lower complexity (and a lower cost). Therefore, not always the best resolution and the best complexity contribute to achieving the best results, at least not in all speed dynamics.

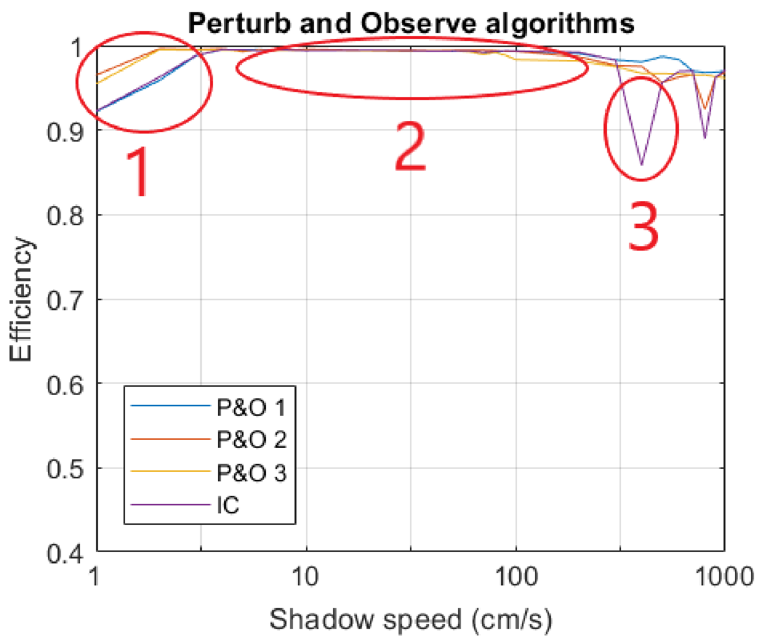

Figure 6.11: *Vertical shadow x1: Efficiency plot*

After seeing this last approach, it can be observed that it is a fact that Group A can fail in some scenarios. However, it is interesting to see how the rest of the groups are affected at this speed point. For this purpose, the same simulation where IC has been recently checked has been done but for every MPPT algorithm of the list. Figure (6.12) collects the efficiency of every MPPT algorithm for the first case of study at $0.1 cm/s$.

Setup 1	P&O 1	P&O 2	P&O 3	IC	SC Current	OC Voltage	Const. Voltage
	0,882	0,878	0,876	0,882	0,946	0,759	0,472
PSO 3	PSO 4	PSO 5	GA	PSO/P&O	PSO/IC	GA/P&O	GA/IC
0,994	0,992	0,991	0,991	0,993	0,993	0,994	0,994

Setup 2	P&O 1	P&O 2	P&O 3	IC	SC Current	OC Voltage	Const. Voltage
	0,988	0,989	0,988	0,989	0,661	0,939	0,988
PSO 3	PSO 4	PSO 5	GA	PSO/P&O	PSO/IC	GA/P&O	GA/IC
0,976	0,964	0,972	0,978	0,987	0,988	0,987	0,988

Setup 3	P&O 1	P&O 2	P&O 3	IC	SC Current	OC Voltage	Const. Voltage
	0,883	0,884	0,877	0,883	0,946	0,757	0,477
PSO 3	PSO 4	PSO 5	GA	PSO/P&O	PSO/IC	GA/P&O	GA/IC
0,995	0,992	0,993	0,993	0,994	0,994	0,994	0,994

Figure 6.12: *Vertical shadow x1: Efficiency at 0.1 cm/s*

As it was described, group A in setup 1 and 3 gets stuck in a local maximum. Actually, every MPPT from group A has this problem, while every stochastic and combined MPPT is able to find the correct global maxima, presenting a slightly better behaviour the combined algorithm from group D than the stochastic from group C.

Constant reference from group B is not dependent on the speed at low dynamics and it just follows the trend found in the other speed simulations (in the 3 different setups).

6.5 MPPT selection

In this last section, an approach of a possible setup and MPPT selection to control the PV system is developed , among the possible scenarios.

Setup and MPPT selection considering the simulation results

Uniquely taking into consideration the results here found, the choice of one setup and MPPT technique would be following these points:

- Selecting setup 1: This setup 1 has the advantage to avoid the issues related to the orientation of the shading advance, thanks to the full series arrangement. In this way, the loss of power with respect to the other 2 setups is lower. The backdraw would be the output power which is quite restricted regarding its values of V_{oc} and I_{sc}, being the first one high and the second one too low for many applications. Then, its versatility is not so good, but it is still the one that obtains the better ideal MPP curve.

  It is also necessary to notice that this choice between setup 1 and 3 or setup 2 also gives an extra restriction with respect to the use of the MPPT group B, due to the arrangement orientation, which must be taken into consideration in designing phase.

- Selecting group A: The choice is the MPPT algorithms belonging to group A if the knowledge of the shading scenario is good, since the microcontroller sampling frequency can be adjusted to enter into the best region in the efficiency plot saw in figure (6.11)), the region 2.

- Selecting group B: If the climatic condition is smooth and predictable, this can be the best solution among the others, since it is the less complex application of the MPPT.

- Selecting group C and D: If, on the other hand, the climatic scenario is chaotic not only in its direction trend, but also in its wind speed, using groups C and D is the suggested choice in preference to group B, and it should be used also in preference to MPPT algorithms of group A. So, in front of random conditions, stochastic algorithms are a must.

General MPPT selection

Taking into consideration a general scenario where knowledge about the PV arrangement or the climatology are not assured, the possible choice would be:

- Knowledge about the clime (smooth) and knowledge about the PV array parameters: Group B is usually the most efficient in economic terms. The choice of the setup configuration depends on the orientation and so does the MPPT method inside the group B.
- Knowledge about the clime (smooth) but PV array parameters ignorance: Group A is the optional choice before Group B, since the constants in that MPPT methods depend on the knowledge of the PV system (and it's unknown). Group A becomes the best option after it and the sampling frequency ratio can be used to compensate, if necessary, the shadow speed to achieve the correct region and avoid the local peak chasing.
- Knowledge about the clime (chaotic): To deal with the randomness of the clime, stochastic or combined are a must. Group C and D can be both selected to overcome the partial shading issue under random weather condition.
- Unknowledge about the clime (unknown): In this case there is a clear option, which is group D. Its versatility permits to act as a stochastic or deterministic method after the installation. Tuning (a posteriori) the threshold criteria to trigger the stochastic subroutine gives the MPPT a high versatility towards the possible scenario if there is no physical time to study it previously. Consequently, it is the best choice to adapt the control to any issue.

CHAPTER 7

Conclusions

This master thesis work has proposed a comparison study between MPPT techniques under diverse setups scenarios and a wide range of dynamics, simulated in MATLAB.

Firstly, a search of the actual methods, that the literature widely provides, has been done to clarify which kind of techniques are the most used and in which type of scenario are more used. Not only a wide range of MPPT methods has been extracted from the literature, but also their general knowledge, their main advantages and their weaknesses against the irradiating conditions that can be found over a PV solar system.

A basic overview over the main functioning, from the cell until the PV array configuration, has been done. First of all, studying the known models that can represent mathematically the model of a solar cell, choosing the five parameters model due to its fair trade-off between accuracy and complexity. Then, a short explanation about the most important parameters found in the power curve and how they are affected by external influence has been made. In this way, a first approach to the partial shading problematic has been realized, checking how the modelled power curve can be influenced due to a low or partial irradiation condition.

A PV array configuration scenario has been defined, considering three different array arrangements with their different output power curves. After that, a brief look into the main converter's configuration has been done, choosing the one that will perform in the designed model, a DC-DC buck-boost converter type. At last, the complete model has been proved towards a very first shading condition, to check the knowledge gathered previously.

Once the PV system model has been completed, the full shading scenario has been defined and written in MATLAB code. This entire scheme has been designed with an early stage which defines the position of the PV panel array and the shadow that passes over it, a second stage which computes the irradiation that the PV panels receive and the region that is covered by the shadow. Once these stages are defined, it has been defined the MPPT tracking algorithms that will pursue the MPP of the PV system power curve at every time step of the simulation, and at the end of it, the efficiency and the average efficiency of the whole system has been calculated. In this task, several flowcharts have accompanied the MPPT code and the scheme explanation to ease its comprehension.

Finally, the complete simulation has been done, comparing the effectiveness of fifteen different MPPT techniques over three PV arrangements at twenty-eight different speeds. The data obtained has been analysed and the efficiency of the whole set of MPPT methods has been compared.

The first analysis of the efficiency trend has shown that the simulation design and its conditions have favoured the performance of the deterministic methods above the rest of the MPPT methods, but showing some peculiarities with respect to the stochastic and combined methods and, finally, a reflexion of the utility of the perturb and observe based techniques along the speed range has been done.

On the one hand, combined techniques have proven to be more robust at high speed in comparison to the stochastic algorithms, but both of them at a lower efficiency rate if compared to deterministic techniques. On the other hand, the stochastic characteristic from both groups, stochastic and combined algorithms, has demonstrated to be very robust in the short-range shadow speed whereas in high speed they have found a high reduction of efficiency and some fails at tracking the global maxima due to the constant changing of reference during the partial shading transient.

Constant reference algorithms have shown dependence on the shadow shape orientation and the PV arrangement setup. And, finally, the perturb and observe type algorithms have presented a decreasing of the effectiveness in the short-range speed, which has been caused because of the local peak tracking.

At this point, it has been demonstrated that the equivalent sampling ratio can totally affect the behaviour of the perturb and observe based algorithms, making the microprocessor frequency a possible tool to benefit the low complexity MPPT algorithms that work on a perturb and observe basis.

Some further improvements can be always done in this field, expanding the designed study to any kind of shading scenario, enhancing the resolution used in the dynamic range study or testing it over a completely different PV arrangement, which can also involve a further enhancement in other MPPT methodologies, that could fit better in other scenario designs.

Furthermore, the model can be updated and expanded with extra external parameters to take them into account, such as wind and humidity, which can develope a lower interaction with the PV system response with respect to the main parameters involved, irradiation and temperature, but they still affect the final results.

A future proposal could be testing a variable frequency microprocessor to control the sampling rate, that could be able to provide a better performance to the perturb and observe MPPT techniques towards more complex stochastic MPPT algorithms during partial shading condition.

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Appendices

APPENDIX A

Appendix A - MATLAB plots

A.1 Average efficiency charts

The efficiency charts obtained in MatLab are presented in the next pages.

Each shadow scenario is analysed with the 3 setup arrays. The MPPT techniques are divided in 4 groups to clarify the view over the efficiency results.

The efficiency ranges from 0 to 1, but mostly of the graphs are represented from 0.4 to 1, and the shadow speed ranges from $1cm/s$ to $10m/s$.

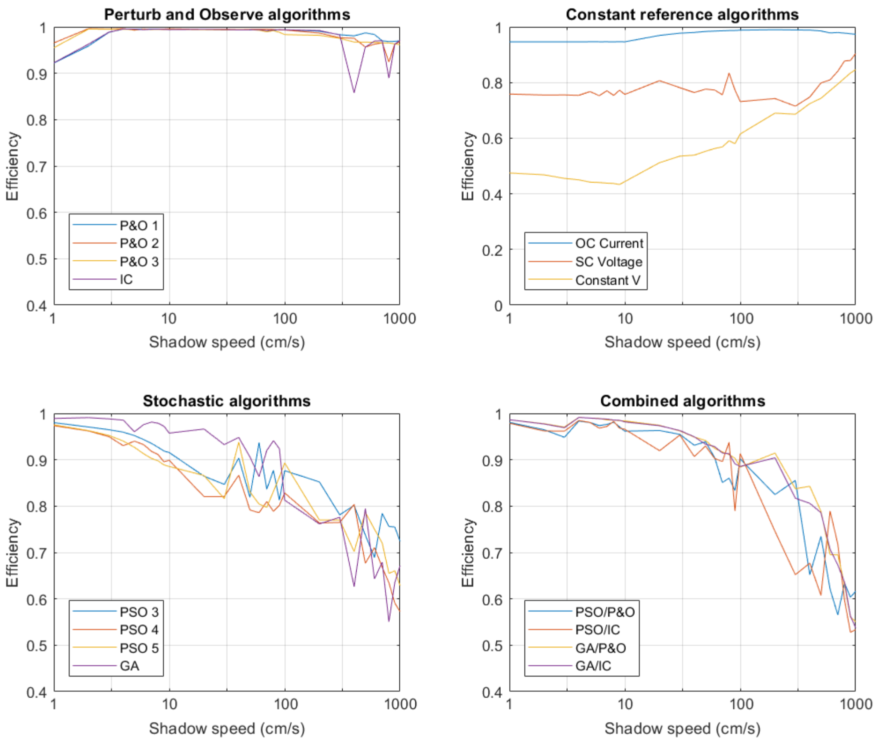

Figure A.1: *Vertical shadow (x1 size): Setup 1*

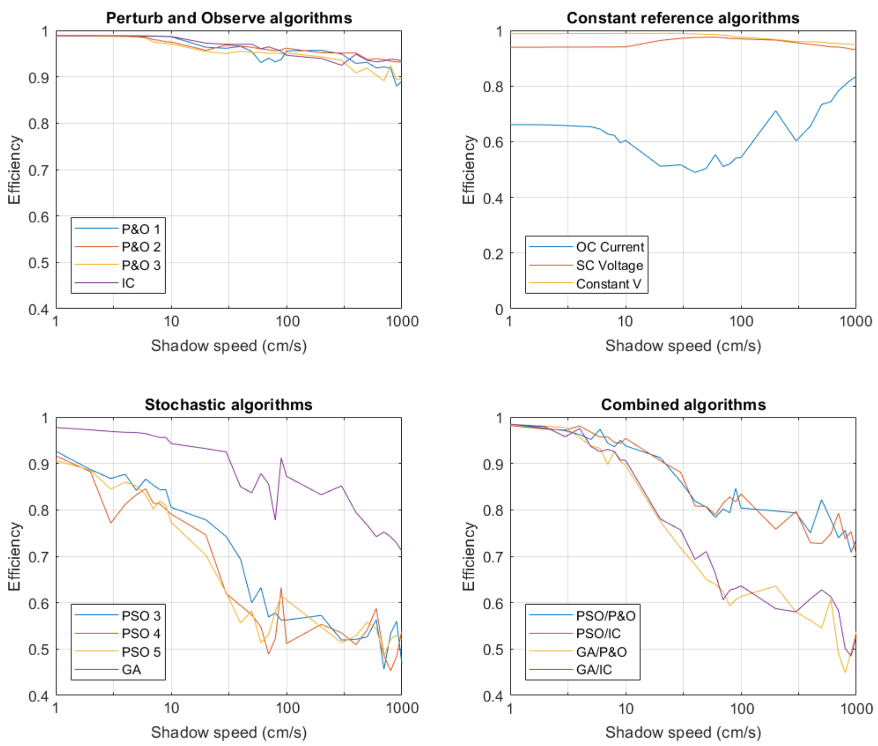

Figure A.2: *Vertical shadow (x1 size): Setup 2*

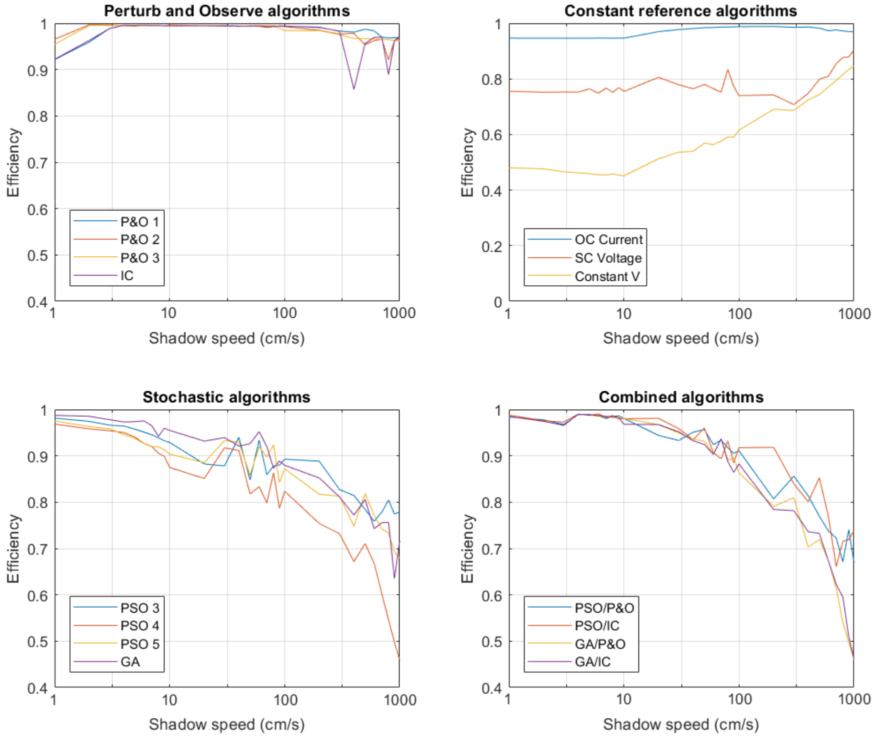

Figure A.3: *Vertical shadow (x1 size): Setup 3*

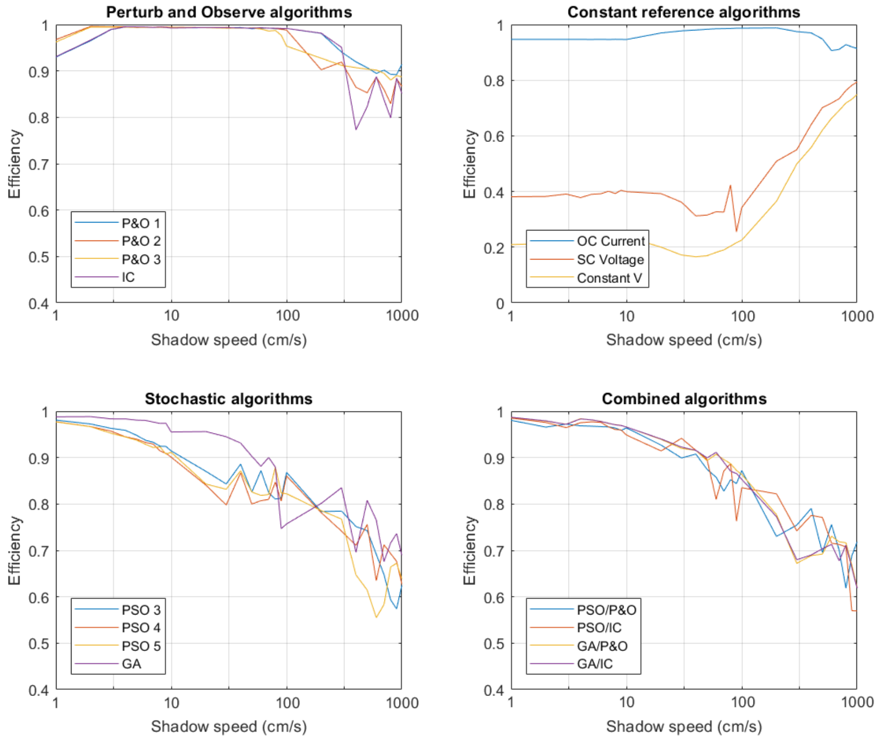

Figure A.4: *Vertical shadow (x2 size): Setup 1*

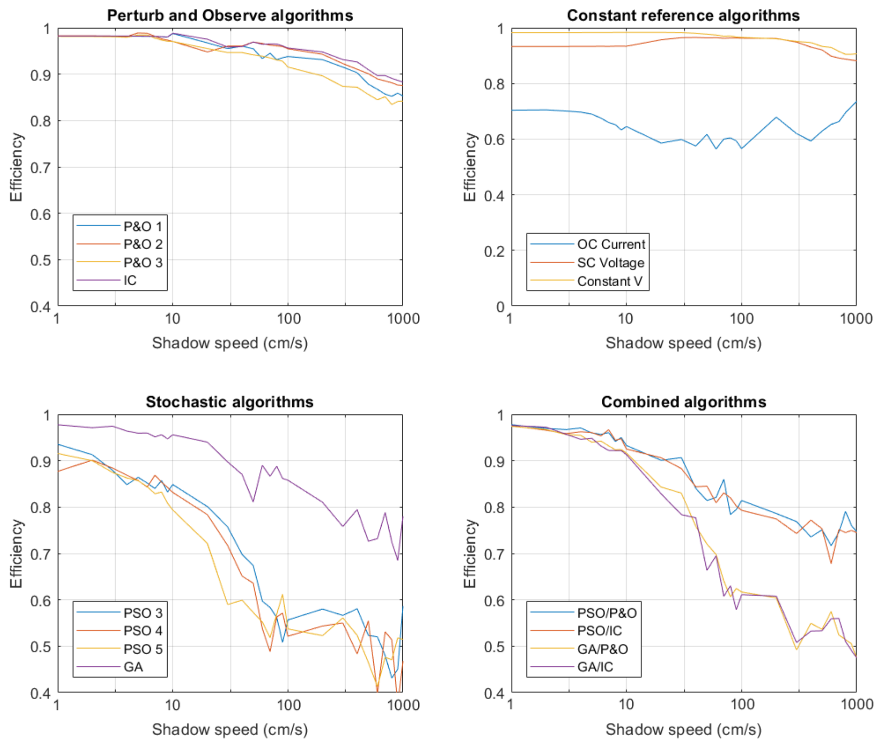

Figure A.5: *Vertical shadow (x2 size): Setup 2*

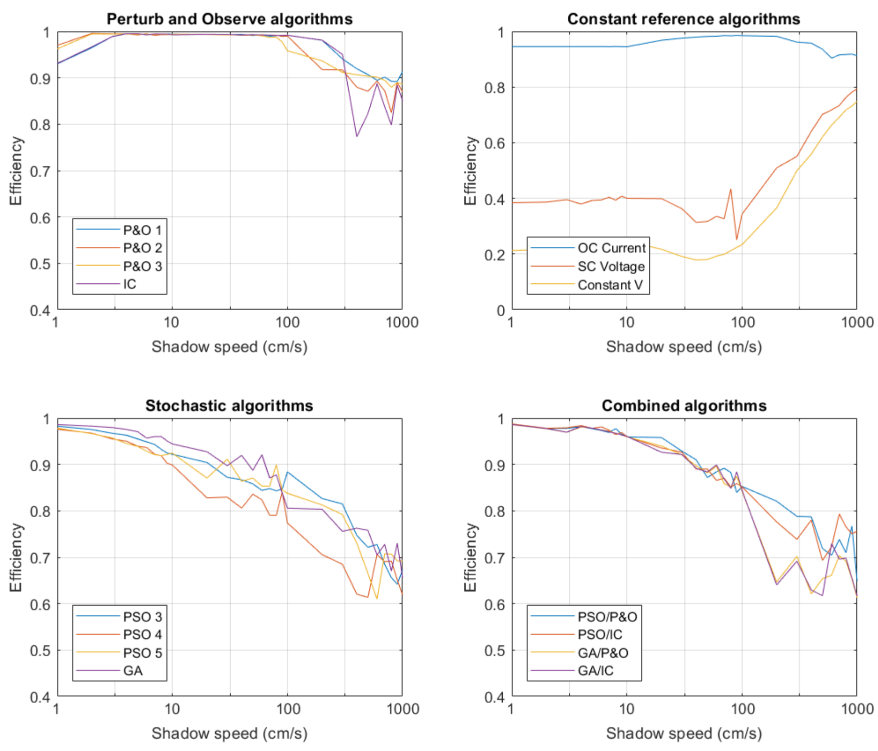

Figure A.6: *Vertical shadow (x2 size): Setup 3*

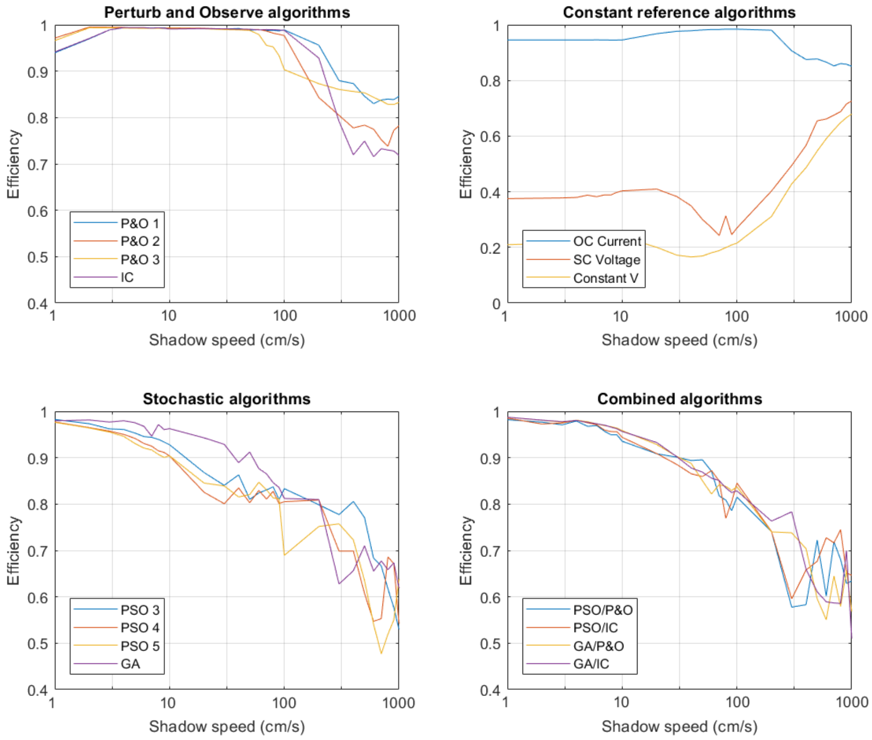

Figure A.7: *Vertical shadow (x3 size): Setup 1*

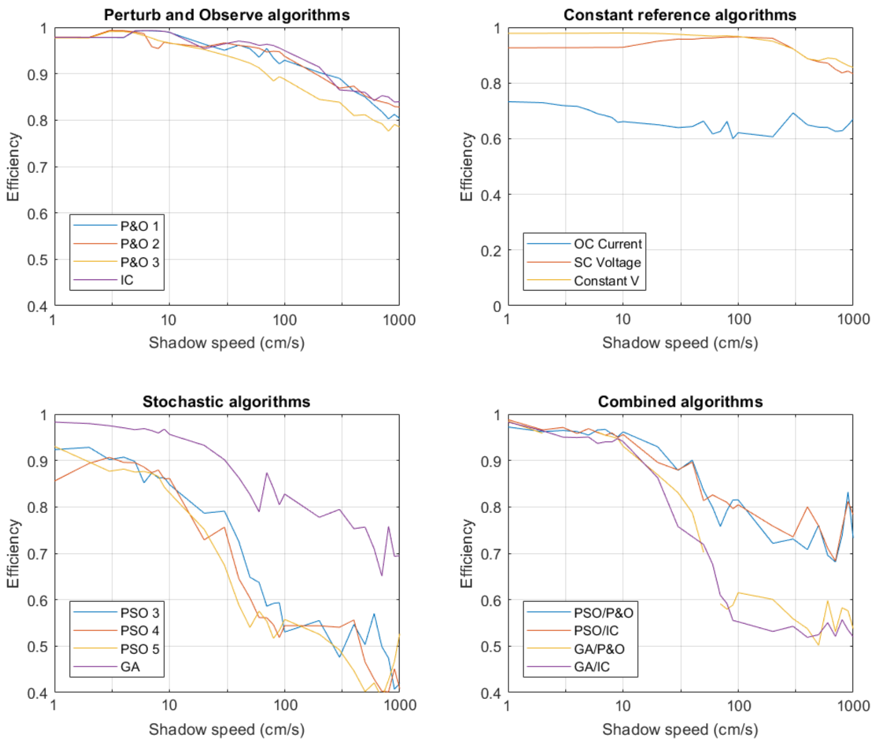

Figure A.8: *Vertical shadow (x3 size): Setup 2*

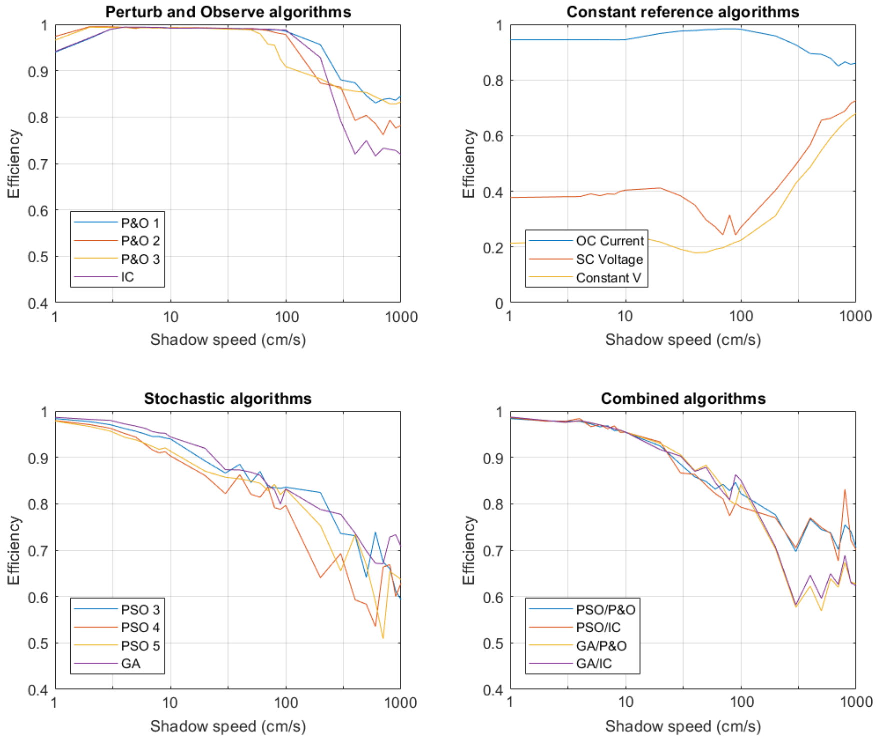

Figure A.9: *Vertical shadow (x3 size): Setup 3*

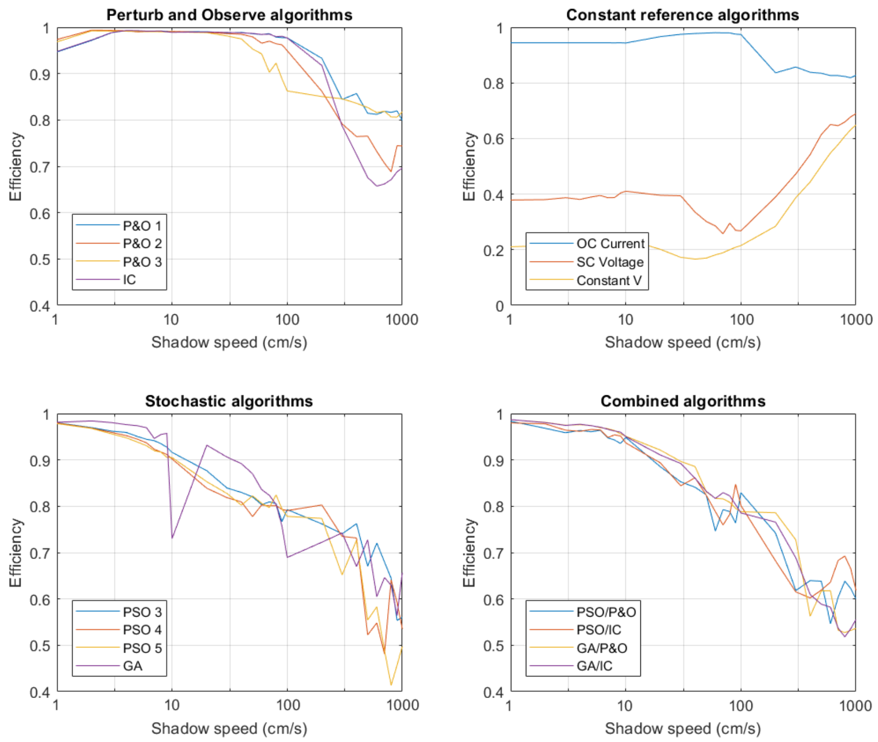

Figure A.10: *Vertical shadow (x4 size): Setup 1*

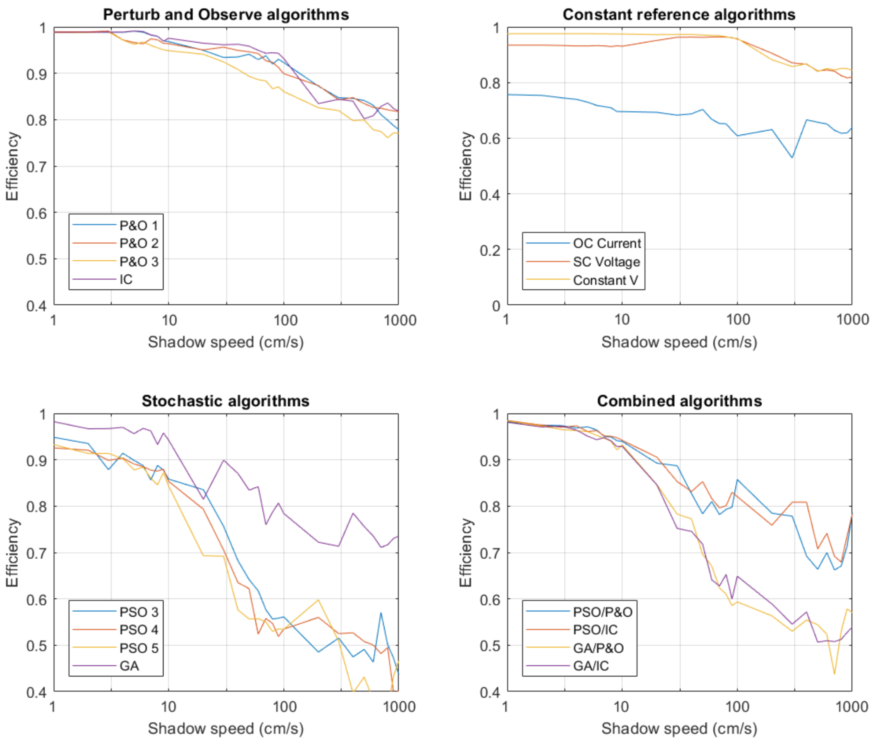

Figure A.11: *Vertical shadow (x4 size): Setup 2*

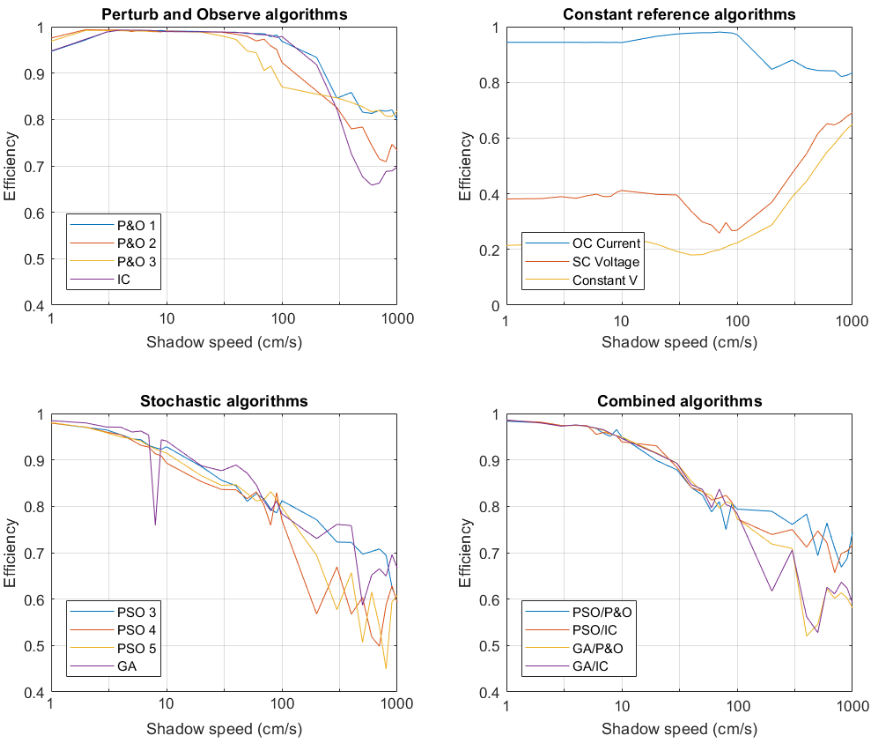

Figure A.12: *Vertical shadow (x4 size): Setup 3*

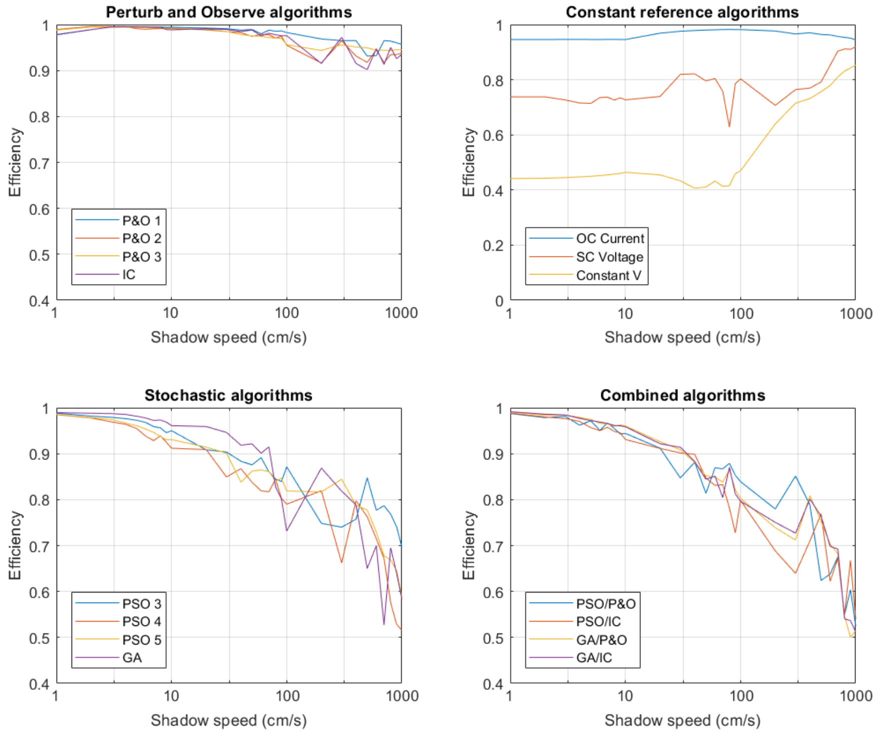

Figure A.13: *Horizontal shadow (x3-y1 size): Setup 1*

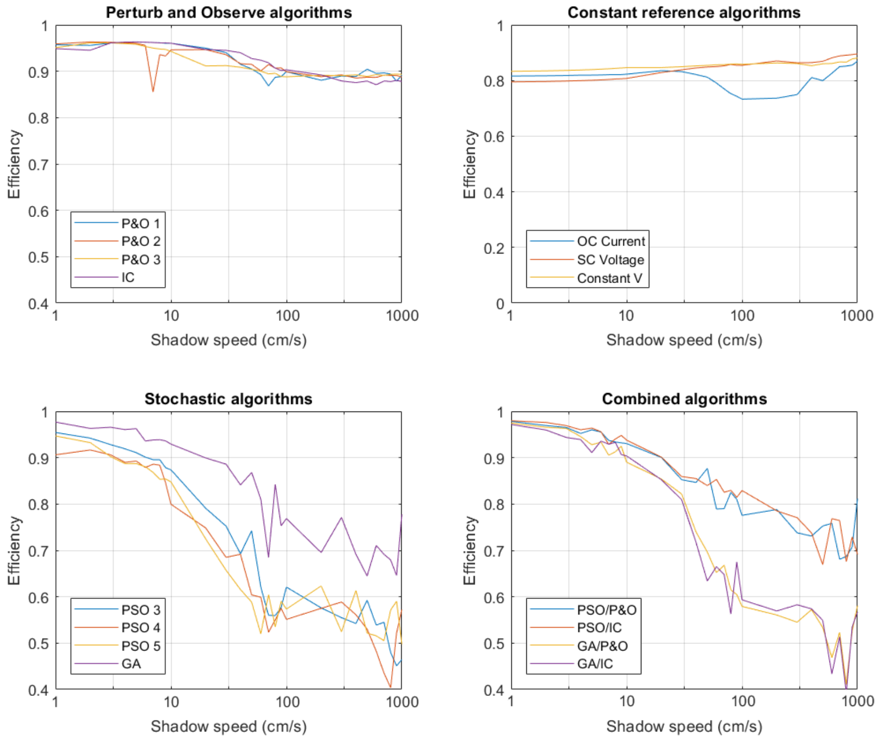

Figure A.14: *Horizontal shadow (x3-y1 size): Setup 2*

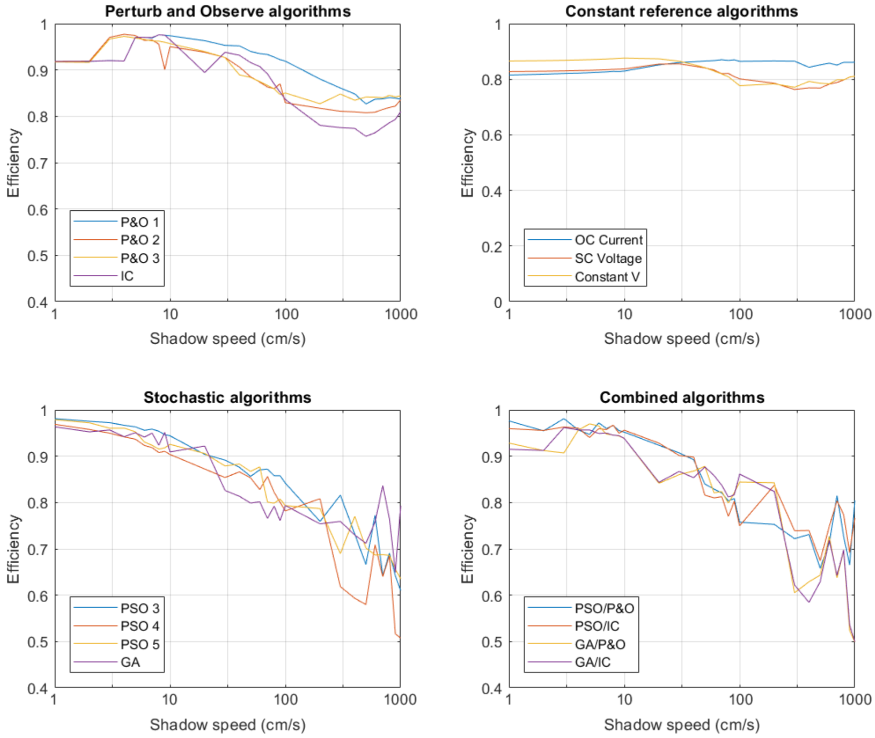

Figure A.15: *Horizontal shadow (x3-y1 size): Setup 3*

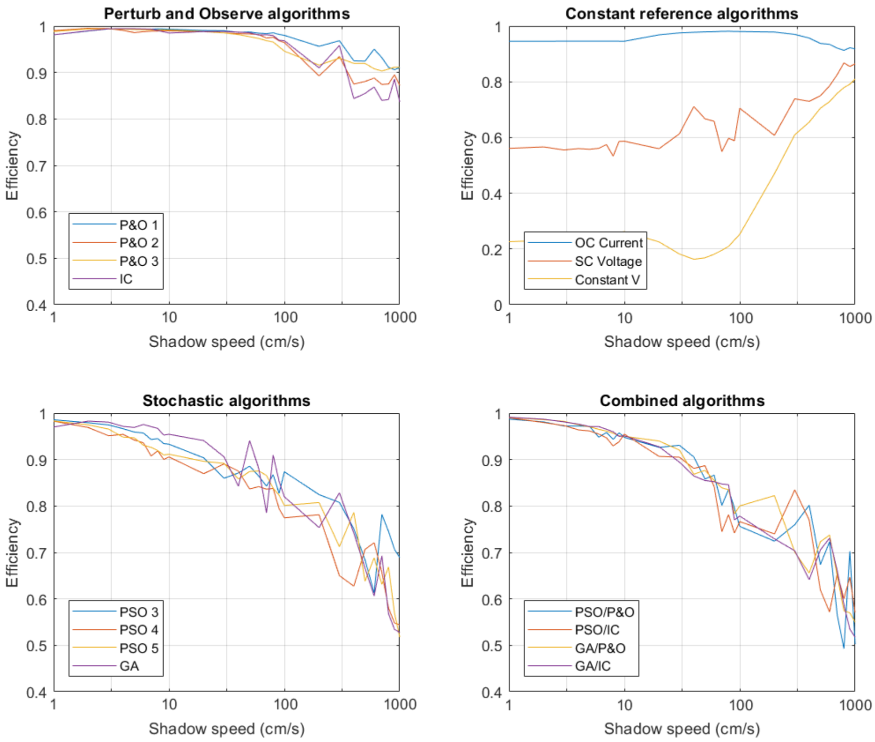

Figure A.16: *Horizontal shadow (x4-y2 size): Setup 1*

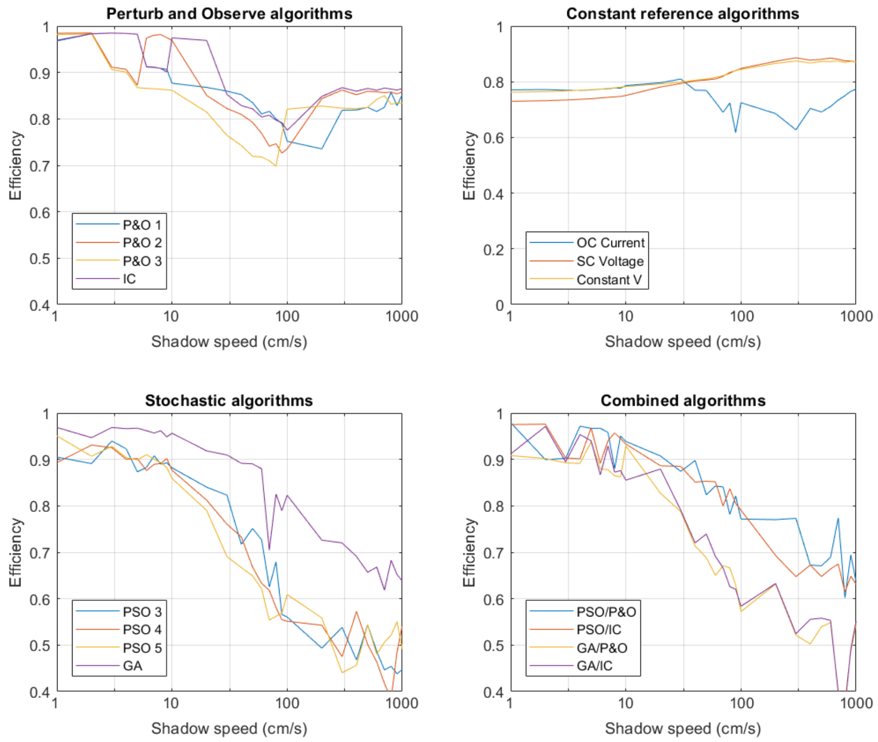

Figure A.17: *Horizontal shadow (x4-y2 size): Setup 2*

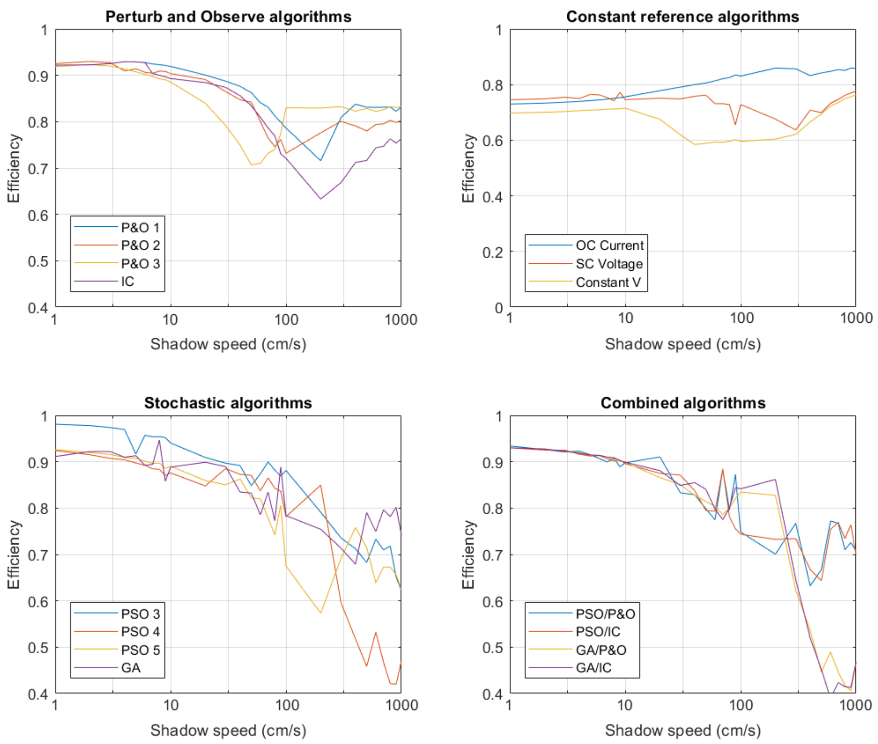

Figure A.18: *Horizontal shadow (x4-y2 size): Setup 3*

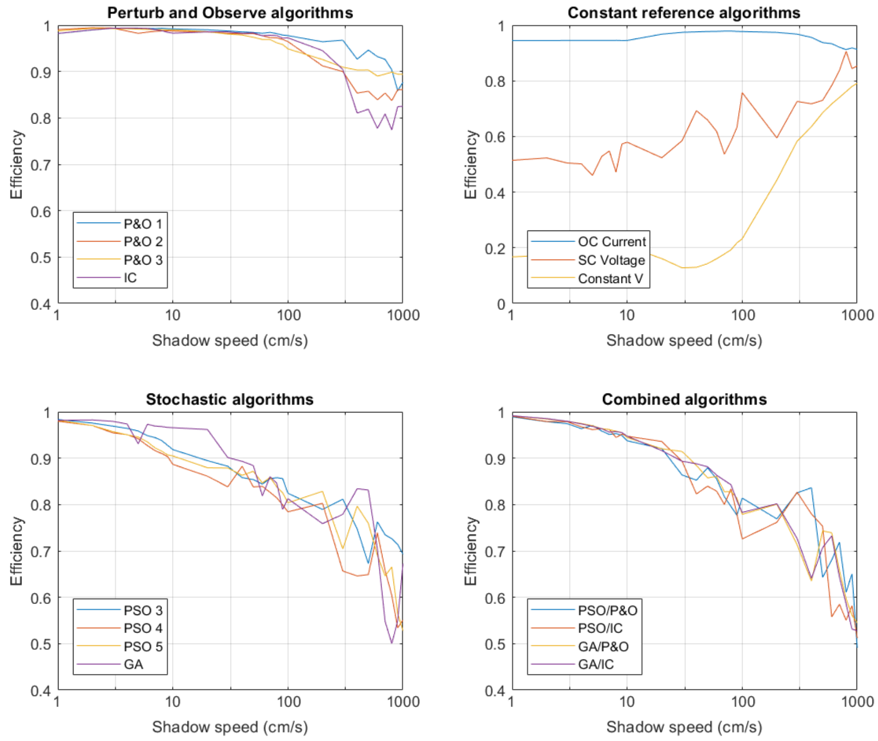

Figure A.19: *Horizontal shadow (x5-y3 size): Setup 1*

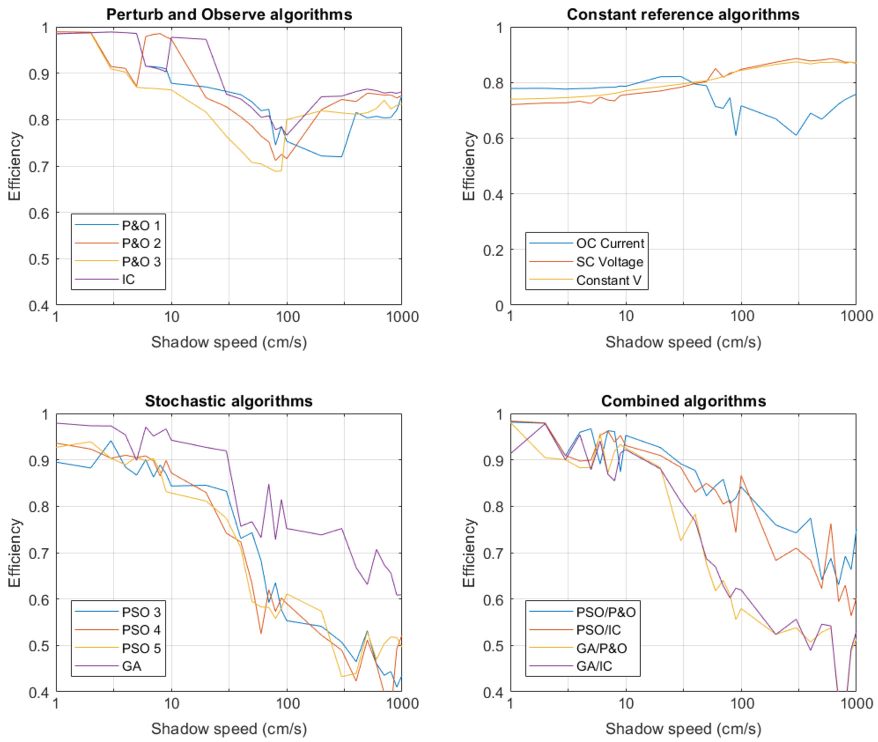

Figure A.20: *Horizontal shadow (x5-y3 size): Setup 2*

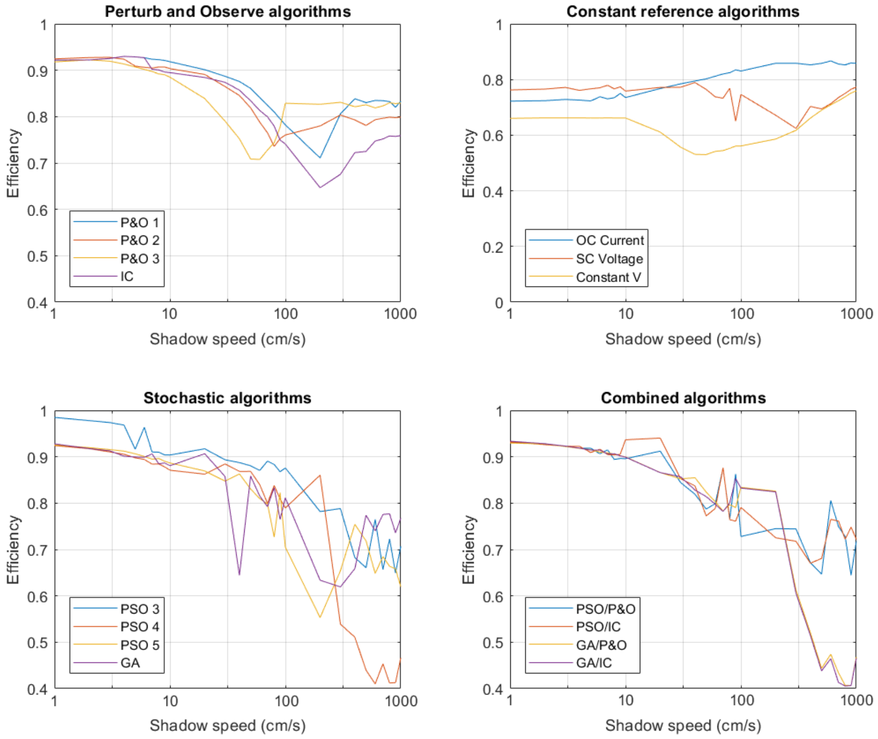

Figure A.21: *Horizontal shadow (x5-y3 size): Setup 3*

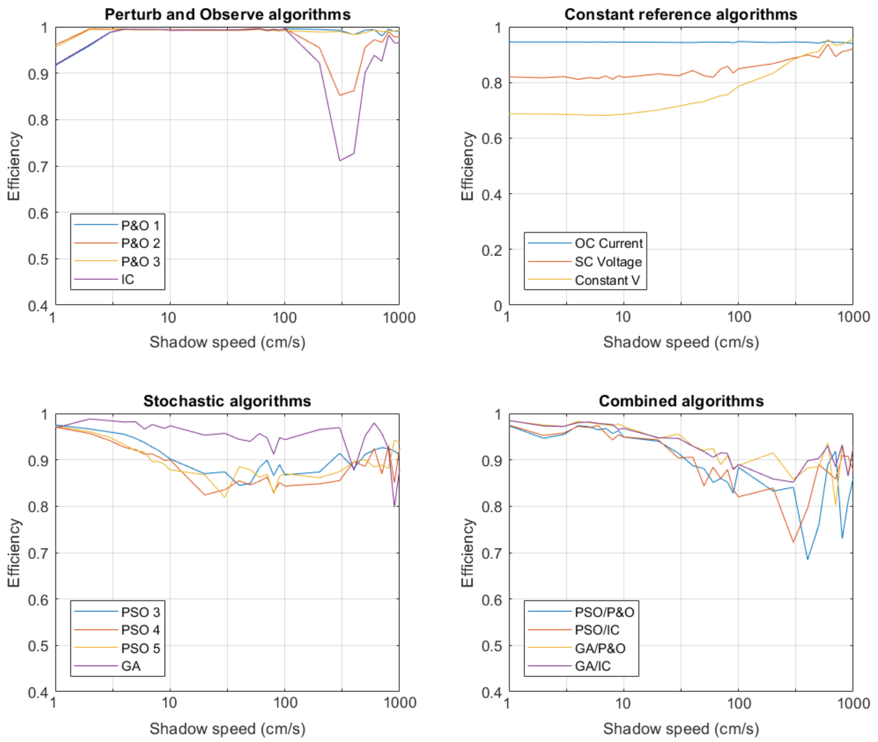

Figure A.22: *Partial shadow (3 shadows): Setup 1*

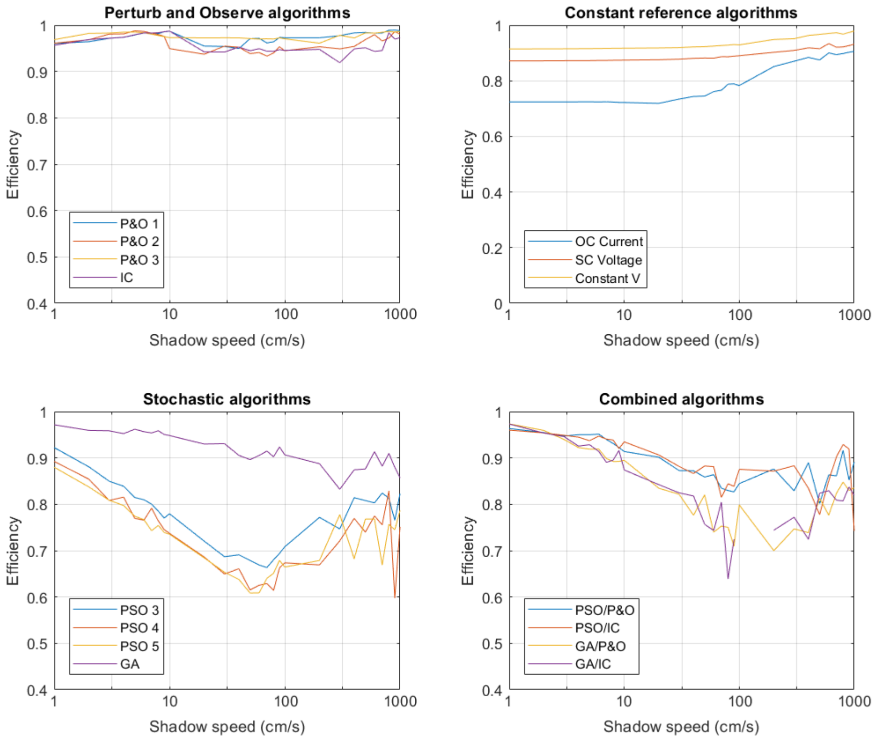

Figure A.23: *Partial shadow (3 shadows): Setup 2*

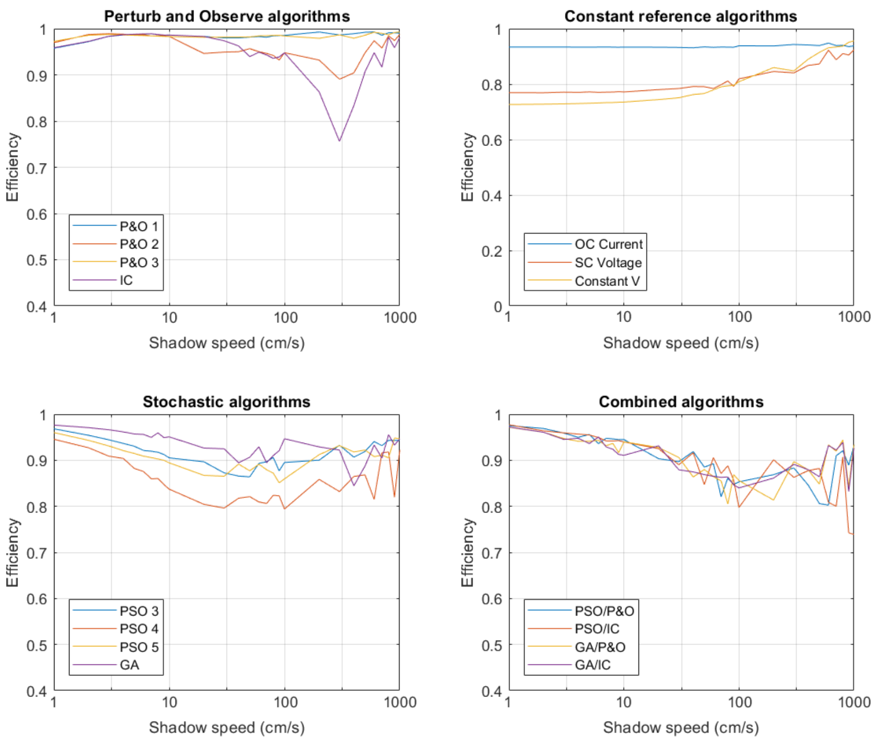

Figure A.24: *Partial shadow (3 shadows): Setup 3*

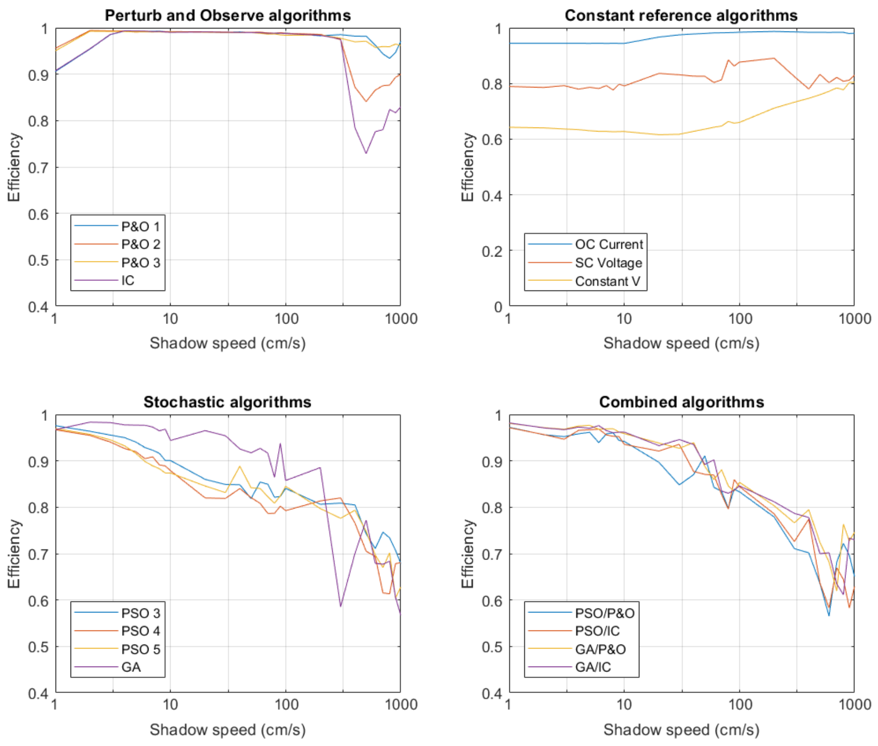

Figure A.25: *Partial shadow (4 shadows): Setup 1*

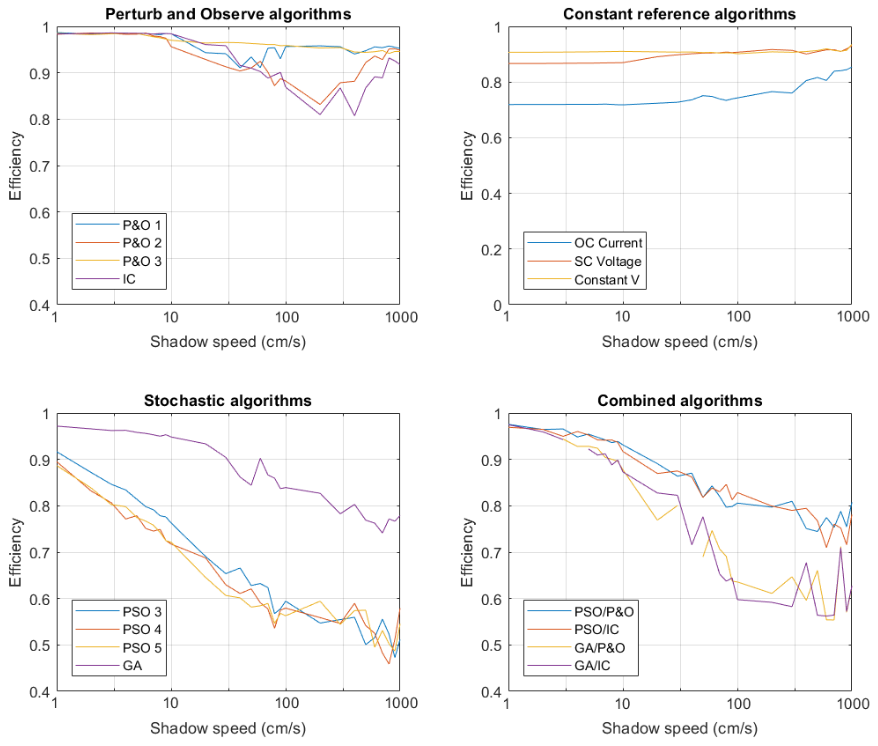

Figure A.26: *Partial shadow (4 shadows): Setup 2*

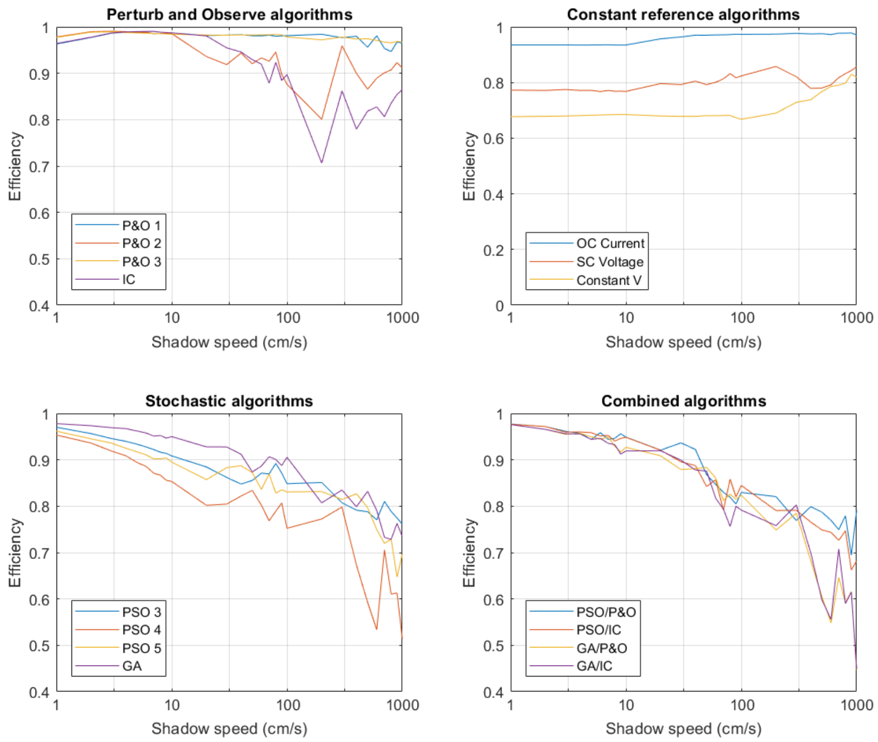

Figure A.27: *Partial shadow (4 shadows): Setup 3*

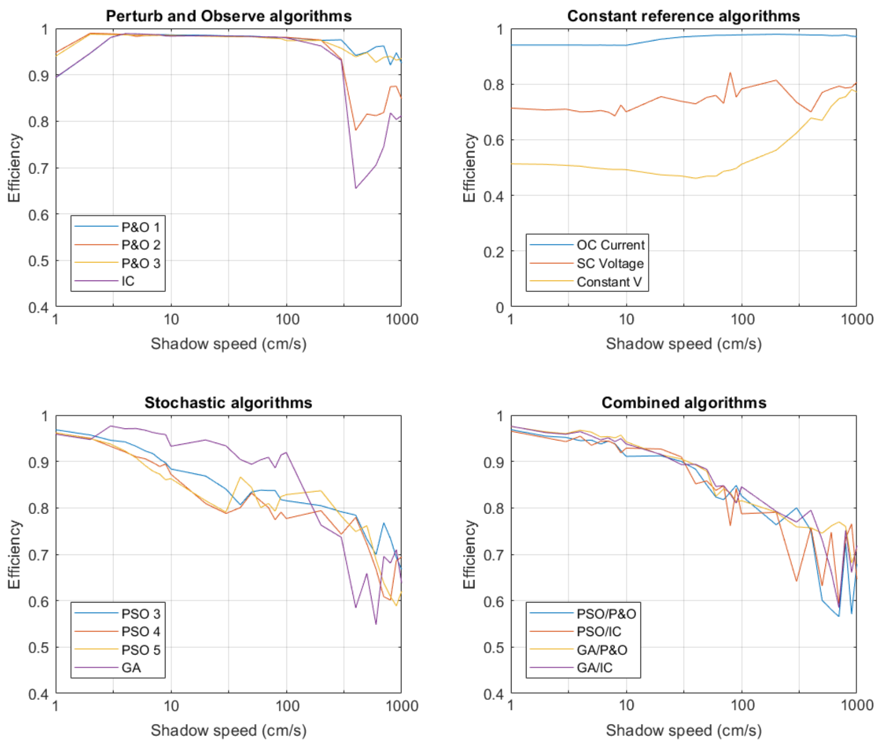

Figure A.28: *Partial shadow (5 shadows): Setup 1*

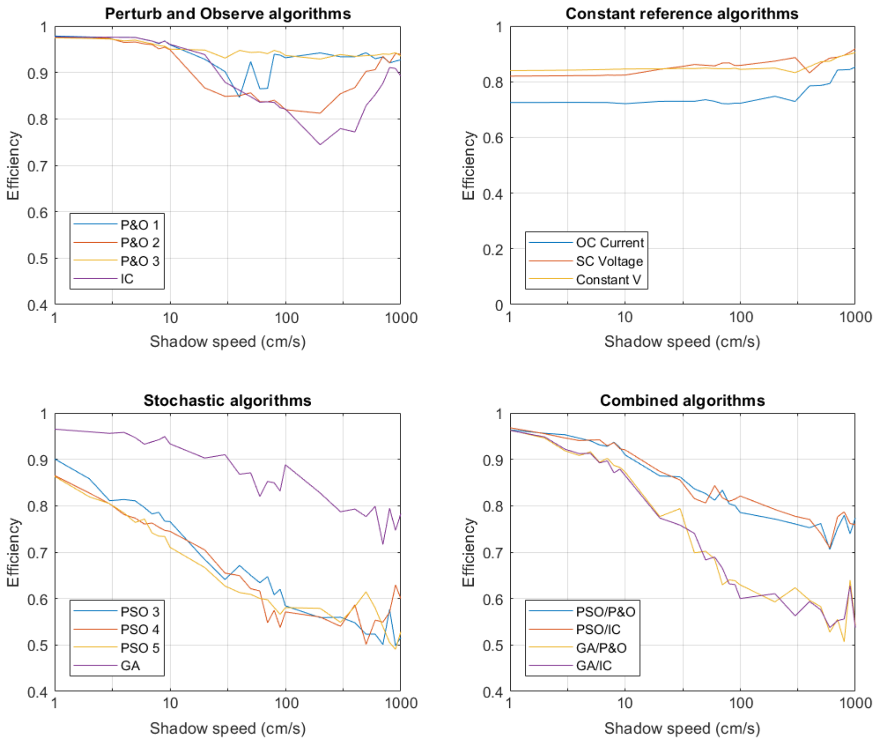

Figure A.29: *Partial shadow (5 shadows): Setup 2*

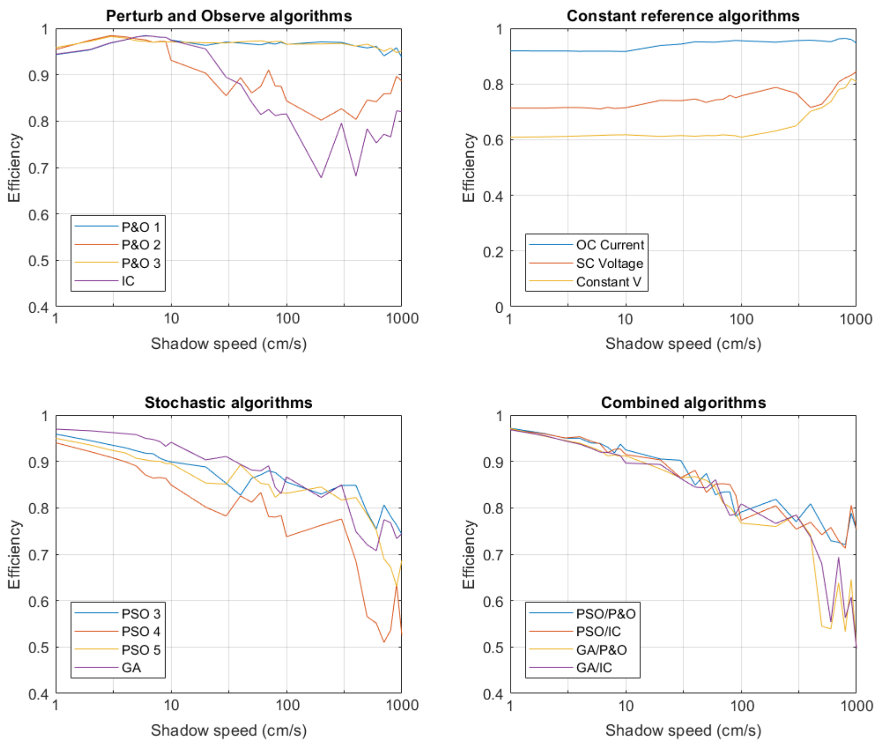

Figure A.30: *Partial shadow (5 shadows): Setup 3*

APPENDIX *B*

Appendix B - Result tables

B.1 Average efficiency charts

The efficiency results are described in the next figures.

All MPPT efficiencies along the speed range are presented in a table form, where the best and the worst result is highlighted in green and red respectively.

The MPPT techniques used are divided into 4 subgroups, being A, the Perturb and Observe algorithms, B, the constant reference algorithms, C, the stochastic algorithms and D, the combined algorithms. This pretends to highlight in a clearer way which subgroup of algorithms has the trend to develop a best or a worst behaviour along with the speed range. It is done in this manner because each subgroup contains MPPT algorithms that share many similarities and therefore their behaviour it's also alike.

Each shadow scenario is analysed with the 3 setup arrays, in a total of 30 tables.

Vertical shadow (x1 size)

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,922	0,959	0,988	0,995	0,995	0,995	0,995	0,995	0,995	0,995	0,995	0,994	0,994	0,993	0,994	0,992	0,992	0,994	0,994	0,991	0,983	0,981	0,987	0,984	0,970	0,968	0,969	0,970
P&O 2	0,965	0,996	0,995	0,996	0,993	0,995	0,995	0,995	0,995	0,996	0,995	0,995	0,994	0,995	0,995	0,995	0,994	0,993	0,993	0,987	0,977	0,975	0,957	0,963	0,966	0,925	0,963	0,968
P&O 3	0,955	0,995	0,995	0,995	0,994	0,995	0,994	0,995	0,994	0,995	0,994	0,993	0,994	0,994	0,993	0,990	0,992	0,988	0,983	0,982	0,975	0,967	0,967	0,966	0,966	0,965	0,963	0,962
IC	0,922	0,963	0,989	0,995	0,995	0,994	0,995	0,995	0,995	0,994	0,995	0,994	0,994	0,994	0,994	0,992	0,993	0,994	0,994	0,992	0,983	0,858	0,956	0,970	0,970	0,890	0,963	0,971
SC Current	0,946	0,946	0,946	0,946	0,946	0,946	0,946	0,946	0,947	0,946	0,969	0,977	0,980	0,984	0,985	0,986	0,987	0,987	0,988	0,990	0,989	0,989	0,985	0,978	0,980	0,978	0,975	0,973
OC Voltage	0,759	0,755	0,755	0,754	0,767	0,753	0,771	0,754	0,773	0,757	0,807	0,781	0,764	0,776	0,773	0,756	0,834	0,773	0,731	0,743	0,715	0,748	0,798	0,810	0,841	0,877	0,879	0,904
Const. Voltage	0,475	0,468	0,455	0,450	0,442	0,441	0,438	0,437	0,433	0,444	0,512	0,535	0,539	0,553	0,563	0,569	0,591	0,580	0,615	0,690	0,686	0,724	0,743	0,771	0,794	0,816	0,834	0,847
PSO 3	0,980	0,971	0,965	0,960	0,952	0,943	0,936	0,927	0,919	0,916	0,865	0,847	0,903	0,819	0,937	0,836	0,877	0,813	0,877	0,852	0,781	0,802	0,737	0,689	0,784	0,756	0,755	0,724
PSO 4	0,974	0,962	0,950	0,930	0,940	0,933	0,918	0,911	0,895	0,899	0,821	0,821	0,867	0,792	0,786	0,810	0,789	0,802	0,828	0,764	0,765	0,804	0,677	0,710	0,668	0,635	0,591	0,572
PSO 5	0,975	0,963	0,952	0,940	0,927	0,913	0,903	0,898	0,889	0,885	0,866	0,816	0,938	0,831	0,804	0,797	0,832	0,862	0,893	0,770	0,770	0,702	0,787	0,750	0,720	0,655	0,660	0,629
GA	0,989	0,991	0,988	0,985	0,960	0,976	0,981	0,979	0,972	0,957	0,966	0,933	0,948	0,906	0,863	0,920	0,941	0,924	0,813	0,762	0,776	0,626	0,795	0,643	0,679	0,551	0,635	0,672
PSO/P&O	0,981	0,965	0,948	0,983	0,980	0,974	0,976	0,981	0,971	0,962	0,963	0,955	0,931	0,939	0,905	0,851	0,860	0,834	0,902	0,825	0,855	0,652	0,735	0,621	0,565	0,634	0,603	0,616
PSO/IC	0,979	0,962	0,962	0,985	0,980	0,968	0,972	0,983	0,968	0,966	0,920	0,953	0,907	0,930	0,903	0,896	0,938	0,789	0,913	0,746	0,652	0,677	0,608	0,789	0,718	0,597	0,528	0,534
GA/P&O	0,986	0,978	0,970	0,991	0,990	0,989	0,986	0,986	0,984	0,984	0,974	0,962	0,949	0,942	0,924	0,917	0,911	0,903	0,884	0,914	0,838	0,843	0,789	0,695	0,695	0,631	0,561	0,550
GA/IC	0,986	0,977	0,969	0,991	0,990	0,989	0,988	0,986	0,985	0,982	0,973	0,963	0,949	0,934	0,928	0,915	0,913	0,891	0,886	0,904	0,817	0,806	0,786	0,707	0,673	0,636	0,563	0,537
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	D	C	D	D	D	C	D	D
Setup 1	C	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	A	A	B	B	B	B

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,988	0,988	0,988	0,988	0,988	0,988	0,987	0,987	0,987	0,986	0,964	0,961	0,966	0,955	0,931	0,940	0,932	0,937	0,956	0,957	0,949	0,929	0,931	0,919	0,921	0,918	0,880	0,890
P&O 2	0,989	0,989	0,989	0,988	0,987	0,985	0,980	0,978	0,975	0,975	0,957	0,969	0,966	0,964	0,960	0,958	0,956	0,959	0,962	0,952	0,951	0,951	0,937	0,939	0,937	0,934	0,932	0,932
P&O 3	0,988	0,987	0,987	0,986	0,985	0,984	0,975	0,973	0,972	0,971	0,955	0,950	0,955	0,952	0,952	0,950	0,951	0,950	0,951	0,943	0,935	0,909	0,919	0,904	0,891	0,924	0,894	0,897
IC	0,989	0,989	0,989	0,989	0,988	0,988	0,988	0,988	0,987	0,987	0,973	0,970	0,970	0,970	0,961	0,964	0,960	0,955	0,946	0,940	0,925	0,949	0,936	0,932	0,934	0,938	0,937	0,934
SC Current	0,662	0,661	0,658	0,655	0,654	0,645	0,628	0,623	0,596	0,605	0,512	0,517	0,489	0,504	0,554	0,511	0,520	0,541	0,543	0,711	0,603	0,656	0,734	0,744	0,783	0,805	0,823	0,834
OC Voltage	0,940	0,940	0,940	0,940	0,940	0,940	0,940	0,940	0,941	0,941	0,964	0,971	0,974	0,976	0,976	0,974	0,971	0,971	0,969	0,965	0,956	0,950	0,945	0,941	0,940	0,937	0,933	0,931
Const. Voltage	0,989	0,989	0,989	0,989	0,989	0,989	0,989	0,989	0,989	0,989	0,989	0,989	0,988	0,985	0,986	0,983	0,981	0,976	0,976	0,967	0,960	0,959	0,958	0,954	0,953	0,951	0,950	0,948
PSO 3	0,926	0,887	0,868	0,877	0,842	0,866	0,854	0,843	0,844	0,805	0,779	0,743	0,693	0,600	0,632	0,569	0,578	0,562	0,563	0,572	0,519	0,521	0,526	0,563	0,457	0,534	0,560	0,468
PSO 4	0,917	0,882	0,772	0,812	0,833	0,845	0,815	0,813	0,801	0,791	0,746	0,619	0,594	0,574	0,548	0,489	0,522	0,633	0,512	0,553	0,535	0,509	0,541	0,588	0,485	0,453	0,484	0,540
PSO 5	0,907	0,885	0,845	0,860	0,852	0,833	0,802	0,820	0,809	0,773	0,702	0,622	0,556	0,583	0,514	0,531	0,581	0,615	0,606	0,547	0,514	0,529	0,558	0,545	0,483	0,522	0,529	0,521
GA	0,977	0,972	0,969	0,967	0,967	0,964	0,960	0,956	0,956	0,943	0,932	0,925	0,850	0,837	0,878	0,855	0,778	0,912	0,872	0,833	0,852	0,794	0,767	0,742	0,752	0,742	0,728	0,711
PSO/P&O	0,984	0,976	0,971	0,962	0,952	0,974	0,944	0,936	0,950	0,938	0,912	0,861	0,819	0,806	0,783	0,802	0,794	0,846	0,804	0,797	0,793	0,751	0,822	0,779	0,740	0,756	0,708	0,737
PSO/IC	0,982	0,974	0,972	0,981	0,968	0,957	0,957	0,945	0,943	0,954	0,906	0,881	0,808	0,807	0,789	0,814	0,828	0,817	0,834	0,758	0,797	0,729	0,727	0,748	0,793	0,738	0,753	0,703
GA/P&O	0,984	0,981	0,977	0,956	0,938	0,933	0,898	0,926	0,904	0,896	0,775	0,718	0,682	0,650	0,640	0,624	0,593	0,606	0,613	0,636	0,580	0,561	0,545	0,607	0,491	0,449	0,493	0,538
GA/IC	0,984	0,979	0,958	0,975	0,937	0,925	0,930	0,926	0,907	0,907	0,780	0,757	0,693	0,710	0,663	0,606	0,627	0,631	0,636	0,587	0,580	0,608	0,628	0,613	0,583	0,501	0,485	0,528
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	C	C	C	C	C	C	C	D	C	C
Setup 2	A	A	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,921	0,959	0,988	0,996	0,995	0,996	0,995	0,995	0,994	0,995	0,995	0,995	0,994	0,994	0,994	0,992	0,993	0,994	0,994	0,991	0,983	0,981	0,987	0,984	0,970	0,968	0,969	0,970
P&O 2	0,966	0,997	0,996	0,995	0,993	0,996	0,995	0,995	0,994	0,996	0,995	0,995	0,993	0,995	0,995	0,994	0,994	0,993	0,993	0,985	0,977	0,978	0,954	0,962	0,965	0,921	0,963	0,968
P&O 3	0,954	0,995	0,995	0,995	0,994	0,995	0,994	0,995	0,994	0,995	0,994	0,993	0,994	0,994	0,993	0,991	0,993	0,989	0,984	0,984	0,975	0,967	0,967	0,966	0,965	0,965	0,963	0,961
IC	0,922	0,963	0,988	0,996	0,995	0,996	0,995	0,995	0,994	0,994	0,995	0,994	0,994	0,994	0,994	0,992	0,993	0,994	0,994	0,991	0,983	0,857	0,956	0,969	0,970	0,889	0,963	0,971
SC Current	0,946	0,946	0,946	0,946	0,946	0,946	0,947	0,946	0,947	0,946	0,970	0,977	0,981	0,984	0,985	0,986	0,987	0,987	0,988	0,988	0,985	0,987	0,982	0,973	0,976	0,972	0,970	0,969
OC Voltage	0,755	0,752	0,753	0,752	0,764	0,749	0,767	0,751	0,769	0,755	0,805	0,779	0,764	0,780	0,765	0,752	0,834	0,773	0,740	0,742	0,708	0,748	0,798	0,810	0,855	0,877	0,879	0,904
Const. Voltage	0,480	0,476	0,466	0,462	0,459	0,455	0,455	0,458	0,454	0,451	0,513	0,536	0,540	0,569	0,563	0,576	0,591	0,590	0,616	0,690	0,686	0,724	0,743	0,771	0,794	0,815	0,834	0,846
PSO 3	0,981	0,974	0,966	0,964	0,958	0,951	0,945	0,939	0,932	0,929	0,882	0,878	0,940	0,848	0,934	0,859	0,878	0,880	0,893	0,888	0,827	0,814	0,784	0,759	0,779	0,804	0,774	0,779
PSO 4	0,968	0,958	0,954	0,950	0,940	0,926	0,920	0,905	0,899	0,875	0,851	0,917	0,911	0,818	0,833	0,798	0,863	0,787	0,824	0,754	0,732	0,672	0,711	0,668	0,602	0,546	0,497	0,459
PSO 5	0,975	0,963	0,959	0,946	0,938	0,926	0,920	0,919	0,913	0,904	0,885	0,933	0,930	0,858	0,920	0,897	0,924	0,842	0,872	0,817	0,813	0,748	0,818	0,771	0,742	0,733	0,692	0,680
GA	0,987	0,985	0,978	0,973	0,974	0,975	0,965	0,942	0,960	0,955	0,932	0,939	0,921	0,926	0,952	0,920	0,873	0,889	0,880	0,852	0,811	0,772	0,806	0,743	0,756	0,756	0,635	0,717
PSO/P&O	0,984	0,978	0,968	0,989	0,989	0,986	0,981	0,985	0,987	0,981	0,944	0,933	0,951	0,957	0,924	0,934	0,917	0,905	0,911	0,807	0,856	0,814	0,769	0,737	0,723	0,671	0,741	0,670
PSO/IC	0,988	0,976	0,973	0,990	0,987	0,991	0,983	0,987	0,980	0,980	0,981	0,959	0,935	0,960	0,907	0,893	0,932	0,885	0,918	0,918	0,840	0,801	0,853	0,768	0,661	0,716	0,719	0,739
GA/P&O	0,985	0,975	0,965	0,990	0,988	0,985	0,985	0,982	0,982	0,981	0,967	0,949	0,936	0,932	0,904	0,937	0,890	0,896	0,863	0,791	0,810	0,703	0,719	0,674	0,615	0,540	0,498	0,460
GA/IC	0,985	0,975	0,966	0,990	0,988	0,987	0,985	0,985	0,983	0,968	0,967	0,952	0,932	0,924	0,903	0,937	0,888	0,864	0,883	0,784	0,782	0,736	0,733	0,673	0,623	0,595	0,510	0,462
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	C	C	C	C	D	C	C
Setup 3	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B	A	B	B	B	A

Figure B.1: *Vertical shadow (x1 size)*

Vertical shadow (x2 size)

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,930	0,965	0,989	0,995	0,995	0,995	0,994	0,995	0,994	0,993	0,993	0,993	0,994	0,991	0,992	0,992	0,991	0,990	0,992	0,981	0,941	0,919	0,907	0,895	0,902	0,893	0,892	0,914
P&O 2	0,967	0,996	0,995	0,995	0,994	0,995	0,994	0,995	0,995	0,994	0,993	0,994	0,992	0,993	0,993	0,992	0,992	0,990	0,988	0,902	0,919	0,865	0,853	0,887	0,860	0,829	0,883	0,867
P&O 3	0,962	0,995	0,994	0,994	0,994	0,994	0,994	0,994	0,994	0,994	0,993	0,992	0,992	0,993	0,990	0,986	0,987	0,977	0,953	0,927	0,912	0,907	0,904	0,902	0,895	0,880	0,890	0,887
IC	0,930	0,966	0,989	0,995	0,995	0,995	0,994	0,995	0,994	0,993	0,994	0,993	0,993	0,992	0,993	0,992	0,992	0,992	0,992	0,981	0,951	0,773	0,823	0,887	0,838	0,798	0,885	0,851
SC Current	0,946	0,946	0,946	0,947	0,946	0,947	0,946	0,947	0,947	0,946	0,970	0,977	0,980	0,983	0,985	0,985	0,986	0,987	0,987	0,988	0,975	0,970	0,948	0,906	0,911	0,928	0,920	0,914
OC Voltage	0,381	0,382	0,391	0,378	0,390	0,392	0,401	0,392	0,405	0,400	0,392	0,362	0,312	0,315	0,327	0,326	0,423	0,255	0,342	0,509	0,550	0,641	0,702	0,718	0,734	0,763	0,782	0,794
Const. Voltage	0,209	0,213	0,216	0,219	0,222	0,226	0,229	0,233	0,236	0,238	0,200	0,172	0,166	0,169	0,181	0,190	0,204	0,216	0,225	0,365	0,499	0,559	0,620	0,663	0,691	0,718	0,731	0,749
PSO 3	0,981	0,972	0,963	0,959	0,948	0,937	0,933	0,925	0,924	0,914	0,870	0,843	0,886	0,826	0,872	0,824	0,811	0,813	0,868	0,784	0,785	0,751	0,743	0,691	0,648	0,593	0,574	0,625
PSO 4	0,977	0,967	0,957	0,945	0,940	0,932	0,929	0,914	0,909	0,901	0,841	0,798	0,867	0,800	0,807	0,810	0,847	0,807	0,861	0,781	0,741	0,711	0,756	0,635	0,712	0,693	0,676	0,627
PSO 5	0,977	0,967	0,953	0,944	0,938	0,929	0,922	0,923	0,908	0,911	0,843	0,832	0,872	0,826	0,818	0,820	0,880	0,823	0,822	0,786	0,767	0,647	0,615	0,555	0,584	0,664	0,672	0,638
GA	0,988	0,988	0,984	0,983	0,981	0,980	0,977	0,974	0,974	0,955	0,956	0,945	0,931	0,903	0,881	0,900	0,880	0,747	0,757	0,801	0,835	0,696	0,808	0,765	0,676	0,716	0,736	0,690
PSO/P&O	0,980	0,966	0,972	0,969	0,968	0,967	0,966	0,964	0,958	0,964	0,927	0,899	0,908	0,875	0,858	0,828	0,852	0,844	0,872	0,730	0,755	0,791	0,696	0,756	0,699	0,619	0,688	0,718
PSO/IC	0,985	0,976	0,965	0,975	0,977	0,976	0,966	0,961	0,960	0,949	0,914	0,942	0,916	0,896	0,810	0,871	0,887	0,763	0,835	0,822	0,742	0,775	0,771	0,716	0,713	0,707	0,570	0,569
GA/P&O	0,987	0,979	0,972	0,984	0,981	0,978	0,973	0,971	0,969	0,966	0,939	0,920	0,916	0,894	0,907	0,896	0,887	0,872	0,864	0,777	0,672	0,689	0,692	0,731	0,718	0,716	0,668	0,621
GA/IC	0,987	0,979	0,972	0,983	0,981	0,978	0,974	0,971	0,969	0,966	0,940	0,923	0,916	0,899	0,911	0,890	0,871	0,866	0,853	0,773	0,680	0,690	0,703	0,713	0,677	0,712	0,663	0,618
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	C	C	C	C	D	D
Setup 1	C	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B	B	B	B	B	B	B

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,982	0,982	0,982	0,982	0,982	0,981	0,981	0,980	0,980	0,987	0,967	0,955	0,961	0,955	0,934	0,945	0,931	0,935	0,938	0,931	0,915	0,903	0,878	0,867	0,857	0,852	0,859	0,853
P&O 2	0,983	0,983	0,982	0,981	0,989	0,988	0,982	0,976	0,973	0,970	0,948	0,961	0,961	0,969	0,966	0,963	0,961	0,960	0,955	0,943	0,923	0,911	0,901	0,890	0,885	0,881	0,877	0,875
P&O 3	0,981	0,981	0,981	0,979	0,984	0,984	0,978	0,974	0,971	0,970	0,955	0,947	0,947	0,942	0,939	0,935	0,931	0,928	0,915	0,896	0,874	0,872	0,856	0,845	0,851	0,834	0,841	0,842
IC	0,982	0,982	0,982	0,982	0,982	0,982	0,981	0,981	0,980	0,988	0,975	0,958	0,959	0,969	0,964	0,965	0,965	0,961	0,956	0,948	0,931	0,926	0,910	0,897	0,897	0,891	0,887	0,883
SC Current	0,704	0,705	0,701	0,697	0,690	0,675	0,660	0,652	0,633	0,645	0,586	0,599	0,575	0,617	0,564	0,600	0,604	0,593	0,566	0,679	0,620	0,593	0,629	0,653	0,663	0,695	0,716	0,736
OC Voltage	0,933	0,933	0,933	0,933	0,933	0,933	0,933	0,934	0,934	0,934	0,957	0,964	0,965	0,964	0,964	0,962	0,963	0,963	0,963	0,962	0,948	0,931	0,920	0,898	0,891	0,887	0,884	0,881
Const. Voltage	0,982	0,983	0,983	0,983	0,983	0,983	0,983	0,983	0,983	0,983	0,983	0,983	0,980	0,977	0,974	0,970	0,971	0,967	0,965	0,961	0,951	0,947	0,933	0,929	0,915	0,905	0,905	0,906
PSO 3	0,935	0,913	0,879	0,848	0,864	0,852	0,840	0,857	0,832	0,849	0,801	0,757	0,698	0,674	0,597	0,583	0,562	0,508	0,557	0,580	0,566	0,581	0,523	0,520	0,480	0,431	0,450	0,587
PSO 4	0,877	0,901	0,884	0,869	0,857	0,843	0,869	0,853	0,843	0,832	0,784	0,717	0,651	0,636	0,538	0,488	0,563	0,571	0,521	0,544	0,550	0,483	0,555	0,398	0,531	0,514	0,372	0,468
PSO 5	0,916	0,900	0,875	0,863	0,857	0,844	0,829	0,833	0,808	0,794	0,722	0,590	0,599	0,573	0,552	0,518	0,569	0,612	0,537	0,523	0,561	0,523	0,465	0,413	0,476	0,471	0,518	0,514
GA	0,977	0,971	0,974	0,964	0,959	0,960	0,951	0,956	0,947	0,956	0,940	0,897	0,870	0,811	0,890	0,866	0,888	0,862	0,858	0,810	0,758	0,795	0,726	0,732	0,788	0,725	0,685	0,780
PSO/P&O	0,978	0,970	0,967	0,971	0,960	0,957	0,961	0,942	0,950	0,933	0,901	0,907	0,840	0,814	0,821	0,860	0,784	0,795	0,814	0,786	0,769	0,735	0,751	0,717	0,746	0,791	0,760	0,747
PSO/IC	0,975	0,966	0,958	0,962	0,961	0,953	0,967	0,944	0,947	0,925	0,906	0,883	0,844	0,845	0,809	0,831	0,820	0,802	0,793	0,774	0,743	0,772	0,753	0,678	0,752	0,745	0,750	0,745
GA/P&O	0,974	0,967	0,956	0,955	0,940	0,942	0,932	0,923	0,924	0,916	0,843	0,830	0,758	0,720	0,698	0,641	0,607	0,624	0,617	0,604	0,492	0,549	0,536	0,575	0,524	0,514	0,505	0,474
GA/IC	0,976	0,972	0,957	0,946	0,948	0,932	0,922	0,922	0,922	0,913	0,829	0,784	0,777	0,664	0,695	0,607	0,630	0,579	0,611	0,608	0,508	0,532	0,533	0,559	0,560	0,510	0,491	0,475
Final group	B	B	B	B	B	B	B	B	B	B	B	C	B	C	C	C	C	C	C	C	D	C	C	C	C	C	C	C
Setup 2	A	A	B	B	A	A	B	B	B	A	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,930	0,965	0,989	0,995	0,995	0,992	0,994	0,994	0,994	0,994	0,993	0,993	0,994	0,991	0,993	0,990	0,991	0,991	0,992	0,981	0,941	0,919	0,907	0,895	0,902	0,892	0,892	0,914
P&O 2	0,970	0,996	0,995	0,995	0,992	0,995	0,991	0,993	0,993	0,994	0,994	0,993	0,992	0,992	0,993	0,992	0,992	0,989	0,990	0,918	0,917	0,880	0,871	0,893	0,872	0,825	0,890	0,869
P&O 3	0,962	0,994	0,994	0,994	0,994	0,994	0,994	0,994	0,993	0,994	0,993	0,992	0,992	0,992	0,990	0,987	0,988	0,977	0,958	0,937	0,912	0,907	0,903	0,901	0,894	0,880	0,890	0,887
IC	0,931	0,967	0,989	0,995	0,995	0,993	0,995	0,994	0,994	0,993	0,994	0,993	0,992	0,993	0,992	0,992	0,991	0,991	0,992	0,981	0,951	0,773	0,823	0,887	0,837	0,798	0,884	0,851
SC Current	0,945	0,945	0,945	0,945	0,946	0,945	0,945	0,946	0,945	0,945	0,968	0,976	0,979	0,982	0,983	0,985	0,984	0,986	0,985	0,982	0,961	0,958	0,936	0,904	0,916	0,917	0,918	0,913
OC Voltage	0,385	0,387	0,396	0,380	0,393	0,395	0,404	0,394	0,408	0,400	0,399	0,363	0,314	0,317	0,335	0,327	0,434	0,251	0,343	0,510	0,551	0,641	0,702	0,718	0,734	0,763	0,781	0,794
Const. Voltage	0,213	0,217	0,220	0,224	0,228	0,231	0,235	0,239	0,243	0,246	0,217	0,191	0,179	0,181	0,192	0,199	0,212	0,224	0,233	0,366	0,500	0,559	0,621	0,663	0,692	0,718	0,732	0,749
PSO 3	0,983	0,975	0,967	0,963	0,955	0,948	0,943	0,933	0,925	0,922	0,904	0,872	0,867	0,858	0,844	0,848	0,843	0,847	0,884	0,826	0,815	0,747	0,721	0,728	0,684	0,656	0,642	0,673
PSO 4	0,976	0,967	0,955	0,950	0,939	0,936	0,922	0,919	0,903	0,899	0,828	0,830	0,806	0,836	0,824	0,791	0,790	0,840	0,774	0,706	0,685	0,621	0,613	0,705	0,690	0,692	0,651	0,619
PSO 5	0,978	0,966	0,957	0,945	0,939	0,928	0,921	0,919	0,922	0,924	0,871	0,911	0,864	0,871	0,853	0,853	0,899	0,845	0,838	0,813	0,792	0,731	0,665	0,610	0,708	0,707	0,692	0,692
GA	0,986	0,982	0,980	0,976	0,971	0,957	0,960	0,960	0,951	0,944	0,927	0,897	0,920	0,887	0,921	0,871	0,878	0,839	0,806	0,803	0,756	0,763	0,758	0,705	0,728	0,671	0,730	0,656
PSO/P&O	0,986	0,977	0,978	0,981	0,977	0,973	0,969	0,977	0,965	0,959	0,958	0,929	0,910	0,872	0,884	0,892	0,883	0,839	0,853	0,821	0,788	0,787	0,719	0,704	0,738	0,710	0,767	0,649
PSO/IC	0,987	0,978	0,979	0,984	0,978	0,981	0,974	0,964	0,969	0,960	0,935	0,926	0,890	0,890	0,866	0,870	0,851	0,859	0,852	0,776	0,739	0,780	0,693	0,723	0,793	0,765	0,750	0,756
GA/P&O	0,986	0,977	0,969	0,981	0,978	0,974	0,972	0,967	0,964	0,960	0,940	0,921	0,897	0,882	0,896	0,858	0,852	0,875	0,843	0,647	0,702	0,621	0,654	0,661	0,703	0,691	0,654	0,613
GA/IC	0,986	0,977	0,970	0,982	0,978	0,974	0,970	0,967	0,963	0,961	0,926	0,922	0,892	0,884	0,899	0,869	0,849	0,884	0,845	0,640	0,692	0,629	0,617	0,729	0,696	0,698	0,655	0,617
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	C	C	C	C	C	D
Setup 3	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B	B	B	B	B	B	A

Figure B.2: *Vertical shadow (x2 size)*

Vertical shadow (x3 size)

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,940	0,970	0,989	0,994	0,994	0,994	0,993	0,993	0,993	0,993	0,992	0,991	0,992	0,989	0,989	0,988	0,988	0,987	0,989	0,956	0,880	0,873	0,846	0,830	0,838	0,840	0,839	0,846
P&O 2	0,971	0,995	0,995	0,994	0,993	0,993	0,993	0,993	0,993	0,993	0,992	0,991	0,990	0,990	0,990	0,987	0,982	0,979	0,977	0,843	0,805	0,777	0,784	0,775	0,752	0,738	0,773	0,782
P&O 3	0,966	0,993	0,993	0,993	0,993	0,992	0,992	0,992	0,992	0,992	0,991	0,990	0,989	0,988	0,979	0,956	0,952	0,934	0,903	0,873	0,861	0,856	0,853	0,844	0,836	0,828	0,828	0,832
IC	0,941	0,971	0,989	0,994	0,994	0,994	0,993	0,994	0,992	0,991	0,992	0,991	0,991	0,990	0,989	0,990	0,989	0,989	0,988	0,928	0,792	0,719	0,749	0,716	0,733	0,730	0,728	0,718
SC Current	0,945	0,945	0,946	0,945	0,945	0,946	0,945	0,945	0,945	0,945	0,968	0,977	0,979	0,981	0,983	0,983	0,984	0,984	0,984	0,981	0,906	0,875	0,877	0,866	0,852	0,861	0,858	0,851
OC Voltage	0,375	0,377	0,378	0,379	0,388	0,382	0,389	0,389	0,398	0,403	0,409	0,382	0,349	0,300	0,271	0,242	0,314	0,246	0,270	0,403	0,494	0,566	0,655	0,661	0,675	0,688	0,715	0,726
Const. Voltage	0,210	0,213	0,216	0,220	0,223	0,226	0,230	0,233	0,236	0,238	0,200	0,172	0,166	0,169	0,180	0,188	0,199	0,209	0,215	0,311	0,428	0,486	0,546	0,591	0,623	0,648	0,667	0,679
PSO 3	0,983	0,973	0,962	0,961	0,953	0,945	0,944	0,939	0,934	0,928	0,868	0,840	0,863	0,810	0,824	0,830	0,837	0,809	0,833	0,799	0,777	0,806	0,771	0,683	0,666	0,617	0,577	0,530
PSO 4	0,977	0,965	0,957	0,950	0,942	0,931	0,925	0,915	0,911	0,904	0,825	0,801	0,835	0,803	0,830	0,811	0,827	0,801	0,805	0,809	0,699	0,699	0,607	0,547	0,553	0,686	0,672	0,542
PSO 5	0,976	0,964	0,955	0,946	0,931	0,921	0,917	0,907	0,901	0,904	0,845	0,839	0,815	0,820	0,847	0,831	0,813	0,811	0,689	0,752	0,757	0,723	0,635	0,541	0,477	0,519	0,550	0,638
GA	0,980	0,981	0,977	0,980	0,975	0,967	0,946	0,972	0,960	0,963	0,943	0,929	0,889	0,912	0,876	0,865	0,846	0,836	0,812	0,810	0,628	0,656	0,710	0,655	0,677	0,658	0,674	0,619
PSO/P&O	0,982	0,977	0,971	0,979	0,968	0,969	0,957	0,949	0,949	0,935	0,909	0,901	0,894	0,895	0,871	0,818	0,809	0,786	0,815	0,741	0,578	0,583	0,722	0,602	0,719	0,680	0,629	0,634
PSO/IC	0,985	0,973	0,975	0,981	0,975	0,971	0,960	0,956	0,956	0,944	0,909	0,885	0,865	0,859	0,872	0,850	0,770	0,805	0,845	0,741	0,596	0,658	0,676	0,727	0,716	0,745	0,651	0,647
GA/P&O	0,987	0,981	0,977	0,981	0,977	0,973	0,969	0,967	0,964	0,958	0,928	0,903	0,887	0,850	0,822	0,842	0,838	0,829	0,837	0,740	0,738	0,704	0,596	0,551	0,645	0,579	0,657	0,568
GA/IC	0,987	0,981	0,978	0,980	0,976	0,973	0,970	0,966	0,962	0,957	0,933	0,902	0,878	0,869	0,856	0,851	0,835	0,825	0,828	0,763	0,783	0,659	0,611	0,589	0,587	0,586	0,700	0,510
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	C	C	C	C	D
Setup 1	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B	B	B	B	B	B	B

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,978	0,978	0,978	0,978	0,992	0,993	0,992	0,992	0,991	0,989	0,964	0,950	0,962	0,954	0,935	0,954	0,934	0,921	0,929	0,902	0,890	0,862	0,850	0,832	0,818	0,803	0,812	0,804
P&O 2	0,979	0,978	0,993	0,993	0,990	0,986	0,958	0,954	0,968	0,965	0,958	0,966	0,961	0,958	0,955	0,947	0,948	0,948	0,937	0,895	0,869	0,873	0,852	0,844	0,839	0,836	0,829	0,828
P&O 3	0,977	0,977	0,991	0,991	0,987	0,982	0,977	0,972	0,968	0,966	0,952	0,940	0,931	0,923	0,913	0,898	0,884	0,894	0,888	0,845	0,838	0,810	0,811	0,799	0,792	0,776	0,791	0,785
IC	0,978	0,978	0,978	0,978	0,993	0,993	0,993	0,992	0,991	0,990	0,954	0,964	0,970	0,967	0,961	0,963	0,961	0,955	0,950	0,914	0,865	0,863	0,860	0,842	0,853	0,850	0,839	0,840
SC Current	0,733	0,729	0,719	0,716	0,704	0,690	0,683	0,676	0,659	0,661	0,650	0,640	0,643	0,663	0,617	0,626	0,662	0,600	0,621	0,607	0,692	0,649	0,641	0,640	0,626	0,628	0,648	0,670
OC Voltage	0,926	0,927	0,927	0,927	0,927	0,928	0,928	0,928	0,928	0,928	0,950	0,958	0,957	0,961	0,961	0,963	0,965	0,965	0,966	0,961	0,923	0,888	0,876	0,871	0,849	0,836	0,843	0,833
Const. Voltage	0,978	0,978	0,979	0,979	0,979	0,979	0,979	0,979	0,979	0,980	0,978	0,975	0,972	0,970	0,968	0,969	0,969	0,968	0,967	0,950	0,923	0,887	0,880	0,890	0,887	0,873	0,863	0,856
PSO 3	0,923	0,928	0,902	0,907	0,898	0,852	0,873	0,862	0,863	0,848	0,786	0,791	0,725	0,648	0,637	0,586	0,592	0,594	0,530	0,555	0,476	0,547	0,503	0,570	0,499	0,474	0,407	0,420
PSO 4	0,856	0,894	0,907	0,896	0,895	0,886	0,874	0,879	0,860	0,861	0,729	0,756	0,645	0,604	0,561	0,561	0,546	0,519	0,544	0,544	0,541	0,556	0,466	0,429	0,403	0,401	0,451	0,408
PSO 5	0,930	0,897	0,877	0,881	0,875	0,876	0,872	0,866	0,843	0,830	0,752	0,674	0,589	0,540	0,575	0,554	0,517	0,534	0,558	0,526	0,492	0,447	0,402	0,421	0,388	0,427	0,467	0,527
GA	0,983	0,980	0,975	0,970	0,966	0,969	0,964	0,959	0,968	0,956	0,933	0,902	0,863	0,827	0,789	0,874	0,840	0,805	0,828	0,778	0,795	0,753	0,757	0,710	0,651	0,758	0,693	0,695
PSO/P&O	0,972	0,962	0,965	0,962	0,955	0,966	0,967	0,957	0,951	0,962	0,929	0,879	0,901	0,836	0,799	0,758	0,792	0,815	0,815	0,721	0,731	0,708	0,761	0,696	0,681	0,738	0,832	0,733
PSO/IC	0,988	0,966	0,971	0,958	0,969	0,960	0,954	0,960	0,950	0,956	0,896	0,880	0,897	0,813	0,826	0,817	0,810	0,796	0,805	0,759	0,735	0,800	0,759	0,711	0,684	0,754	0,812	0,783
GA/P&O	0,985	0,959	0,955	0,958	0,942	0,961	0,954	0,951	0,947	0,931	0,869	0,831	0,787	0,702	0,664	0,591	0,580	0,589	0,615	0,601	0,559	0,538	0,502	0,598	0,531	0,583	0,576	0,538
GA/IC	0,983	0,964	0,950	0,949	0,951	0,937	0,940	0,940	0,947	0,941	0,863	0,758	0,736	0,719	0,676	0,609	0,592	0,555	0,552	0,532	0,543	0,519	0,525	0,550	0,521	0,557	0,535	0,520
Final group	B	B	B	B	B	B	B	B	B	B	B	B	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Setup 2	D	C	A	A	A	A	A	A	A	A	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,940	0,970	0,989	0,994	0,994	0,994	0,993	0,993	0,993	0,992	0,992	0,991	0,991	0,989	0,990	0,988	0,988	0,987	0,985	0,956	0,880	0,874	0,846	0,830	0,838	0,840	0,836	0,846
P&O 2	0,974	0,995	0,995	0,993	0,991	0,994	0,992	0,992	0,991	0,993	0,992	0,991	0,989	0,990	0,989	0,987	0,983	0,980	0,978	0,873	0,864	0,793	0,804	0,786	0,762	0,793	0,776	0,782
P&O 3	0,966	0,994	0,993	0,993	0,993	0,992	0,992	0,992	0,992	0,992	0,992	0,989	0,989	0,988	0,979	0,957	0,955	0,925	0,909	0,883	0,861	0,856	0,853	0,843	0,836	0,828	0,828	0,832
IC	0,941	0,971	0,989	0,994	0,994	0,994	0,993	0,993	0,993	0,991	0,992	0,992	0,991	0,991	0,989	0,989	0,989	0,988	0,988	0,928	0,792	0,720	0,750	0,716	0,733	0,730	0,728	0,719
SC Current	0,945	0,945	0,945	0,945	0,945	0,945	0,944	0,944	0,944	0,945	0,967	0,976	0,978	0,981	0,982	0,984	0,983	0,983	0,982	0,958	0,926	0,895	0,892	0,878	0,850	0,865	0,856	0,861
OC Voltage	0,378	0,379	0,381	0,381	0,391	0,384	0,391	0,389	0,400	0,404	0,412	0,384	0,351	0,297	0,272	0,243	0,315	0,243	0,270	0,404	0,496	0,567	0,656	0,662	0,676	0,688	0,716	0,727
Const. Voltage	0,213	0,218	0,221	0,225	0,228	0,232	0,236	0,240	0,243	0,247	0,218	0,192	0,179	0,181	0,192	0,197	0,208	0,217	0,224	0,312	0,429	0,487	0,547	0,591	0,624	0,649	0,667	0,680
PSO 3	0,983	0,977	0,971	0,962	0,956	0,950	0,945	0,945	0,942	0,940	0,892	0,866	0,885	0,846	0,870	0,836	0,835	0,833	0,836	0,824	0,736	0,731	0,641	0,739	0,674	0,660	0,612	0,593
PSO 4	0,979	0,971	0,963	0,952	0,944	0,929	0,916	0,910	0,912	0,903	0,861	0,822	0,863	0,820	0,814	0,836	0,792	0,788	0,796	0,641	0,693	0,593	0,583	0,535	0,664	0,669	0,600	0,629
PSO 5	0,978	0,966	0,957	0,944	0,938	0,930	0,924	0,917	0,921	0,913	0,870	0,857	0,854	0,849	0,844	0,828	0,842	0,819	0,831	0,753	0,655	0,734	0,669	0,589	0,509	0,654	0,645	0,637
GA	0,986	0,982	0,980	0,972	0,967	0,963	0,956	0,953	0,952	0,944	0,920	0,873	0,873	0,868	0,861	0,841	0,830	0,799	0,832	0,788	0,777	0,737	0,699	0,672	0,671	0,728	0,733	0,707
PSO/P&O	0,984	0,979	0,978	0,978	0,972	0,966	0,968	0,958	0,958	0,954	0,925	0,885	0,858	0,848	0,832	0,842	0,828	0,846	0,822	0,776	0,697	0,767	0,744	0,738	0,702	0,754	0,741	0,705
PSO/IC	0,986	0,978	0,978	0,984	0,966	0,970	0,961	0,968	0,954	0,954	0,933	0,866	0,863	0,840	0,822	0,810	0,774	0,801	0,793	0,770	0,705	0,770	0,749	0,736	0,677	0,832	0,721	0,701
GA/P&O	0,987	0,980	0,975	0,979	0,974	0,970	0,966	0,962	0,958	0,954	0,930	0,906	0,871	0,883	0,858	0,837	0,807	0,799	0,842	0,703	0,577	0,623	0,569	0,639	0,620	0,674	0,631	0,627
GA/IC	0,987	0,980	0,976	0,979	0,975	0,970	0,966	0,962	0,959	0,955	0,917	0,903	0,870	0,879	0,846	0,825	0,809	0,863	0,851	0,707	0,582	0,646	0,596	0,649	0,626	0,689	0,630	0,623
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	C	C	B	C	C
Setup 3	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B	B	B	B	B	B	B

Figure B.3: *Vertical shadow (x3 size)*

Vertical shadow (x4 size)

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,947	0,972	0,988	0,993	0,993	0,992	0,992	0,992	0,991	0,991	0,990	0,988	0,989	0,986	0,984	0,986	0,979	0,978	0,977	0,933	0,844	0,857	0,814	0,812	0,819	0,816	0,820	0,799
P&O 2	0,974	0,994	0,993	0,992	0,990	0,991	0,991	0,991	0,991	0,991	0,989	0,986	0,985	0,979	0,966	0,970	0,964	0,962	0,949	0,862	0,791	0,764	0,765	0,732	0,707	0,688	0,745	0,744
P&O 3	0,968	0,992	0,992	0,991	0,991	0,991	0,990	0,990	0,990	0,990	0,988	0,981	0,975	0,953	0,943	0,903	0,923	0,889	0,863	0,850	0,846	0,836	0,827	0,816	0,819	0,806	0,806	0,817
IC	0,948	0,973	0,989	0,993	0,993	0,992	0,992	0,992	0,990	0,989	0,990	0,989	0,988	0,987	0,985	0,985	0,980	0,981	0,977	0,917	0,787	0,725	0,676	0,657	0,662	0,671	0,688	0,696
SC Current	0,944	0,944	0,944	0,944	0,944	0,944	0,944	0,944	0,944	0,943	0,966	0,975	0,977	0,979	0,980	0,980	0,980	0,975	0,974	0,836	0,857	0,838	0,835	0,826	0,826	0,823	0,818	0,827
OC Voltage	0,379	0,380	0,387	0,381	0,390	0,395	0,387	0,388	0,404	0,410	0,396	0,394	0,335	0,302	0,286	0,257	0,295	0,270	0,268	0,390	0,472	0,542	0,614	0,650	0,646	0,659	0,678	0,689
Const. Voltage	0,211	0,214	0,217	0,221	0,224	0,227	0,231	0,235	0,237	0,239	0,201	0,173	0,166	0,170	0,181	0,189	0,200	0,209	0,215	0,284	0,387	0,444	0,502	0,548	0,578	0,608	0,632	0,649
PSO 3	0,980	0,970	0,962	0,959	0,950	0,944	0,941	0,935	0,927	0,916	0,877	0,839	0,830	0,820	0,803	0,809	0,806	0,767	0,793	0,762	0,740	0,762	0,671	0,721	0,680	0,644	0,554	0,560
PSO 4	0,980	0,969	0,959	0,952	0,945	0,937	0,923	0,917	0,912	0,902	0,839	0,819	0,809	0,778	0,803	0,801	0,801	0,793	0,791	0,803	0,735	0,731	0,522	0,548	0,481	0,641	0,592	0,535
PSO 5	0,978	0,968	0,956	0,948	0,938	0,931	0,920	0,917	0,905	0,905	0,853	0,827	0,802	0,822	0,806	0,797	0,825	0,794	0,778	0,774	0,652	0,727	0,554	0,583	0,489	0,414	0,457	0,498
GA	0,981	0,984	0,980	0,976	0,974	0,969	0,946	0,955	0,957	0,730	0,932	0,906	0,892	0,870	0,836	0,824	0,804	0,758	0,689	0,722	0,742	0,670	0,727	0,605	0,646	0,630	0,564	0,657
PSO/P&O	0,983	0,968	0,959	0,964	0,961	0,964	0,947	0,943	0,935	0,948	0,885	0,853	0,841	0,825	0,747	0,793	0,788	0,764	0,829	0,742	0,618	0,640	0,638	0,546	0,604	0,638	0,623	0,600
PSO/IC	0,980	0,978	0,964	0,962	0,966	0,965	0,949	0,954	0,952	0,937	0,893	0,844	0,861	0,824	0,788	0,759	0,783	0,847	0,802	0,682	0,615	0,602	0,619	0,636	0,683	0,692	0,665	0,618
GA/P&O	0,987	0,981	0,975	0,976	0,974	0,969	0,967	0,963	0,956	0,951	0,921	0,897	0,886	0,831	0,817	0,816	0,808	0,795	0,788	0,786	0,727	0,563	0,617	0,618	0,533	0,527	0,532	0,536
GA/IC	0,987	0,981	0,974	0,977	0,974	0,971	0,966	0,962	0,960	0,950	0,911	0,892	0,860	0,832	0,817	0,829	0,822	0,803	0,786	0,766	0,689	0,609	0,589	0,582	0,537	0,518	0,536	0,556
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	D	C	C	C	C
Setup 1	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	A	B	B	B	B	A	B

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,988	0,988	0,988	0,988	0,991	0,989	0,982	0,980	0,970	0,968	0,950	0,934	0,935	0,941	0,930	0,938	0,920	0,930	0,923	0,872	0,847	0,846	0,841	0,831	0,811	0,799	0,787	0,778
P&O 2	0,989	0,989	0,991	0,972	0,966	0,963	0,974	0,972	0,965	0,964	0,950	0,956	0,949	0,946	0,942	0,927	0,924	0,912	0,899	0,873	0,843	0,847	0,835	0,826	0,825	0,821	0,819	0,817
P&O 3	0,988	0,988	0,989	0,972	0,963	0,967	0,960	0,955	0,951	0,949	0,941	0,924	0,908	0,893	0,886	0,884	0,866	0,871	0,861	0,826	0,819	0,798	0,799	0,778	0,774	0,761	0,771	0,771
IC	0,988	0,989	0,989	0,989	0,991	0,990	0,983	0,980	0,969	0,975	0,965	0,961	0,962	0,958	0,950	0,943	0,944	0,943	0,932	0,835	0,844	0,840	0,802	0,808	0,829	0,836	0,824	0,818
SC Current	0,757	0,754	0,745	0,740	0,729	0,718	0,713	0,709	0,696	0,696	0,693	0,683	0,688	0,703	0,668	0,653	0,652	0,627	0,608	0,631	0,529	0,666	0,657	0,651	0,628	0,618	0,619	0,639
OC Voltage	0,935	0,934	0,933	0,931	0,931	0,933	0,932	0,929	0,932	0,930	0,951	0,963	0,963	0,962	0,963	0,964	0,963	0,961	0,956	0,905	0,871	0,866	0,842	0,845	0,841	0,825	0,817	0,819
Const. Voltage	0,975	0,975	0,976	0,976	0,976	0,975	0,975	0,975	0,974	0,974	0,972	0,973	0,973	0,971	0,969	0,968	0,965	0,960	0,959	0,882	0,857	0,867	0,839	0,850	0,845	0,851	0,850	0,843
PSO 3	0,948	0,935	0,879	0,914	0,899	0,887	0,856	0,888	0,878	0,858	0,835	0,756	0,682	0,641	0,617	0,576	0,556	0,558	0,561	0,485	0,515	0,475	0,491	0,464	0,571	0,501	0,472	0,437
PSO 4	0,926	0,920	0,899	0,904	0,891	0,885	0,878	0,875	0,880	0,853	0,793	0,705	0,635	0,622	0,524	0,558	0,547	0,519	0,535	0,560	0,525	0,527	0,508	0,501	0,482	0,495	0,397	0,402
PSO 5	0,933	0,913	0,914	0,902	0,878	0,884	0,860	0,846	0,872	0,843	0,693	0,692	0,576	0,557	0,557	0,550	0,529	0,535	0,534	0,598	0,509	0,397	0,432	0,382	0,395	0,362	0,433	0,467
GA	0,982	0,967	0,967	0,970	0,956	0,968	0,962	0,933	0,958	0,942	0,815	0,899	0,870	0,835	0,842	0,760	0,787	0,807	0,784	0,722	0,713	0,785	0,756	0,735	0,711	0,717	0,730	0,736
PSO/P&O	0,982	0,967	0,967	0,970	0,956	0,968	0,962	0,933	0,958	0,942	0,815	0,899	0,870	0,835	0,842	0,760	0,787	0,807	0,784	0,722	0,713	0,785	0,756	0,735	0,711	0,717	0,730	0,736
PSO/IC	0,985	0,974	0,970	0,973	0,961	0,963	0,951	0,950	0,948	0,942	0,905	0,853	0,831	0,853	0,816	0,796	0,801	0,830	0,820	0,759	0,808	0,808	0,708	0,741	0,692	0,679	0,735	0,784
GA/P&O	0,984	0,973	0,965	0,963	0,961	0,953	0,946	0,940	0,921	0,932	0,846	0,783	0,772	0,696	0,671	0,623	0,610	0,585	0,593	0,563	0,530	0,554	0,544	0,524	0,437	0,530	0,578	0,571
GA/IC	0,981	0,971	0,972	0,964	0,951	0,943	0,948	0,941	0,928	0,929	0,846	0,752	0,745	0,718	0,641	0,628	0,653	0,600	0,649	0,589	0,545	0,572	0,507	0,510	0,508	0,513	0,528	0,539
Final group	B	B	B	B	B	B	B	B	B	B	B	B	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Setup 2	A	A	A	A	A	A	A	A	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,947	0,972	0,988	0,993	0,992	0,992	0,992	0,991	0,992	0,991	0,990	0,988	0,988	0,985	0,985	0,985	0,979	0,982	0,969	0,934	0,846	0,858	0,816	0,813	0,820	0,818	0,821	0,800
P&O 2	0,976	0,994	0,993	0,993	0,989	0,992	0,990	0,989	0,989	0,991	0,988	0,988	0,984	0,979	0,969	0,973	0,959	0,951	0,923	0,861	0,826	0,780	0,784	0,744	0,715	0,709	0,747	0,734
P&O 3	0,969	0,992	0,992	0,991	0,991	0,990	0,990	0,990	0,990	0,990	0,988	0,980	0,972	0,948	0,944	0,905	0,915	0,891	0,870	0,855	0,847	0,837	0,828	0,816	0,820	0,807	0,807	0,818
IC	0,948	0,973	0,988	0,993	0,992	0,992	0,992	0,991	0,990	0,989	0,989	0,989	0,987	0,987	0,984	0,982	0,981	0,977	0,979	0,918	0,822	0,726	0,677	0,658	0,663	0,688	0,689	0,697
SC Current	0,944	0,944	0,944	0,944	0,943	0,944	0,944	0,943	0,944	0,943	0,965	0,974	0,977	0,978	0,978	0,981	0,979	0,977	0,972	0,847	0,880	0,851	0,843	0,842	0,841	0,821	0,826	0,834
OC Voltage	0,381	0,382	0,390	0,383	0,393	0,398	0,390	0,390	0,405	0,412	0,398	0,396	0,337	0,299	0,287	0,259	0,297	0,267	0,269	0,370	0,474	0,544	0,616	0,652	0,647	0,661	0,679	0,690
Const. Voltage	0,214	0,219	0,222	0,226	0,230	0,233	0,238	0,241	0,245	0,249	0,219	0,193	0,180	0,182	0,193	0,199	0,209	0,218	0,223	0,288	0,388	0,445	0,503	0,549	0,580	0,609	0,633	0,650
PSO 3	0,979	0,970	0,965	0,954	0,945	0,943	0,931	0,926	0,923	0,928	0,886	0,856	0,844	0,811	0,827	0,816	0,794	0,786	0,812	0,771	0,723	0,722	0,697	0,703	0,708	0,694	0,625	0,595
PSO 4	0,979	0,971	0,960	0,954	0,943	0,931	0,928	0,913	0,909	0,893	0,853	0,836	0,836	0,816	0,831	0,802	0,759	0,829	0,770	0,568	0,669	0,568	0,603	0,519	0,499	0,587	0,629	0,592
PSO 5	0,980	0,970	0,959	0,949	0,946	0,941	0,930	0,924	0,918	0,915	0,866	0,845	0,847	0,828	0,812	0,815	0,832	0,815	0,797	0,694	0,577	0,657	0,507	0,615	0,542	0,449	0,594	0,608
GA	0,985	0,980	0,971	0,971	0,960	0,962	0,954	0,759	0,943	0,941	0,887	0,877	0,889	0,871	0,846	0,811	0,790	0,811	0,784	0,730	0,761	0,758	0,587	0,652	0,666	0,650	0,696	0,667
PSO/P&O	0,983	0,980	0,973	0,974	0,972	0,968	0,957	0,951	0,965	0,949	0,899	0,879	0,841	0,824	0,788	0,810	0,750	0,807	0,794	0,789	0,761	0,783	0,694	0,764	0,710	0,669	0,688	0,743
PSO/IC	0,985	0,981	0,974	0,974	0,974	0,955	0,959	0,956	0,952	0,939	0,930	0,884	0,840	0,832	0,814	0,818	0,823	0,809	0,773	0,739	0,750	0,712	0,747	0,722	0,657	0,698	0,704	0,717
GA/P&O	0,986	0,979	0,973	0,975	0,972	0,968	0,963	0,956	0,952	0,949	0,915	0,893	0,854	0,831	0,823	0,796	0,809	0,806	0,773	0,719	0,709	0,520	0,546	0,622	0,602	0,613	0,602	0,581
GA/IC	0,986	0,979	0,973	0,975	0,972	0,969	0,965	0,957	0,952	0,946	0,914	0,893	0,847	0,836	0,797	0,837	0,804	0,799	0,784	0,617	0,705	0,562	0,528	0,626	0,611	0,636	0,623	0,591
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	C	C	C	C	D
Setup 3	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	A	B	B	B	B	B	B

Figure B.4: *Vertical shadow (x4 size)*

Horizontal shadow (x3-y1 size)

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,977	0,989	0,995	0,995	0,995	0,995	0,995	0,995	0,994	0,994	0,992	0,991	0,988	0,989	0,980	0,988	0,986	0,986	0,983	0,969	0,965	0,965	0,931	0,932	0,965	0,964	0,960	0,957
P&O 2	0,989	0,996	0,996	0,995	0,991	0,990	0,991	0,991	0,991	0,991	0,989	0,985	0,982	0,974	0,979	0,978	0,970	0,974	0,955	0,916	0,965	0,931	0,918	0,945	0,917	0,935	0,935	0,938
P&O 3	0,988	0,995	0,994	0,994	0,994	0,993	0,993	0,993	0,992	0,992	0,990	0,985	0,978	0,975	0,974	0,972	0,970	0,970	0,956	0,944	0,956	0,951	0,949	0,944	0,944	0,944	0,945	0,945
IC	0,978	0,989	0,995	0,995	0,995	0,995	0,994	0,994	0,989	0,989	0,991	0,989	0,985	0,988	0,975	0,981	0,978	0,976	0,976	0,915	0,972	0,915	0,902	0,947	0,913	0,950	0,926	0,935
SC Current	0,946	0,946	0,946	0,946	0,946	0,946	0,946	0,946	0,946	0,946	0,969	0,976	0,978	0,980	0,981	0,982	0,982	0,982	0,982	0,976	0,966	0,970	0,964	0,963	0,957	0,953	0,951	0,944
OC Voltage	0,738	0,738	0,727	0,715	0,714	0,735	0,737	0,726	0,735	0,727	0,739	0,819	0,821	0,795	0,804	0,758	0,628	0,786	0,803	0,707	0,764	0,770	0,792	0,853	0,904	0,911	0,910	0,919
Const. Voltage	0,441	0,442	0,445	0,447	0,449	0,452	0,455	0,457	0,460	0,464	0,455	0,433	0,406	0,411	0,432	0,413	0,415	0,459	0,470	0,640	0,715	0,732	0,757	0,779	0,810	0,831	0,842	0,853
PSO 3	0,988	0,982	0,979	0,976	0,973	0,968	0,959	0,956	0,946	0,950	0,908	0,903	0,884	0,876	0,891	0,860	0,845	0,839	0,871	0,748	0,740	0,757	0,848	0,777	0,787	0,768	0,741	0,697
PSO 4	0,985	0,978	0,969	0,964	0,954	0,938	0,928	0,939	0,925	0,912	0,909	0,849	0,867	0,838	0,819	0,817	0,844	0,803	0,790	0,819	0,662	0,798	0,763	0,715	0,672	0,575	0,529	0,515
PSO 5	0,985	0,978	0,974	0,967	0,961	0,953	0,946	0,937	0,930	0,931	0,914	0,901	0,838	0,862	0,865	0,861	0,841	0,846	0,819	0,817	0,844	0,788	0,777	0,729	0,678	0,669	0,646	0,588
GA	0,989	0,988	0,987	0,985	0,981	0,977	0,972	0,973	0,969	0,961	0,959	0,946	0,918	0,921	0,901	0,915	0,828	0,801	0,732	0,869	0,818	0,788	0,650	0,700	0,527	0,695	0,640	0,584
PSO/P&O	0,987	0,978	0,981	0,962	0,972	0,951	0,967	0,955	0,943	0,944	0,912	0,847	0,882	0,813	0,869	0,867	0,879	0,853	0,839	0,780	0,851	0,789	0,624	0,638	0,676	0,550	0,604	0,524
PSO/IC	0,988	0,980	0,976	0,970	0,957	0,950	0,957	0,948	0,945	0,931	0,911	0,902	0,898	0,847	0,831	0,832	0,782	0,728	0,798	0,688	0,639	0,710	0,769	0,622	0,672	0,550	0,668	0,540
GA/P&O	0,991	0,984	0,984	0,979	0,975	0,966	0,964	0,960	0,963	0,960	0,926	0,908	0,881	0,852	0,849	0,838	0,865	0,821	0,803	0,739	0,712	0,809	0,753	0,703	0,682	0,546	0,501	0,515
GA/IC	0,991	0,986	0,984	0,977	0,972	0,969	0,966	0,961	0,961	0,959	0,922	0,914	0,883	0,844	0,851	0,804	0,870	0,812	0,796	0,751	0,727	0,801	0,764	0,698	0,692	0,540	0,537	0,512
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	D	D	D	D	C	D	D	D
Setup 1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	A	A	A	A	B	A	B	B	B	A	A	A	A

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,957	0,956	0,961	0,963	0,963	0,963	0,962	0,961	0,960	0,960	0,950	0,940	0,915	0,905	0,893	0,868	0,887	0,889	0,899	0,881	0,890	0,889	0,904	0,895	0,896	0,894	0,879	0,891
P&O 2	0,959	0,963	0,962	0,962	0,960	0,956	0,855	0,936	0,933	0,946	0,947	0,936	0,916	0,915	0,901	0,915	0,907	0,907	0,899	0,888	0,892	0,885	0,887	0,887	0,892	0,891	0,891	0,888
P&O 3	0,951	0,961	0,961	0,960	0,958	0,953	0,950	0,948	0,947	0,943	0,911	0,912	0,909	0,904	0,900	0,894	0,896	0,888	0,888	0,891	0,890	0,892	0,889	0,893	0,891	0,893	0,894	0,893
IC	0,949	0,945	0,961	0,963	0,963	0,963	0,962	0,961	0,961	0,960	0,947	0,945	0,940	0,927	0,924	0,918	0,907	0,902	0,903	0,892	0,879	0,875	0,879	0,871	0,879	0,878	0,880	0,878
SC Current	0,816	0,817	0,818	0,819	0,819	0,820	0,821	0,821	0,821	0,823	0,835	0,832	0,821	0,812	0,791	0,770	0,753	0,743	0,733	0,736	0,749	0,811	0,800	0,826	0,850	0,852	0,855	0,870
OC Voltage	0,795	0,796	0,798	0,800	0,801	0,802	0,804	0,805	0,806	0,807	0,829	0,839	0,845	0,849	0,850	0,853	0,858	0,855	0,855	0,870	0,864	0,864	0,869	0,881	0,889	0,891	0,893	0,896
Const. Voltage	0,833	0,835	0,836	0,838	0,839	0,841	0,842	0,844	0,845	0,847	0,846	0,850	0,853	0,854	0,857	0,857	0,859	0,860	0,858	0,863	0,861	0,853	0,860	0,861	0,867	0,866	0,877	0,881
PSO 3	0,954	0,942	0,928	0,919	0,911	0,901	0,896	0,896	0,878	0,874	0,791	0,752	0,693	0,743	0,621	0,560	0,559	0,577	0,621	0,576	0,555	0,542	0,592	0,539	0,545	0,480	0,451	0,465
PSO 4	0,906	0,917	0,906	0,890	0,893	0,879	0,886	0,884	0,845	0,799	0,748	0,685	0,692	0,604	0,599	0,523	0,550	0,575	0,551	0,575	0,589	0,561	0,530	0,483	0,436	0,404	0,522	0,572
PSO 5	0,947	0,932	0,902	0,887	0,887	0,880	0,868	0,853	0,854	0,848	0,725	0,657	0,616	0,588	0,520	0,604	0,535	0,590	0,573	0,623	0,525	0,613	0,522	0,516	0,505	0,572	0,590	0,498
GA	0,977	0,963	0,966	0,961	0,963	0,936	0,938	0,939	0,936	0,929	0,899	0,886	0,841	0,868	0,811	0,685	0,842	0,753	0,769	0,695	0,771	0,692	0,645	0,711	0,692	0,679	0,646	0,778
PSO/P&O	0,978	0,969	0,965	0,952	0,960	0,955	0,937	0,934	0,932	0,930	0,900	0,852	0,847	0,877	0,789	0,790	0,825	0,810	0,776	0,788	0,738	0,731	0,753	0,758	0,681	0,687	0,707	0,812
PSO/IC	0,980	0,976	0,969	0,960	0,964	0,956	0,929	0,940	0,948	0,938	0,901	0,859	0,855	0,840	0,853	0,825	0,830	0,815	0,829	0,785	0,771	0,737	0,669	0,768	0,764	0,676	0,729	0,691
GA/P&O	0,975	0,966	0,963	0,945	0,928	0,933	0,905	0,913	0,925	0,890	0,854	0,821	0,739	0,697	0,652	0,668	0,615	0,605	0,579	0,561	0,545	0,572	0,534	0,468	0,523	0,411	0,526	0,581
GA/IC	0,972	0,960	0,944	0,939	0,911	0,936	0,929	0,933	0,907	0,904	0,853	0,809	0,717	0,634	0,665	0,648	0,563	0,675	0,593	0,569	0,583	0,574	0,549	0,434	0,513	0,393	0,535	0,567
Final group	B	B	B	B	B	B	B	B	B	C	C	C	C	C	C	C	C	C	C	D	C	C	C	D	C	D	C	C
Setup 2	D	D	D	A	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,918	0,918	0,920	0,919	0,970	0,970	0,969	0,976	0,975	0,974	0,963	0,953	0,952	0,940	0,935	0,933	0,928	0,922	0,919	0,880	0,861	0,848	0,827	0,837	0,838	0,840	0,839	0,837
P&O 2	0,919	0,919	0,970	0,977	0,974	0,964	0,965	0,956	0,901	0,950	0,938	0,927	0,906	0,885	0,874	0,863	0,860	0,870	0,829	0,817	0,811	0,810	0,808	0,809	0,815	0,819	0,822	0,836
P&O 3	0,917	0,916	0,967	0,972	0,969	0,966	0,963	0,962	0,960	0,957	0,940	0,927	0,889	0,884	0,875	0,867	0,859	0,847	0,850	0,827	0,848	0,835	0,842	0,841	0,840	0,845	0,842	0,844
IC	0,918	0,919	0,920	0,919	0,970	0,970	0,970	0,976	0,975	0,965	0,894	0,938	0,932	0,916	0,907	0,892	0,870	0,852	0,836	0,781	0,776	0,774	0,757	0,765	0,776	0,786	0,793	0,810
SC Current	0,815	0,818	0,821	0,822	0,824	0,825	0,826	0,828	0,828	0,829	0,852	0,860	0,863	0,865	0,867	0,870	0,867	0,870	0,864	0,866	0,865	0,843	0,852	0,858	0,851	0,861	0,861	0,861
OC Voltage	0,828	0,829	0,830	0,831	0,832	0,833	0,834	0,836	0,836	0,837	0,854	0,855	0,847	0,841	0,833	0,820	0,821	0,809	0,801	0,786	0,763	0,769	0,768	0,782	0,788	0,797	0,807	0,811
Const. Voltage	0,866	0,867	0,868	0,869	0,870	0,871	0,873	0,874	0,875	0,876	0,873	0,865	0,852	0,842	0,830	0,819	0,809	0,792	0,777	0,783	0,771	0,792	0,786	0,783	0,798	0,798	0,808	0,811
PSO 3	0,981	0,975	0,972	0,967	0,963	0,956	0,958	0,954	0,946	0,944	0,904	0,892	0,876	0,857	0,870	0,872	0,858	0,858	0,842	0,759	0,816	0,732	0,666	0,773	0,642	0,691	0,642	0,610
PSO 4	0,969	0,958	0,950	0,942	0,937	0,923	0,919	0,908	0,911	0,904	0,872	0,854	0,866	0,853	0,828	0,856	0,822	0,800	0,782	0,808	0,618	0,593	0,580	0,709	0,640	0,685	0,517	0,507
PSO 5	0,979	0,972	0,960	0,960	0,953	0,931	0,923	0,915	0,918	0,926	0,906	0,879	0,883	0,867	0,877	0,801	0,799	0,808	0,793	0,787	0,690	0,770	0,702	0,687	0,688	0,686	0,656	0,635
GA	0,963	0,952	0,957	0,942	0,951	0,941	0,950	0,924	0,951	0,909	0,922	0,826	0,813	0,799	0,802	0,766	0,792	0,761	0,794	0,754	0,759	0,730	0,712	0,758	0,837	0,765	0,649	0,793
PSO/P&O	0,976	0,955	0,981	0,956	0,947	0,972	0,960	0,966	0,955	0,952	0,924	0,907	0,892	0,840	0,829	0,821	0,804	0,809	0,758	0,753	0,722	0,731	0,658	0,713	0,815	0,727	0,665	0,805
PSO/IC	0,959	0,955	0,963	0,960	0,940	0,959	0,957	0,967	0,950	0,956	0,928	0,901	0,898	0,816	0,810	0,813	0,770	0,803	0,750	0,837	0,739	0,740	0,675	0,749	0,804	0,773	0,692	0,767
GA/P&O	0,928	0,912	0,907	0,956	0,970	0,966	0,948	0,946	0,944	0,938	0,842	0,860	0,868	0,878	0,821	0,824	0,799	0,821	0,844	0,843	0,605	0,629	0,643	0,727	0,638	0,697	0,524	0,499
GA/IC	0,915	0,912	0,962	0,957	0,957	0,949	0,950	0,945	0,944	0,938	0,844	0,867	0,854	0,877	0,858	0,837	0,812	0,817	0,861	0,824	0,622	0,585	0,629	0,719	0,642	0,698	0,536	0,500
Final group	B	B	B	B	B	B	B	B	B	B	B	C	C	C	C	C	D	C	D	D	D	D	C	C	D	C	C	D
Setup 3	C	C	D	A	A	D	A	A	AA	A	A	A	A	A	A	A	A	A	A	A	B	A	B	B	B	B	B	B

Figure B.5: *Vertical shadow (x3-y1 size)*

Horizontal shadow (x4-y2 size)

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,981	0,989	0,994	0,994	0,994	0,994	0,993	0,994	0,994	0,993	0,990	0,990	0,987	0,987	0,985	0,984	0,985	0,982	0,980	0,956	0,968	0,925	0,924	0,950	0,932	0,911	0,906	0,910
P&O 2	0,990	0,995	0,995	0,991	0,986	0,988	0,989	0,989	0,990	0,990	0,988	0,985	0,984	0,983	0,982	0,974	0,976	0,968	0,965	0,893	0,934	0,875	0,881	0,888	0,874	0,875	0,895	0,872
P&O 3	0,988	0,994	0,993	0,993	0,993	0,992	0,992	0,992	0,992	0,991	0,988	0,985	0,982	0,977	0,973	0,968	0,966	0,955	0,946	0,916	0,931	0,920	0,919	0,908	0,903	0,907	0,911	0,911
IC	0,981	0,990	0,994	0,994	0,994	0,994	0,994	0,991	0,987	0,985	0,988	0,988	0,987	0,986	0,981	0,981	0,980	0,969	0,969	0,910	0,958	0,844	0,855	0,869	0,840	0,842	0,886	0,837
SC Current	0,945	0,945	0,946	0,946	0,946	0,946	0,946	0,946	0,946	0,946	0,968	0,975	0,978	0,979	0,980	0,981	0,981	0,981	0,980	0,978	0,970	0,957	0,938	0,934	0,921	0,913	0,922	0,918
OC Voltage	0,561	0,566	0,555	0,560	0,558	0,561	0,575	0,533	0,586	0,587	0,560	0,613	0,711	0,667	0,658	0,550	0,597	0,589	0,705	0,608	0,739	0,730	0,750	0,785	0,826	0,868	0,855	0,864
Const. Voltage	0,226	0,231	0,234	0,238	0,241	0,245	0,250	0,255	0,259	0,262	0,225	0,182	0,163	0,168	0,181	0,195	0,209	0,232	0,252	0,470	0,610	0,655	0,705	0,729	0,759	0,779	0,791	0,810
PSO 3	0,986	0,979	0,975	0,966	0,959	0,957	0,943	0,945	0,934	0,933	0,904	0,860	0,871	0,886	0,864	0,843	0,867	0,827	0,874	0,825	0,808	0,751	0,684	0,613	0,782	0,745	0,707	0,689
PSO 4	0,983	0,969	0,951	0,954	0,942	0,936	0,908	0,919	0,900	0,906	0,870	0,891	0,875	0,837	0,842	0,836	0,838	0,794	0,775	0,781	0,650	0,627	0,706	0,721	0,657	0,580	0,548	0,544
PSO 5	0,983	0,975	0,966	0,948	0,947	0,931	0,926	0,919	0,910	0,911	0,896	0,892	0,858	0,874	0,875	0,866	0,838	0,823	0,801	0,807	0,712	0,786	0,638	0,688	0,631	0,669	0,570	0,518
GA	0,970	0,983	0,981	0,971	0,969	0,976	0,971	0,967	0,953	0,954	0,941	0,906	0,843	0,941	0,881	0,785	0,910	0,853	0,820	0,753	0,828	0,742	0,666	0,606	0,693	0,568	0,534	0,528
PSO/P&O	0,987	0,981	0,972	0,972	0,971	0,948	0,958	0,944	0,958	0,948	0,926	0,931	0,906	0,858	0,867	0,801	0,836	0,795	0,756	0,724	0,760	0,802	0,674	0,723	0,565	0,493	0,703	0,503
PSO/IC	0,990	0,980	0,973	0,964	0,962	0,955	0,947	0,929	0,938	0,955	0,907	0,905	0,881	0,887	0,842	0,745	0,781	0,742	0,766	0,740	0,835	0,770	0,619	0,572	0,654	0,601	0,647	0,570
GA/P&O	0,991	0,986	0,982	0,975	0,970	0,965	0,961	0,957	0,951	0,950	0,940	0,920	0,868	0,877	0,855	0,839	0,835	0,783	0,800	0,822	0,701	0,656	0,723	0,737	0,649	0,574	0,570	0,550
GA/IC	0,991	0,987	0,981	0,976	0,971	0,971	0,965	0,960	0,950	0,951	0,928	0,894	0,865	0,855	0,852	0,847	0,846	0,770	0,778	0,729	0,704	0,641	0,705	0,731	0,661	0,587	0,535	0,518
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	C	D	D	D	D	C	D
Setup 1	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B	B	A	A	B	B	B

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,968	0,983	0,985	0,984	0,982	0,912	0,911	0,909	0,907	0,877	0,868	0,860	0,852	0,835	0,811	0,816	0,800	0,790	0,752	0,735	0,819	0,819	0,825	0,816	0,825	0,857	0,828	0,852
P&O 2	0,985	0,985	0,911	0,907	0,873	0,974	0,980	0,982	0,975	0,969	0,850	0,822	0,810	0,793	0,769	0,741	0,747	0,726	0,735	0,844	0,862	0,852	0,859	0,858	0,857	0,858	0,854	0,858
P&O 3	0,982	0,983	0,906	0,901	0,867	0,866	0,865	0,864	0,863	0,862	0,815	0,764	0,743	0,719	0,718	0,710	0,698	0,766	0,821	0,828	0,823	0,822	0,825	0,842	0,850	0,831	0,834	0,834
IC	0,969	0,983	0,985	0,984	0,982	0,912	0,912	0,908	0,901	0,974	0,969	0,852	0,829	0,822	0,804	0,808	0,797	0,792	0,775	0,848	0,867	0,860	0,866	0,862	0,867	0,864	0,862	0,865
SC Current	0,771	0,772	0,769	0,769	0,771	0,773	0,775	0,778	0,777	0,786	0,796	0,810	0,769	0,769	0,727	0,690	0,724	0,617	0,725	0,686	0,627	0,704	0,691	0,711	0,734	0,750	0,766	0,774
OC Voltage	0,730	0,732	0,734	0,737	0,739	0,742	0,744	0,746	0,747	0,751	0,781	0,794	0,803	0,806	0,810	0,820	0,834	0,840	0,848	0,873	0,886	0,877	0,880	0,885	0,881	0,875	0,874	0,871
Const. Voltage	0,762	0,765	0,767	0,770	0,771	0,774	0,776	0,778	0,781	0,783	0,792	0,798	0,805	0,810	0,815	0,822	0,829	0,841	0,844	0,866	0,874	0,867	0,873	0,873	0,874	0,869	0,873	0,871
PSO 3	0,905	0,891	0,940	0,923	0,873	0,883	0,908	0,890	0,893	0,882	0,840	0,823	0,717	0,751	0,727	0,625	0,679	0,566	0,560	0,493	0,538	0,468	0,544	0,486	0,446	0,454	0,438	0,447
PSO 4	0,893	0,931	0,925	0,900	0,902	0,876	0,890	0,891	0,902	0,877	0,812	0,760	0,733	0,668	0,633	0,618	0,581	0,555	0,551	0,543	0,475	0,573	0,502	0,464	0,417	0,384	0,485	0,542
PSO 5	0,951	0,907	0,928	0,904	0,899	0,910	0,900	0,893	0,883	0,859	0,790	0,691	0,667	0,649	0,621	0,554	0,562	0,569	0,609	0,558	0,440	0,457	0,543	0,480	0,506	0,521	0,551	0,491
GA	0,969	0,947	0,969	0,966	0,967	0,962	0,957	0,962	0,948	0,956	0,918	0,910	0,892	0,890	0,880	0,704	0,825	0,790	0,823	0,726	0,720	0,691	0,657	0,668	0,618	0,683	0,652	0,638
PSO/P&O	0,979	0,900	0,902	0,972	0,967	0,967	0,958	0,880	0,950	0,939	0,907	0,874	0,898	0,824	0,843	0,841	0,782	0,821	0,772	0,770	0,773	0,672	0,671	0,689	0,774	0,602	0,694	0,636
PSO/IC	0,975	0,976	0,903	0,901	0,968	0,891	0,940	0,957	0,945	0,933	0,886	0,885	0,851	0,853	0,852	0,800	0,837	0,805	0,791	0,693	0,647	0,673	0,648	0,664	0,675	0,614	0,648	0,631
GA/P&O	0,908	0,902	0,893	0,891	0,938	0,879	0,878	0,865	0,862	0,929	0,827	0,787	0,713	0,688	0,650	0,671	0,666	0,629	0,572	0,631	0,522	0,502	0,539	0,549	0,400	0,377	0,487	0,544
GA/IC	0,912	0,971	0,895	0,954	0,940	0,867	0,929	0,873	0,876	0,855	0,879	0,790	0,720	0,739	0,691	0,666	0,626	0,620	0,584	0,633	0,524	0,556	0,558	0,553	0,397	0,365	0,492	0,551
Final group	B	B	B	B	B	B	B	B	B	B	B	C	C	C	C	C	C	C	C	C	C	C	C	C	D	D	C	C
Setup 2	A	A	A	A	A	A	A	A	A	A	A	C	D	C	C	D	D	B	B	B	B	B	B	B	B	B	B	B

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,922	0,923	0,925	0,929	0,929	0,928	0,925	0,923	0,921	0,919	0,901	0,887	0,876	0,863	0,841	0,832	0,813	0,799	0,786	0,716	0,809	0,838	0,831	0,831	0,831	0,832	0,822	0,833
P&O 2	0,925	0,930	0,928	0,909	0,914	0,906	0,905	0,909	0,909	0,904	0,891	0,865	0,847	0,842	0,800	0,765	0,746	0,762	0,732	0,776	0,801	0,791	0,780	0,794	0,796	0,803	0,798	0,803
P&O 3	0,919	0,923	0,920	0,914	0,908	0,902	0,898	0,892	0,891	0,886	0,840	0,792	0,750	0,707	0,710	0,732	0,740	0,774	0,830	0,829	0,832	0,823	0,828	0,822	0,826	0,832	0,831	0,832
IC	0,922	0,923	0,925	0,929	0,929	0,927	0,904	0,900	0,897	0,893	0,884	0,874	0,856	0,834	0,810	0,786	0,769	0,731	0,721	0,633	0,669	0,712	0,716	0,743	0,747	0,763	0,754	0,764
SC Current	0,730	0,733	0,737	0,740	0,743	0,745	0,748	0,751	0,753	0,756	0,778	0,791	0,800	0,806	0,814	0,821	0,825	0,835	0,831	0,859	0,857	0,833	0,842	0,848	0,854	0,851	0,860	0,858
OC Voltage	0,745	0,749	0,754	0,750	0,765	0,763	0,753	0,742	0,772	0,746	0,751	0,749	0,758	0,762	0,731	0,732	0,728	0,655	0,728	0,676	0,637	0,708	0,699	0,733	0,747	0,762	0,769	0,778
Const. Voltage	0,698	0,700	0,703	0,706	0,708	0,710	0,711	0,713	0,713	0,716	0,675	0,620	0,585	0,589	0,594	0,592	0,597	0,602	0,596	0,604	0,621	0,666	0,695	0,722	0,735	0,750	0,756	0,764
PSO 3	0,981	0,978	0,974	0,969	0,917	0,957	0,954	0,954	0,952	0,940	0,909	0,897	0,892	0,848	0,874	0,900	0,882	0,869	0,881	0,791	0,735	0,712	0,683	0,733	0,710	0,718	0,651	0,622
PSO 4	0,924	0,915	0,907	0,904	0,897	0,892	0,885	0,884	0,870	0,876	0,848	0,885	0,873	0,871	0,837	0,865	0,843	0,837	0,781	0,850	0,595	0,518	0,458	0,532	0,467	0,421	0,420	0,470
PSO 5	0,926	0,920	0,916	0,909	0,907	0,901	0,896	0,897	0,886	0,890	0,859	0,850	0,863	0,822	0,820	0,779	0,742	0,806	0,675	0,573	0,692	0,758	0,715	0,639	0,673	0,673	0,656	0,625
GA	0,911	0,922	0,922	0,910	0,913	0,892	0,894	0,947	0,858	0,888	0,899	0,889	0,835	0,832	0,785	0,834	0,773	0,889	0,784	0,754	0,713	0,679	0,790	0,749	0,797	0,781	0,802	0,742
PSO/P&O	0,934	0,926	0,921	0,923	0,915	0,907	0,899	0,908	0,889	0,898	0,910	0,833	0,829	0,798	0,775	0,883	0,796	0,873	0,749	0,700	0,767	0,632	0,667	0,772	0,767	0,710	0,726	0,707
PSO/IC	0,930	0,925	0,925	0,916	0,912	0,913	0,906	0,901	0,904	0,896	0,875	0,871	0,837	0,795	0,793	0,885	0,781	0,755	0,744	0,732	0,734	0,667	0,643	0,754	0,769	0,734	0,764	0,699
GA/P&O	0,930	0,928	0,923	0,919	0,914	0,914	0,910	0,905	0,902	0,899	0,866	0,850	0,827	0,814	0,804	0,786	0,800	0,820	0,835	0,828	0,623	0,536	0,446	0,490	0,446	0,418	0,406	0,465
GA/IC	0,930	0,928	0,922	0,918	0,915	0,914	0,910	0,909	0,902	0,899	0,881	0,849	0,855	0,840	0,798	0,775	0,800	0,844	0,842	0,862	0,646	0,520	0,452	0,390	0,424	0,415	0,413	0,467
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	C	C	C	D	D	D	D	D	D
Setup 3	C	C	C	C	A	C	C	C	C	C	D	C	C	C	C	C	C	C	C	D	B	A	B	B	B	B	B	B

Figure B.6: *Vertical shadow (x4-y2 size)*

Horizontal shadow (x5-y3 size)

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,982	0,990	0,993	0,994	0,993	0,993	0,992	0,993	0,992	0,992	0,990	0,987	0,985	0,984	0,982	0,984	0,982	0,979	0,977	0,964	0,968	0,927	0,946	0,932	0,926	0,904	0,859	0,877
P&O 2	0,990	0,994	0,994	0,987	0,982	0,985	0,987	0,987	0,988	0,987	0,985	0,982	0,981	0,982	0,977	0,973	0,973	0,969	0,965	0,912	0,900	0,853	0,858	0,839	0,854	0,837	0,861	0,861
P&O 3	0,988	0,993	0,992	0,992	0,991	0,991	0,990	0,990	0,990	0,990	0,986	0,981	0,979	0,974	0,969	0,969	0,962	0,958	0,949	0,926	0,909	0,903	0,903	0,890	0,894	0,899	0,894	0,894
IC	0,982	0,990	0,993	0,994	0,993	0,993	0,990	0,988	0,985	0,983	0,986	0,985	0,982	0,983	0,977	0,978	0,977	0,972	0,973	0,945	0,905	0,810	0,819	0,777	0,809	0,774	0,824	0,825
SC Current	0,944	0,945	0,945	0,945	0,945	0,945	0,945	0,945	0,945	0,945	0,967	0,974	0,976	0,977	0,977	0,979	0,979	0,977	0,977	0,974	0,968	0,956	0,937	0,933	0,921	0,912	0,918	0,913
OC Voltage	0,514	0,523	0,505	0,501	0,460	0,528	0,548	0,472	0,573	0,579	0,523	0,585	0,693	0,659	0,618	0,536	0,583	0,632	0,757	0,595	0,726	0,717	0,730	0,783	0,837	0,906	0,844	0,853
Const. Voltage	0,167	0,173	0,177	0,181	0,184	0,189	0,194	0,199	0,202	0,206	0,161	0,128	0,130	0,143	0,161	0,178	0,193	0,218	0,232	0,443	0,583	0,635	0,685	0,717	0,740	0,761	0,780	0,791
PSO 3	0,983	0,976	0,969	0,964	0,958	0,949	0,944	0,938	0,928	0,918	0,895	0,883	0,858	0,854	0,844	0,856	0,858	0,856	0,824	0,790	0,812	0,747	0,673	0,763	0,735	0,726	0,714	0,693
PSO 4	0,980	0,970	0,955	0,951	0,942	0,927	0,916	0,910	0,903	0,887	0,861	0,838	0,882	0,838	0,839	0,826	0,814	0,799	0,784	0,803	0,657	0,646	0,649	0,739	0,658	0,604	0,534	0,551
PSO 5	0,982	0,970	0,957	0,950	0,945	0,935	0,922	0,915	0,907	0,905	0,879	0,879	0,863	0,872	0,847	0,859	0,838	0,825	0,804	0,828	0,705	0,796	0,760	0,690	0,646	0,665	0,565	0,528
GA	0,982	0,982	0,979	0,974	0,931	0,973	0,969	0,968	0,966	0,966	0,962	0,901	0,893	0,884	0,819	0,860	0,846	0,790	0,813	0,759	0,779	0,834	0,831	0,703	0,548	0,500	0,549	0,672
PSO/P&O	0,989	0,979	0,974	0,964	0,970	0,958	0,951	0,953	0,949	0,937	0,921	0,864	0,852	0,879	0,855	0,817	0,795	0,777	0,814	0,769	0,825	0,836	0,643	0,680	0,719	0,611	0,650	0,491
PSO/IC	0,990	0,979	0,979	0,968	0,962	0,964	0,962	0,945	0,952	0,947	0,936	0,893	0,823	0,840	0,829	0,800	0,834	0,779	0,726	0,762	0,827	0,780	0,753	0,558	0,585	0,551	0,582	0,512
GA/P&O	0,991	0,984	0,980	0,975	0,970	0,963	0,961	0,958	0,955	0,945	0,920	0,914	0,884	0,857	0,861	0,828	0,828	0,814	0,779	0,801	0,713	0,635	0,743	0,739	0,658	0,597	0,561	0,545
GA/IC	0,991	0,985	0,980	0,974	0,968	0,963	0,956	0,957	0,955	0,947	0,916	0,893	0,888	0,881	0,863	0,852	0,843	0,808	0,783	0,802	0,727	0,641	0,707	0,732	0,643	0,585	0,532	0,528
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	D	C	C	D	D
Setup 1	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B	A	B	A	B	B	B

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,985	0,987	0,989	0,987	0,985	0,915	0,914	0,912	0,909	0,878	0,870	0,861	0,854	0,838	0,819	0,822	0,745	0,786	0,753	0,721	0,720	0,816	0,804	0,807	0,803	0,804	0,821	0,852
P&O 2	0,989	0,988	0,914	0,910	0,871	0,979	0,984	0,985	0,978	0,973	0,847	0,828	0,806	0,786	0,764	0,752	0,712	0,725	0,716	0,821	0,843	0,839	0,857	0,855	0,853	0,853	0,847	0,852
P&O 3	0,986	0,986	0,909	0,903	0,870	0,868	0,867	0,866	0,865	0,864	0,816	0,764	0,733	0,707	0,704	0,696	0,688	0,689	0,800	0,819	0,814	0,811	0,815	0,824	0,842	0,823	0,831	0,834
IC	0,985	0,987	0,989	0,987	0,986	0,915	0,912	0,908	0,903	0,977	0,973	0,855	0,844	0,825	0,805	0,808	0,778	0,784	0,766	0,849	0,850	0,861	0,866	0,862	0,857	0,859	0,857	0,860
SC Current	0,778	0,779	0,776	0,778	0,779	0,782	0,783	0,783	0,787	0,786	0,821	0,821	0,794	0,788	0,713	0,707	0,745	0,609	0,716	0,669	0,610	0,690	0,668	0,698	0,722	0,739	0,749	0,759
OC Voltage	0,720	0,726	0,727	0,732	0,724	0,747	0,737	0,734	0,753	0,756	0,770	0,783	0,796	0,803	0,850	0,819	0,833	0,839	0,847	0,873	0,886	0,877	0,881	0,885	0,881	0,872	0,873	0,868
Const. Voltage	0,740	0,742	0,745	0,748	0,751	0,754	0,757	0,761	0,765	0,770	0,785	0,794	0,802	0,806	0,814	0,821	0,828	0,840	0,843	0,865	0,874	0,867	0,872	0,872	0,874	0,869	0,873	0,871
PSO 3	0,895	0,882	0,942	0,884	0,867	0,900	0,863	0,889	0,870	0,844	0,845	0,833	0,731	0,743	0,682	0,592	0,635	0,577	0,553	0,541	0,507	0,465	0,532	0,461	0,436	0,444	0,410	0,436
PSO 4	0,936	0,923	0,904	0,910	0,905	0,909	0,898	0,865	0,899	0,872	0,830	0,742	0,723	0,633	0,525	0,620	0,573	0,602	0,590	0,522	0,490	0,423	0,512	0,459	0,397	0,355	0,493	0,523
PSO 5	0,927	0,939	0,903	0,890	0,906	0,897	0,903	0,876	0,832	0,828	0,811	0,774	0,710	0,595	0,583	0,582	0,558	0,580	0,611	0,574	0,433	0,440	0,530	0,469	0,504	0,518	0,517	0,496
GA	0,979	0,973	0,973	0,954	0,899	0,971	0,951	0,959	0,967	0,942	0,927	0,919	0,757	0,767	0,732	0,848	0,728	0,815	0,752	0,738	0,752	0,668	0,631	0,707	0,674	0,656	0,609	0,609
PSO/P&O	0,981	0,979	0,909	0,959	0,967	0,891	0,963	0,961	0,874	0,953	0,926	0,891	0,877	0,823	0,844	0,858	0,806	0,818	0,842	0,760	0,743	0,774	0,642	0,688	0,631	0,692	0,664	0,751
PSO/IC	0,983	0,980	0,910	0,898	0,899	0,953	0,962	0,938	0,953	0,931	0,909	0,884	0,831	0,849	0,834	0,804	0,813	0,743	0,866	0,683	0,710	0,684	0,623	0,763	0,594	0,630	0,564	0,604
GA/P&O	0,981	0,905	0,900	0,883	0,884	0,957	0,872	0,919	0,933	0,925	0,883	0,725	0,783	0,676	0,617	0,640	0,609	0,556	0,579	0,524	0,538	0,507	0,529	0,537	0,386	0,358	0,489	0,514
GA/IC	0,913	0,978	0,900	0,954	0,879	0,940	0,869	0,854	0,915	0,922	0,881	0,810	0,768	0,687	0,670	0,628	0,602	0,623	0,620	0,524	0,556	0,489	0,546	0,542	0,378	0,362	0,493	0,530
Final group	B	B	B	B	B	B	B	B	B	B	B	D	C	C	C	C	C	D	C	C	C	C	C	C	D	C	C	C
Setup 2	A	A	A	A	A	A	A	A	A	A	A	C	D	D	B	D	B	B	D	B	B	B	B	B	B	B	B	B

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,922	0,922	0,925	0,930	0,929	0,927	0,924	0,923	0,921	0,918	0,901	0,887	0,876	0,861	0,841	0,824	0,810	0,795	0,782	0,711	0,806	0,839	0,830	0,835	0,834	0,832	0,820	0,833
P&O 2	0,925	0,927	0,928	0,924	0,909	0,906	0,905	0,907	0,907	0,904	0,891	0,865	0,846	0,819	0,788	0,765	0,736	0,752	0,760	0,780	0,804	0,793	0,781	0,793	0,797	0,799	0,798	0,799
P&O 3	0,918	0,922	0,920	0,913	0,907	0,902	0,897	0,892	0,890	0,885	0,839	0,790	0,752	0,709	0,708	0,728	0,744	0,777	0,829	0,827	0,831	0,821	0,825	0,819	0,823	0,830	0,828	0,829
IC	0,922	0,922	0,925	0,930	0,929	0,927	0,902	0,901	0,896	0,895	0,884	0,874	0,857	0,834	0,813	0,800	0,780	0,749	0,741	0,647	0,676	0,722	0,725	0,747	0,752	0,758	0,757	0,759
SC Current	0,722	0,724	0,728	0,726	0,723	0,738	0,731	0,735	0,750	0,735	0,768	0,784	0,795	0,802	0,812	0,820	0,825	0,835	0,831	0,858	0,858	0,853	0,858	0,867	0,856	0,853	0,860	0,858
OC Voltage	0,763	0,766	0,772	0,761	0,767	0,770	0,779	0,767	0,774	0,758	0,772	0,772	0,789	0,764	0,738	0,733	0,768	0,650	0,746	0,672	0,624	0,703	0,694	0,713	0,735	0,750	0,765	0,773
Const. Voltage	0,660	0,662	0,662	0,662	0,662	0,662	0,662	0,662	0,662	0,662	0,611	0,557	0,531	0,530	0,542	0,545	0,553	0,561	0,561	0,586	0,618	0,661	0,690	0,709	0,724	0,738	0,752	0,759
PSO 3	0,985	0,978	0,974	0,968	0,916	0,963	0,910	0,910	0,904	0,904	0,917	0,894	0,887	0,881	0,870	0,891	0,883	0,868	0,876	0,782	0,788	0,682	0,661	0,765	0,657	0,723	0,649	0,707
PSO 4	0,924	0,917	0,910	0,905	0,898	0,894	0,884	0,885	0,878	0,871	0,862	0,885	0,868	0,868	0,840	0,799	0,838	0,809	0,789	0,860	0,539	0,511	0,440	0,410	0,453	0,412	0,413	0,466
PSO 5	0,925	0,920	0,916	0,912	0,906	0,901	0,895	0,896	0,890	0,887	0,869	0,848	0,863	0,830	0,810	0,798	0,727	0,823	0,705	0,553	0,654	0,754	0,719	0,648	0,685	0,664	0,658	0,620
GA	0,928	0,918	0,913	0,901	0,899	0,899	0,906	0,885	0,887	0,881	0,907	0,858	0,644	0,858	0,815	0,792	0,833	0,765	0,811	0,634	0,619	0,659	0,774	0,740	0,776	0,777	0,736	0,767
PSO/P&O	0,932	0,928	0,922	0,918	0,918	0,906	0,915	0,894	0,896	0,896	0,912	0,844	0,819	0,787	0,799	0,876	0,766	0,863	0,728	0,745	0,744	0,671	0,647	0,806	0,750	0,728	0,644	0,718
PSO/IC	0,931	0,926	0,923	0,922	0,909	0,916	0,905	0,904	0,905	0,937	0,940	0,853	0,837	0,772	0,789	0,876	0,764	0,761	0,791	0,725	0,718	0,670	0,681	0,765	0,761	0,722	0,748	0,722
GA/P&O	0,929	0,927	0,922	0,918	0,915	0,910	0,908	0,906	0,902	0,900	0,866	0,852	0,855	0,824	0,803	0,783	0,797	0,790	0,834	0,826	0,613	0,521	0,444	0,474	0,434	0,407	0,407	0,468
GA/IC	0,934	0,928	0,923	0,919	0,914	0,914	0,906	0,906	0,902	0,899	0,866	0,857	0,828	0,814	0,798	0,782	0,800	0,853	0,832	0,824	0,606	0,514	0,438	0,464	0,413	0,405	0,407	0,465
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	C	C	C	D	C	D	D	D	D
Setup 3	C	C	C	C	A	C	A	A	A	D	D	C	C	C	C	C	C	C	C	C	B	B	B	B	B	B	B	B

Figure B.7: *Vertical shadow (x5-y3 size)*

Partial shadow (3 shadows)

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,916	0,959	0,988	0,995	0,994	0,994	0,994	0,994	0,994	0,993	0,993	0,993	0,993	0,992	0,992	0,992	0,991	0,990	0,991	0,987	0,987	0,987	0,985	0,970	0,951	0,942	0,954	0,978
P&O 2	0,961	0,996	0,995	0,995	0,993	0,994	0,994	0,994	0,994	0,994	0,993	0,993	0,993	0,992	0,993	0,992	0,991	0,991	0,991	0,989	0,984	0,901	0,869	0,896	0,896	0,895	0,912	0,913
P&O 3	0,956	0,994	0,994	0,994	0,993	0,993	0,993	0,993	0,993	0,993	0,993	0,992	0,992	0,992	0,991	0,990	0,989	0,988	0,987	0,988	0,984	0,980	0,978	0,964	0,969	0,971	0,973	0,969
IC	0,918	0,961	0,988	0,995	0,994	0,994	0,994	0,994	0,994	0,992	0,993	0,993	0,992	0,992	0,992	0,991	0,990	0,990	0,991	0,989	0,982	0,820	0,787	0,842	0,813	0,854	0,847	0,849
SC Current	0,945	0,945	0,945	0,945	0,945	0,945	0,945	0,945	0,945	0,945	0,968	0,976	0,979	0,981	0,984	0,984	0,985	0,986	0,986	0,989	0,988	0,987	0,987	0,985	0,987	0,985	0,984	0,985
OC Voltage	0,820	0,817	0,821	0,811	0,817	0,814	0,823	0,811	0,824	0,818	0,860	0,856	0,850	0,861	0,845	0,837	0,904	0,884	0,882	0,897	0,858	0,821	0,866	0,827	0,840	0,812	0,817	0,835
Const. Voltage	0,687	0,687	0,685	0,684	0,682	0,682	0,682	0,683	0,685	0,686	0,684	0,690	0,695	0,692	0,691	0,694	0,700	0,698	0,696	0,749	0,752	0,782	0,779	0,780	0,799	0,798	0,810	0,809
PSO 3	0,975	0,967	0,960	0,955	0,946	0,937	0,927	0,920	0,910	0,905	0,880	0,870	0,858	0,809	0,861	0,861	0,864	0,851	0,853	0,808	0,813	0,812	0,759	0,717	0,769	0,744	0,711	0,713
PSO 4	0,971	0,957	0,941	0,927	0,922	0,912	0,913	0,906	0,898	0,886	0,839	0,830	0,829	0,827	0,820	0,806	0,817	0,784	0,795	0,813	0,825	0,757	0,741	0,671	0,624	0,603	0,694	0,690
PSO 5	0,973	0,961	0,948	0,933	0,920	0,917	0,896	0,896	0,890	0,886	0,843	0,808	0,877	0,845	0,861	0,841	0,820	0,820	0,826	0,800	0,830	0,795	0,757	0,697	0,741	0,731	0,674	0,642
GA	0,969	0,988	0,984	0,981	0,982	0,966	0,976	0,972	0,968	0,952	0,966	0,925	0,931	0,923	0,928	0,938	0,895	0,952	0,869	0,831	0,661	0,762	0,749	0,669	0,626	0,760	0,749	0,585
PSO/P&O	0,974	0,947	0,955	0,974	0,971	0,965	0,968	0,957	0,963	0,938	0,919	0,882	0,914	0,875	0,883	0,856	0,778	0,803	0,839	0,786	0,684	0,677	0,768	0,560	0,723	0,574	0,651	0,699
PSO/IC	0,975	0,953	0,958	0,972	0,970	0,974	0,956	0,943	0,954	0,948	0,910	0,929	0,865	0,894	0,809	0,871	0,852	0,828	0,794	0,792	0,818	0,785	0,571	0,582	0,732	0,638	0,583	0,716
GA/P&O	0,984	0,975	0,972	0,983	0,980	0,978	0,976	0,973	0,977	0,970	0,965	0,952	0,935	0,903	0,860	0,872	0,852	0,859	0,856	0,804	0,733	0,793	0,726	0,686	0,802	0,789	0,723	0,748
GA/IC	0,985	0,973	0,972	0,980	0,982	0,979	0,977	0,976	0,965	0,966	0,944	0,953	0,935	0,906	0,899	0,871	0,859	0,856	0,853	0,814	0,735	0,789	0,748	0,688	0,792	0,792	0,741	0,749
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	C	D	D	D	C	D	D	C
Setup 1	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B	B	B	B	B	B

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,960	0,964	0,971	0,974	0,979	0,983	0,983	0,982	0,986	0,987	0,947	0,947	0,946	0,956	0,928	0,964	0,966	0,933	0,960	0,955	0,962	0,948	0,935	0,939	0,953	0,957	0,950	0,950
P&O 2	0,961	0,968	0,981	0,981	0,988	0,986	0,983	0,980	0,976	0,949	0,934	0,966	0,931	0,958	0,932	0,930	0,930	0,929	0,904	0,864	0,901	0,906	0,920	0,954	0,933	0,933	0,957	0,952
P&O 3	0,969	0,982	0,983	0,985	0,985	0,983	0,980	0,978	0,975	0,973	0,967	0,971	0,968	0,966	0,966	0,964	0,964	0,965	0,958	0,954	0,952	0,947	0,945	0,954	0,949	0,942	0,948	0,950
IC	0,956	0,969	0,972	0,974	0,979	0,983	0,983	0,984	0,986	0,987	0,948	0,971	0,943	0,941	0,932	0,931	0,932	0,932	0,922	0,873	0,868	0,852	0,853	0,878	0,866	0,893	0,945	0,907
SC Current	0,724	0,724	0,724	0,724	0,724	0,724	0,724	0,723	0,722	0,722	0,727	0,731	0,738	0,756	0,751	0,756	0,756	0,759	0,781	0,818	0,789	0,833	0,833	0,839	0,846	0,846	0,847	0,854
OC Voltage	0,871	0,872	0,872	0,872	0,872	0,873	0,873	0,874	0,874	0,874	0,894	0,901	0,904	0,905	0,905	0,906	0,907	0,907	0,906	0,916	0,922	0,905	0,918	0,918	0,914	0,912	0,918	0,938
Const. Voltage	0,914	0,914	0,915	0,915	0,915	0,916	0,916	0,916	0,917	0,917	0,914	0,913	0,912	0,911	0,910	0,908	0,908	0,907	0,904	0,909	0,916	0,911	0,922	0,922	0,915	0,911	0,913	0,944
PSO 3	0,922	0,881	0,850	0,839	0,815	0,810	0,800	0,785	0,770	0,774	0,723	0,656	0,663	0,633	0,657	0,614	0,591	0,587	0,584	0,550	0,551	0,500	0,546	0,517	0,546	0,488	0,473	0,492
PSO 4	0,893	0,854	0,808	0,815	0,770	0,766	0,792	0,764	0,745	0,729	0,680	0,628	0,645	0,605	0,575	0,549	0,513	0,569	0,526	0,542	0,527	0,557	0,547	0,515	0,495	0,468	0,527	0,588
PSO 5	0,880	0,837	0,809	0,797	0,774	0,767	0,743	0,754	0,739	0,729	0,686	0,636	0,583	0,579	0,602	0,541	0,621	0,527	0,555	0,550	0,538	0,583	0,579	0,530	0,490	0,502	0,528	0,536
GA	0,972	0,959	0,959	0,952	0,962	0,957	0,954	0,959	0,951	0,957	0,905	0,903	0,900	0,892	0,856	0,864	0,861	0,885	0,839	0,866	0,769	0,812	0,742	0,750	0,771	0,785	0,754	0,772
PSO/P&O	0,963	0,955	0,947	0,950	0,950	0,951	0,940	0,931	0,923	0,925	0,887	0,867	0,865	0,863	0,821	0,820	0,838	0,812	0,835	0,790	0,779	0,757	0,762	0,753	0,751	0,781	0,758	0,779
PSO/IC	0,960	0,954	0,949	0,945	0,937	0,947	0,941	0,939	0,920	0,913	0,890	0,850	0,859	0,841	0,842	0,806	0,805	0,802	0,823	0,828	0,799	0,779	0,742	0,741	0,722	0,721	0,754	0,762
GA/P&O	0,973	0,959	0,940	0,922	0,919	0,919	0,899	0,892	0,892	0,888	0,799	0,810	0,782	0,740	0,791	0,638	0,717	0,600	0,673	0,642	0,695	0,610	0,651	0,529	0,543	0,715	0,568	0,624
GA/IC	0,973	0,954	0,946	0,925	0,929	0,914	0,890	0,895	0,916	0,902	0,830	0,807	0,737	0,755	0,771	0,655	0,656	0,644	0,595	0,602	0,644	0,599	0,660	0,543	0,557	0,711	0,569	0,600
Final group	B	B	B	B	B	B	B	B	B	B	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Setup 2	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,958	0,972	0,983	0,986	0,987	0,988	0,989	0,987	0,986	0,986	0,980	0,980	0,982	0,979	0,979	0,980	0,978	0,979	0,977	0,982	0,975	0,982	0,954	0,975	0,958	0,951	0,963	0,967
P&O 2	0,970	0,987	0,989	0,988	0,986	0,987	0,984	0,984	0,984	0,983	0,941	0,960	0,949	0,939	0,939	0,944	0,938	0,904	0,921	0,866	0,944	0,886	0,873	0,903	0,905	0,903	0,911	0,913
P&O 3	0,972	0,986	0,987	0,986	0,986	0,985	0,984	0,984	0,983	0,983	0,980	0,981	0,981	0,982	0,982	0,982	0,983	0,982	0,978	0,973	0,975	0,976	0,975	0,972	0,969	0,967	0,970	0,969
IC	0,959	0,972	0,984	0,987	0,988	0,989	0,989	0,987	0,986	0,986	0,977	0,970	0,955	0,947	0,951	0,934	0,925	0,928	0,916	0,809	0,960	0,827	0,831	0,857	0,815	0,826	0,856	0,864
SC Current	0,934	0,934	0,934	0,933	0,933	0,934	0,934	0,933	0,933	0,933	0,956	0,962	0,968	0,968	0,969	0,970	0,971	0,972	0,971	0,972	0,975	0,973	0,974	0,972	0,977	0,977	0,978	0,969
OC Voltage	0,769	0,769	0,771	0,770	0,772	0,770	0,771	0,771	0,773	0,772	0,795	0,795	0,793	0,796	0,793	0,794	0,806	0,798	0,796	0,814	0,817	0,776	0,812	0,822	0,826	0,823	0,853	0,864
Const. Voltage	0,726	0,728	0,729	0,730	0,731	0,732	0,733	0,734	0,735	0,735	0,732	0,729	0,731	0,729	0,735	0,741	0,744	0,741	0,744	0,723	0,783	0,781	0,786	0,805	0,809	0,807	0,845	0,828
PSO 3	0,968	0,954	0,944	0,937	0,930	0,921	0,920	0,917	0,913	0,910	0,897	0,851	0,831	0,865	0,850	0,878	0,882	0,865	0,842	0,872	0,835	0,811	0,802	0,776	0,802	0,792	0,775	0,740
PSO 4	0,946	0,927	0,909	0,904	0,882	0,875	0,860	0,860	0,847	0,847	0,790	0,813	0,819	0,826	0,803	0,766	0,756	0,736	0,742	0,770	0,807	0,693	0,622	0,730	0,715	0,634	0,625	0,591
PSO 5	0,960	0,943	0,931	0,921	0,915	0,909	0,906	0,903	0,900	0,900	0,856	0,850	0,866	0,874	0,844	0,832	0,834	0,841	0,851	0,835	0,818	0,832	0,801	0,761	0,733	0,731	0,648	0,699
GA	0,976	0,971	0,966	0,962	0,957	0,956	0,950	0,960	0,949	0,941	0,941	0,917	0,897	0,889	0,900	0,853	0,879	0,869	0,884	0,830	0,824	0,781	0,787	0,753	0,729	0,782	0,676	0,758
PSO/P&O	0,975	0,969	0,959	0,950	0,956	0,936	0,948	0,946	0,945	0,946	0,918	0,908	0,885	0,865	0,848	0,811	0,816	0,837	0,794	0,805	0,778	0,774	0,739	0,773	0,793	0,833	0,794	0,729
PSO/IC	0,977	0,964	0,959	0,957	0,955	0,949	0,942	0,942	0,943	0,951	0,912	0,868	0,904	0,831	0,800	0,839	0,817	0,808	0,803	0,794	0,801	0,787	0,754	0,827	0,783	0,733	0,700	0,800
GA/P&O	0,972	0,961	0,947	0,941	0,941	0,943	0,931	0,937	0,917	0,917	0,906	0,876	0,862	0,855	0,854	0,800	0,761	0,798	0,750	0,764	0,775	0,652	0,617	0,554	0,666	0,601	0,618	0,604
GA/IC	0,972	0,961	0,945	0,948	0,936	0,950	0,929	0,924	0,913	0,911	0,920	0,873	0,846	0,844	0,852	0,831	0,782	0,786	0,823	0,777	0,803	0,667	0,621	0,557	0,687	0,599	0,616	0,619
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	C	C	B	D	D	D	D	D	D	D	C
Setup 3	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B	B

Figure B.8: *Partial shadow (3 shadows)*

Partial shadow (4 shadows)

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,906	0,954	0,985	0,993	0,993	0,993	0,992	0,993	0,992	0,991	0,991	0,990	0,991	0,990	0,990	0,989	0,987	0,988	0,989	0,983	0,985	0,982	0,982	0,963	0,944	0,934	0,947	0,971
P&O 2	0,956	0,994	0,993	0,993	0,991	0,992	0,992	0,992	0,992	0,992	0,991	0,991	0,990	0,990	0,991	0,989	0,988	0,989	0,988	0,986	0,974	0,872	0,841	0,866	0,875	0,876	0,893	0,900
P&O 3	0,950	0,993	0,992	0,992	0,991	0,991	0,991	0,991	0,991	0,991	0,990	0,989	0,990	0,990	0,988	0,986	0,987	0,985	0,984	0,985	0,977	0,970	0,971	0,958	0,960	0,959	0,965	0,962
IC	0,907	0,955	0,986	0,993	0,993	0,993	0,992	0,992	0,991	0,990	0,991	0,990	0,990	0,990	0,990	0,988	0,988	0,988	0,988	0,984	0,976	0,785	0,729	0,776	0,780	0,824	0,817	0,830
SC Current	0,944	0,944	0,944	0,944	0,944	0,944	0,944	0,944	0,944	0,944	0,967	0,975	0,978	0,980	0,982	0,982	0,983	0,983	0,984	0,987	0,985	0,984	0,984	0,984	0,984	0,984	0,979	0,981
OC Voltage	0,789	0,786	0,792	0,779	0,786	0,782	0,792	0,776	0,797	0,791	0,836	0,831	0,826	0,826	0,803	0,813	0,884	0,862	0,877	0,891	0,825	0,780	0,833	0,803	0,822	0,808	0,812	0,830
Const. Voltage	0,643	0,640	0,636	0,634	0,630	0,628	0,628	0,626	0,627	0,627	0,616	0,617	0,628	0,636	0,643	0,647	0,663	0,657	0,660	0,711	0,733	0,747	0,759	0,772	0,784	0,777	0,803	0,805
PSO 3	0,976	0,964	0,956	0,950	0,940	0,929	0,923	0,916	0,901	0,901	0,860	0,849	0,849	0,819	0,854	0,850	0,821	0,823	0,841	0,806	0,809	0,805	0,743	0,711	0,746	0,734	0,707	0,678
PSO 4	0,967	0,955	0,941	0,926	0,920	0,905	0,909	0,891	0,889	0,879	0,820	0,819	0,840	0,821	0,808	0,787	0,787	0,802	0,793	0,814	0,820	0,766	0,705	0,694	0,615	0,613	0,678	0,680
PSO 5	0,970	0,957	0,945	0,932	0,916	0,899	0,889	0,883	0,874	0,874	0,846	0,832	0,888	0,842	0,840	0,823	0,809	0,825	0,845	0,797	0,776	0,793	0,748	0,697	0,670	0,702	0,605	0,628
GA	0,967	0,983	0,982	0,978	0,977	0,977	0,973	0,965	0,968	0,944	0,965	0,954	0,926	0,917	0,927	0,917	0,865	0,938	0,858	0,885	0,585	0,701	0,772	0,679	0,677	0,684	0,606	0,567
PSO/P&O	0,972	0,956	0,952	0,958	0,962	0,939	0,958	0,960	0,944	0,942	0,897	0,848	0,870	0,911	0,843	0,834	0,798	0,839	0,833	0,779	0,711	0,702	0,636	0,565	0,681	0,722	0,696	0,650
PSO/IC	0,971	0,957	0,947	0,966	0,967	0,968	0,956	0,953	0,952	0,935	0,921	0,936	0,877	0,871	0,869	0,827	0,796	0,860	0,844	0,786	0,726	0,774	0,637	0,583	0,669	0,644	0,583	0,629
GA/P&O	0,981	0,971	0,968	0,975	0,976	0,968	0,969	0,969	0,962	0,959	0,938	0,927	0,939	0,888	0,860	0,881	0,846	0,835	0,854	0,803	0,766	0,795	0,724	0,682	0,620	0,763	0,727	0,746
GA/IC	0,982	0,971	0,967	0,973	0,970	0,976	0,965	0,961	0,962	0,962	0,933	0,946	0,935	0,892	0,902	0,835	0,830	0,837	0,846	0,812	0,787	0,778	0,700	0,702	0,635	0,611	0,734	0,730
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	C	C	D	D	C	D	D	C
Setup 1	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B	B	B	B	B	B	B

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,987	0,983	0,986	0,985	0,985	0,985	0,983	0,982	0,985	0,984	0,943	0,941	0,911	0,934	0,911	0,953	0,954	0,930	0,957	0,958	0,956	0,940	0,947	0,956	0,954	0,958	0,955	0,952
P&O 2	0,983	0,986	0,985	0,983	0,983	0,986	0,979	0,978	0,975	0,956	0,929	0,913	0,904	0,910	0,925	0,901	0,872	0,887	0,882	0,832	0,879	0,882	0,922	0,936	0,928	0,951	0,951	0,949
P&O 3	0,985	0,982	0,984	0,985	0,985	0,981	0,978	0,975	0,973	0,970	0,964	0,965	0,965	0,963	0,962	0,961	0,961	0,958	0,959	0,953	0,954	0,945	0,944	0,945	0,948	0,942	0,946	0,946
IC	0,984	0,985	0,986	0,985	0,985	0,985	0,983	0,985	0,984	0,984	0,961	0,958	0,916	0,910	0,903	0,888	0,895	0,901	0,869	0,810	0,867	0,807	0,867	0,891	0,889	0,932	0,926	0,917
SC Current	0,719	0,720	0,720	0,720	0,720	0,720	0,721	0,720	0,718	0,718	0,724	0,727	0,736	0,751	0,748	0,739	0,734	0,740	0,743	0,766	0,761	0,805	0,816	0,806	0,839	0,841	0,844	0,854
OC Voltage	0,867	0,867	0,867	0,868	0,868	0,868	0,869	0,869	0,869	0,870	0,891	0,898	0,902	0,904	0,904	0,905	0,908	0,906	0,907	0,917	0,914	0,901	0,909	0,916	0,916	0,910	0,919	0,930
Const. Voltage	0,907	0,907	0,908	0,908	0,908	0,909	0,909	0,910	0,910	0,910	0,908	0,908	0,908	0,906	0,907	0,904	0,905	0,904	0,902	0,909	0,907	0,910	0,913	0,920	0,913	0,911	0,914	0,935
PSO 3	0,917	0,872	0,846	0,834	0,814	0,798	0,791	0,778	0,776	0,763	0,690	0,654	0,666	0,628	0,632	0,624	0,568	0,578	0,594	0,547	0,555	0,560	0,501	0,516	0,556	0,523	0,473	0,512
PSO 4	0,895	0,832	0,806	0,771	0,779	0,751	0,745	0,749	0,725	0,717	0,688	0,630	0,611	0,621	0,591	0,578	0,536	0,575	0,579	0,559	0,546	0,590	0,542	0,525	0,483	0,459	0,512	0,579
PSO 5	0,887	0,838	0,803	0,798	0,775	0,767	0,758	0,743	0,725	0,721	0,646	0,607	0,601	0,582	0,584	0,589	0,546	0,568	0,563	0,594	0,544	0,574	0,575	0,495	0,531	0,502	0,487	0,546
GA	0,972	0,966	0,962	0,963	0,958	0,956	0,953	0,950	0,953	0,948	0,934	0,904	0,862	0,844	0,903	0,866	0,860	0,837	0,839	0,827	0,783	0,803	0,769	0,763	0,741	0,772	0,767	0,779
PSO/P&O	0,976	0,965	0,966	0,948	0,955	0,948	0,942	0,936	0,939	0,931	0,891	0,864	0,870	0,818	0,843	0,820	0,797	0,799	0,806	0,797	0,810	0,751	0,745	0,775	0,753	0,788	0,755	0,807
PSO/IC	0,969	0,965	0,950	0,960	0,953	0,942	0,941	0,942	0,937	0,917	0,870	0,875	0,862	0,818	0,838	0,830	0,846	0,813	0,828	0,799	0,790	0,794	0,768	0,710	0,760	0,752	0,716	0,781
GA/P&O	0,975	0,961	0,944	0,928	0,928	0,924	0,904	0,900	0,896	0,878	0,769	0,801	0,744	0,690	0,747	0,707	0,691	0,638	0,636	0,611	0,647	0,596	0,661	0,554	0,554	0,712	0,570	0,626
GA/IC	0,975	0,959	0,943	0,940	0,923	0,909	0,912	0,888	0,899	0,873	0,828	0,823	0,716	0,776	0,709	0,653	0,638	0,644	0,598	0,592	0,583	0,678	0,564	0,562	0,564	0,710	0,572	0,627
Final group	B	B	B	B	B	B	B	B	B	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Setup 2	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,963	0,977	0,986	0,989	0,989	0,990	0,990	0,988	0,988	0,987	0,981	0,982	0,983	0,981	0,981	0,982	0,980	0,981	0,981	0,984	0,977	0,980	0,956	0,981	0,954	0,947	0,968	0,965
P&O 2	0,978	0,990	0,991	0,990	0,988	0,988	0,985	0,986	0,986	0,986	0,936	0,919	0,943	0,921	0,933	0,926	0,946	0,898	0,876	0,801	0,959	0,900	0,866	0,889	0,901	0,907	0,923	0,912
P&O 3	0,977	0,989	0,989	0,988	0,987	0,986	0,986	0,985	0,985	0,984	0,982	0,982	0,983	0,982	0,983	0,983	0,983	0,983	0,978	0,972	0,978	0,974	0,974	0,971	0,967	0,965	0,969	0,967
IC	0,964	0,978	0,987	0,989	0,990	0,990	0,990	0,989	0,988	0,987	0,981	0,955	0,946	0,929	0,920	0,879	0,923	0,884	0,897	0,706	0,862	0,779	0,818	0,827	0,806	0,835	0,854	0,865
SC Current	0,935	0,935	0,935	0,935	0,935	0,935	0,936	0,935	0,935	0,935	0,957	0,964	0,970	0,970	0,971	0,971	0,972	0,974	0,973	0,974	0,977	0,975	0,976	0,972	0,978	0,977	0,978	0,971
OC Voltage	0,773	0,772	0,775	0,772	0,772	0,768	0,772	0,769	0,769	0,768	0,796	0,793	0,805	0,792	0,801	0,813	0,832	0,817	0,824	0,858	0,821	0,779	0,780	0,792	0,818	0,832	0,843	0,857
Const. Voltage	0,677	0,678	0,680	0,681	0,682	0,683	0,684	0,685	0,685	0,685	0,680	0,678	0,678	0,681	0,681	0,681	0,682	0,673	0,668	0,690	0,729	0,738	0,768	0,786	0,791	0,798	0,830	0,820
PSO 3	0,970	0,957	0,946	0,940	0,934	0,928	0,922	0,916	0,914	0,908	0,885	0,862	0,848	0,855	0,871	0,870	0,892	0,871	0,848	0,851	0,807	0,791	0,788	0,771	0,810	0,789	0,775	0,761
PSO 4	0,954	0,936	0,919	0,909	0,894	0,886	0,871	0,867	0,856	0,853	0,802	0,805	0,822	0,834	0,802	0,768	0,789	0,807	0,752	0,772	0,798	0,673	0,593	0,534	0,706	0,610	0,613	0,514
PSO 5	0,962	0,945	0,936	0,925	0,917	0,911	0,902	0,902	0,904	0,895	0,857	0,883	0,887	0,873	0,836	0,869	0,828	0,835	0,831	0,831	0,814	0,827	0,797	0,750	0,720	0,729	0,647	0,697
GA	0,978	0,974	0,969	0,967	0,962	0,958	0,951	0,952	0,947	0,950	0,928	0,928	0,912	0,874	0,886	0,907	0,901	0,888	0,905	0,807	0,835	0,799	0,832	0,791	0,733	0,728	0,763	0,734
PSO/P&O	0,977	0,972	0,961	0,957	0,944	0,959	0,944	0,946	0,956	0,949	0,921	0,937	0,922	0,868	0,847	0,830	0,819	0,805	0,830	0,821	0,769	0,799	0,787	0,770	0,749	0,779	0,694	0,790
PSO/IC	0,977	0,972	0,960	0,960	0,958	0,951	0,953	0,941	0,946	0,949	0,921	0,896	0,888	0,842	0,857	0,791	0,858	0,820	0,845	0,791	0,791	0,766	0,749	0,744	0,726	0,747	0,662	0,682
GA/P&O	0,976	0,966	0,955	0,957	0,950	0,944	0,949	0,929	0,917	0,927	0,909	0,879	0,881	0,884	0,861	0,812	0,826	0,815	0,823	0,748	0,785	0,683	0,605	0,548	0,646	0,592	0,616	0,447
GA/IC	0,976	0,966	0,956	0,956	0,944	0,946	0,936	0,933	0,912	0,919	0,920	0,899	0,878	0,876	0,817	0,794	0,756	0,800	0,792	0,758	0,803	0,700	0,598	0,556	0,708	0,590	0,615	0,450
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	C	C	C	D	D	C	D
Setup 3	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	A	B	B	B	B

Figure B.9: *Partial shadow (4 shadows)*

Partial shadow (5 shadows)

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,894	0,946	0,980	0,989	0,988	0,988	0,987	0,987	0,986	0,986	0,985	0,984	0,984	0,983	0,982	0,981	0,980	0,981	0,980	0,974	0,975	0,942	0,949	0,960	0,962	0,921	0,948	0,925
P&O 2	0,948	0,989	0,988	0,987	0,983	0,985	0,985	0,985	0,985	0,985	0,983	0,982	0,983	0,983	0,981	0,982	0,981	0,981	0,981	0,975	0,934	0,780	0,815	0,812	0,819	0,874	0,875	0,848
P&O 3	0,940	0,988	0,987	0,986	0,985	0,985	0,985	0,985	0,985	0,985	0,983	0,982	0,982	0,982	0,981	0,979	0,979	0,978	0,974	0,974	0,957	0,939	0,948	0,927	0,938	0,940	0,932	0,935
IC	0,894	0,947	0,981	0,989	0,988	0,988	0,987	0,986	0,984	0,983	0,984	0,983	0,983	0,983	0,982	0,982	0,982	0,980	0,980	0,962	0,931	0,655	0,682	0,705	0,745	0,818	0,804	0,812
SC Current	0,940	0,940	0,940	0,940	0,940	0,940	0,939	0,940	0,939	0,939	0,961	0,969	0,972	0,973	0,975	0,976	0,976	0,976	0,977	0,979	0,978	0,976	0,976	0,974	0,974	0,976	0,972	0,971
OC Voltage	0,714	0,707	0,710	0,700	0,701	0,705	0,699	0,686	0,725	0,700	0,755	0,738	0,729	0,752	0,759	0,731	0,843	0,753	0,782	0,814	0,735	0,700	0,770	0,783	0,793	0,786	0,788	0,806
Const. Voltage	0,513	0,512	0,508	0,505	0,500	0,497	0,494	0,493	0,493	0,492	0,474	0,470	0,461	0,469	0,469	0,487	0,491	0,497	0,512	0,563	0,624	0,678	0,670	0,720	0,748	0,754	0,780	0,771
PSO 3	0,968	0,957	0,946	0,942	0,933	0,923	0,917	0,905	0,897	0,884	0,869	0,840	0,806	0,834	0,838	0,837	0,837	0,818	0,815	0,805	0,792	0,784	0,732	0,700	0,768	0,734	0,693	0,667
PSO 4	0,962	0,950	0,933	0,921	0,910	0,906	0,898	0,889	0,895	0,872	0,809	0,788	0,801	0,832	0,815	0,801	0,774	0,791	0,777	0,794	0,743	0,779	0,722	0,668	0,608	0,601	0,686	0,694
PSO 5	0,962	0,949	0,937	0,923	0,908	0,891	0,879	0,873	0,861	0,863	0,815	0,791	0,867	0,844	0,801	0,810	0,793	0,824	0,828	0,837	0,782	0,749	0,762	0,688	0,638	0,609	0,589	0,620
GA	0,959	0,947	0,977	0,971	0,971	0,967	0,962	0,960	0,958	0,933	0,946	0,934	0,904	0,894	0,904	0,909	0,886	0,914	0,919	0,763	0,737	0,584	0,659	0,548	0,695	0,681	0,710	0,638
PSO/P&O	0,969	0,955	0,952	0,945	0,946	0,938	0,944	0,938	0,923	0,911	0,912	0,900	0,883	0,849	0,823	0,818	0,833	0,848	0,826	0,764	0,800	0,751	0,601	0,580	0,566	0,724	0,571	0,679
PSO/IC	0,965	0,951	0,943	0,954	0,935	0,943	0,944	0,937	0,919	0,929	0,927	0,910	0,852	0,858	0,838	0,848	0,761	0,842	0,787	0,790	0,641	0,757	0,632	0,748	0,594	0,734	0,765	0,646
GA/P&O	0,975	0,964	0,960	0,967	0,963	0,953	0,954	0,951	0,957	0,942	0,914	0,906	0,892	0,879	0,825	0,841	0,832	0,813	0,815	0,790	0,759	0,757	0,745	0,761	0,770	0,760	0,681	0,711
GA/IC	0,976	0,962	0,959	0,964	0,955	0,946	0,951	0,943	0,950	0,938	0,915	0,893	0,894	0,883	0,846	0,848	0,829	0,810	0,845	0,792	0,769	0,795	0,731	0,662	0,585	0,752	0,661	0,718
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	C	D	C	D	C	D	C
Setup 1	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B	B	B	B	B	B	B

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,978	0,976	0,976	0,976	0,976	0,971	0,968	0,962	0,968	0,960	0,928	0,902	0,846	0,923	0,865	0,866	0,939	0,937	0,932	0,942	0,934	0,934	0,942	0,930	0,934	0,921	0,924	0,927
P&O 2	0,976	0,976	0,973	0,965	0,966	0,962	0,960	0,951	0,954	0,949	0,867	0,848	0,850	0,856	0,837	0,837	0,840	0,830	0,820	0,812	0,854	0,867	0,902	0,906	0,935	0,921	0,941	0,939
P&O 3	0,975	0,973	0,972	0,968	0,970	0,965	0,962	0,958	0,956	0,950	0,948	0,931	0,948	0,943	0,944	0,940	0,947	0,944	0,937	0,929	0,939	0,935	0,936	0,937	0,940	0,939	0,943	0,935
IC	0,977	0,975	0,976	0,976	0,975	0,971	0,968	0,963	0,968	0,961	0,939	0,879	0,862	0,848	0,836	0,837	0,835	0,824	0,821	0,744	0,779	0,772	0,829	0,852	0,877	0,911	0,909	0,892
SC Current	0,725	0,726	0,726	0,726	0,726	0,726	0,725	0,724	0,723	0,721	0,730	0,730	0,730	0,736	0,729	0,722	0,721	0,723	0,723	0,748	0,729	0,785	0,787	0,793	0,842	0,843	0,844	0,853
OC Voltage	0,820	0,821	0,821	0,822	0,822	0,822	0,824	0,823	0,824	0,824	0,844	0,854	0,862	0,859	0,857	0,867	0,868	0,858	0,859	0,874	0,887	0,832	0,867	0,885	0,888	0,895	0,906	0,918
Const. Voltage	0,840	0,841	0,842	0,842	0,843	0,844	0,844	0,845	0,845	0,846	0,846	0,848	0,847	0,849	0,847	0,847	0,847	0,848	0,844	0,849	0,833	0,855	0,872	0,874	0,888	0,895	0,899	0,905
PSO 3	0,901	0,858	0,811	0,813	0,810	0,796	0,782	0,786	0,767	0,766	0,684	0,641	0,671	0,650	0,634	0,647	0,608	0,620	0,584	0,559	0,560	0,548	0,523	0,523	0,501	0,577	0,498	0,516
PSO 4	0,865	0,827	0,804	0,781	0,773	0,760	0,763	0,754	0,747	0,745	0,705	0,655	0,649	0,621	0,616	0,548	0,575	0,538	0,571	0,560	0,540	0,586	0,501	0,554	0,549	0,571	0,630	0,600
PSO 5	0,863	0,819	0,804	0,784	0,764	0,771	0,741	0,734	0,734	0,710	0,667	0,627	0,613	0,609	0,600	0,597	0,581	0,566	0,581	0,579	0,549	0,583	0,615	0,580	0,539	0,505	0,490	0,529
GA	0,965	0,959	0,956	0,958	0,947	0,932	0,938	0,942	0,949	0,933	0,903	0,910	0,868	0,871	0,820	0,852	0,849	0,832	0,888	0,827	0,787	0,793	0,776	0,799	0,717	0,794	0,747	0,783
PSO/P&O	0,963	0,956	0,953	0,945	0,940	0,931	0,928	0,937	0,925	0,909	0,864	0,862	0,836	0,826	0,812	0,834	0,804	0,800	0,785	0,771	0,761	0,753	0,762	0,706	0,752	0,779	0,740	0,774
PSO/IC	0,968	0,955	0,946	0,940	0,941	0,942	0,929	0,936	0,923	0,920	0,874	0,855	0,815	0,806	0,844	0,817	0,810	0,814	0,821	0,792	0,777	0,770	0,741	0,709	0,776	0,787	0,762	0,759
GA/P&O	0,963	0,946	0,918	0,908	0,916	0,893	0,902	0,887	0,883	0,873	0,777	0,794	0,699	0,702	0,685	0,630	0,640	0,638	0,629	0,593	0,623	0,596	0,583	0,528	0,555	0,507	0,640	0,542
GA/IC	0,962	0,948	0,922	0,912	0,913	0,892	0,897	0,871	0,879	0,865	0,774	0,758	0,740	0,683	0,690	0,665	0,632	0,630	0,600	0,611	0,563	0,594	0,576	0,538	0,552	0,556	0,628	0,537
Final group	B	B	B	B	B	B	B	B	B	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Setup 2	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A

Speed (cm/s)	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
MPPT (η)																												
P&O 1	0,943	0,954	0,968	0,975	0,981	0,984	0,983	0,981	0,981	0,975	0,963	0,970	0,968	0,966	0,964	0,968	0,966	0,970	0,965	0,971	0,970	0,962	0,958	0,961	0,941	0,950	0,958	0,937
P&O 2	0,954	0,974	0,984	0,982	0,977	0,975	0,970	0,972	0,972	0,931	0,903	0,855	0,894	0,861	0,875	0,910	0,876	0,875	0,844	0,802	0,827	0,804	0,845	0,842	0,859	0,859	0,896	0,886
P&O 3	0,958	0,972	0,982	0,979	0,973	0,972	0,970	0,971	0,970	0,971	0,969	0,968	0,971	0,972	0,973	0,970	0,971	0,972	0,966	0,966	0,967	0,962	0,966	0,958	0,950	0,957	0,947	0,951
IC	0,944	0,954	0,969	0,975	0,981	0,984	0,983	0,981	0,980	0,974	0,955	0,894	0,880	0,840	0,814	0,825	0,812	0,814	0,815	0,678	0,795	0,681	0,783	0,753	0,772	0,766	0,822	0,820
SC Current	0,919	0,918	0,919	0,917	0,918	0,918	0,918	0,917	0,917	0,917	0,938	0,943	0,951	0,951	0,950	0,953	0,954	0,956	0,955	0,950	0,956	0,957	0,954	0,952	0,962	0,963	0,960	0,947
OC Voltage	0,713	0,713	0,715	0,715	0,713	0,710	0,716	0,712	0,713	0,715	0,741	0,740	0,746	0,734	0,743	0,745	0,759	0,750	0,757	0,788	0,767	0,715	0,727	0,766	0,807	0,822	0,831	0,844
Const. Voltage	0,608	0,610	0,612	0,613	0,614	0,615	0,616	0,617	0,617	0,617	0,612	0,615	0,612	0,615	0,614	0,617	0,615	0,614	0,609	0,631	0,650	0,702	0,715	0,736	0,780	0,787	0,818	0,809
PSO 3	0,959	0,945	0,936	0,930	0,923	0,918	0,917	0,907	0,902	0,899	0,888	0,853	0,827	0,864	0,871	0,880	0,876	0,866	0,856	0,830	0,848	0,849	0,790	0,754	0,806	0,782	0,763	0,743
PSO 4	0,940	0,921	0,909	0,900	0,890	0,871	0,864	0,865	0,863	0,850	0,802	0,782	0,826	0,812	0,833	0,781	0,780	0,783	0,738	0,762	0,776	0,686	0,565	0,551	0,510	0,536	0,636	0,525
PSO 5	0,950	0,935	0,925	0,918	0,907	0,903	0,901	0,900	0,895	0,896	0,853	0,851	0,893	0,869	0,853	0,850	0,823	0,833	0,831	0,845	0,817	0,822	0,786	0,752	0,690	0,672	0,631	0,687
GA	0,970	0,966	0,962	0,960	0,958	0,950	0,947	0,943	0,932	0,941	0,903	0,911	0,894	0,881	0,880	0,891	0,844	0,831	0,866	0,822	0,850	0,749	0,721	0,708	0,774	0,768	0,734	0,744
PSO/P&O	0,972	0,960	0,950	0,950	0,940	0,939	0,931	0,919	0,937	0,925	0,905	0,902	0,849	0,874	0,828	0,834	0,834	0,781	0,791	0,818	0,770	0,809	0,765	0,729	0,725	0,721	0,789	0,751
PSO/IC	0,969	0,959	0,951	0,953	0,944	0,938	0,919	0,926	0,927	0,915	0,903	0,865	0,881	0,833	0,851	0,852	0,850	0,827	0,773	0,804	0,754	0,769	0,742	0,758	0,729	0,713	0,806	0,753
GA/P&O	0,971	0,954	0,945	0,939	0,931	0,923	0,912	0,914	0,911	0,912	0,884	0,865	0,867	0,859	0,844	0,810	0,802	0,786	0,767	0,760	0,785	0,741	0,545	0,539	0,638	0,533	0,646	0,498
GA/IC	0,968	0,955	0,944	0,937	0,929	0,920	0,919	0,916	0,912	0,896	0,893	0,863	0,845	0,843	0,861	0,814	0,783	0,787	0,809	0,766	0,785	0,737	0,680	0,554	0,694	0,563	0,608	0,497
Final group	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	A	D	D	C	D	D	D
Setup 3	D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B	A

Figure B.10: *Partial shadow (5 shadows)*