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Maximum Power Point Tracking Algorithms for Photovoltaic Applications

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***Abstract:** Solar panels have a nonlinear voltage-current characteristic, with a distinct max-imum power point (MPP), which depends on the environmental factors, such as temperature and irradiation. In order to continuously harvest maximum power from the solar panels, they have to operate at their MPP despite the inevitable changes in the environment. This is why the controllers of all solar power electronic converters employ some method for maximum power point tracking (MPPT). Over the past decades many MPPT techniques have been published. The first objective of this thesis is to study and analyze them. The three algorithms that where found most suitable for large and medium size photovoltaic (PV) applications are perturb and observe (P&O) and incremental conductance (InCond).These were compared and tested dynamically according a recently issued standard. Several modifications to the P&O and the InCond algorithms are proposed, which overcome their poor performance when the irradiation changes continuously.*

The dynamic MPPT e□ciency tests require long simulations and if detailed models of the power converter are used they can take a lot of memory and compu-tation time. To overcome this challenge a simplified model of the PV system was developed. This model was validated with simulations.

***Keywords:** Maximum power point tracking (MPPT), PID controller, P&O Algorithm, MATLAB/SIMULINK.*

I. INTRODUCTION

Global warming and energy policies have become a hot topic on the international agenda in the last years. Developed countries are trying to reduce their greenhouse gas emissions. For example, the EU has committed to reduce the emissions of greenhouse gas to at least 20% below 1990 levels and to produce no less than 20% of its energy consumption from renewable sources by 2020 [1]. In this context, *photovoltaic* (PV) power generation has an important role to play due to the fact that it is a green source. The only emissions associated with PV power generation are those from the production of its components. After their installation they generate electricity from the solar irradiation without emitting greenhouse gases. In their lifetime, which is around 25 years, PV panels produce more energy than that for their manufacturing [2]. Also they can be installed in places with no other use, such as roofs and deserts, or they can produce electricity for remote locations, where there is no electricity network. The latter type of installations is known as off-grid facilities and sometimes they are the most economical alternative to provide electricity in isolated areas.

However, most of the PV power generation comes from grid-connected installations, where the power is fed in the electricity network. In fact, it is a growing business in developed countries such as Germany which in 2010 is by far the world leader in PV power generation followed by Spain, Japan, USA and Italy [3]. On the other hand, due to the equipment required, PV power generation is more expensive than other resources. Governments are promoting it with subsidies or feed-in tariffs, expecting the development of the technology so that in the near future it will become competitive [3]-[4]. Increasing the efficiency in PV plants so the power generated increases is a key aspect, as it will increase the incomes, reducing consequently the cost of the power generated so it will approach the cost of the power produced from other sources.

A. Solar Cell

Solar cells are the basic components of photovoltaic panels. Most are made from silicon even though other materials are also used. Solar cells take advantage of the photoelectric effect: the ability of some semiconductors to convert electromagnetic radiation directly into electrical current. The charged particles generated by the incident radiation are separated conveniently to create an electrical current by an appropriate design of the structure of the solar cell, as will be explained in brief below.

B. *Equivalent Circuit Of A Solar Cell*

The solar cell can be represented by the electrical model shown in Figure [1]. Its current-voltage characteristic is expressed by the following equation (1):

$$I = I_L - I_0\left(e^{\frac{q(V-IR_S)}{AkT}} - 1\right) - \frac{V - IR_S}{R_{SH}} \tag{1}$$

where I and V are the solar cell output current and voltage respectively, I_0 is the dark saturation current, q is the charge of an electron, A is the diode quality (ideality) factor, k is the Boltzmann constant, T is the absolute temperature and R_S and R_{SH} are the series and shunt resistances of the solar cell. R_S is the resistance offered by the contacts and the bulk semiconductor material of the solar cell. The origin of the shunt resistance R_{SH} is more difficult to explain. It is related to the non ideal nature of the p–n junction and the presence of impurities near the edges of the cell that provide a short-circuit path around the junction . In an ideal case R_S would be zero and R_{SH} infinite. However, this ideal scenario is not possible and manufacturers try to minimize the effect of both resistances to improve their products.

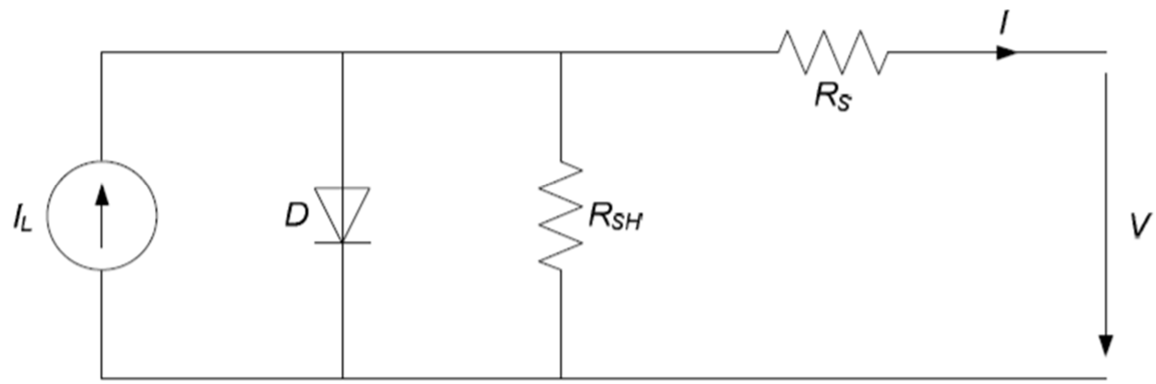

FIG. 1 Equivalent Circuit Of Solar Cell

C. *Operating Principle*

A solar cell is basically a p-n junction which is made from two different layers of silicon doped with a small quantity of impurity atoms: in the case of the n-layer, atoms with one more valence electron, called donors, and in the case of the p-layer, with one less valence electron, known as acceptors. When the two layers are joined together, near the interface the free electrons of the n-layer are diffused in the p-side, leaving behind an area positively charged by the donors. Similarly, the free holes in the p-layer are diffused in the n-side, leaving behind a region negatively charged by the acceptors. This creates an electrical field between the two sides that is a potential barrier to further flow. The equilibrium is reached in the junction when the electrons and holes cannot surpass that potential barrier and consequently they cannot move. This electric field pulls the electrons and holes in opposite directions so the current can flow in one way only: electrons can move from the p-side to the n-side and the holes in the opposite direction. A diagram of the p-n junction showing the effect of the mentioned electric field is illustrated in Figure [1].

II. OPEN CIRCUIT VOLTAGE, SHORT CIRCUIT CURRENT AND MAXIMUM POWER POINT

Two important points of the current-voltage characteristic must be pointed out: the open circuit voltage V_{OC} and the short circuit current I_{SC}. At both points the power generated is zero. V_{OC} can be approximated from when the output current of the cell is zero, i.e. I=0 and the shunt resistance R_{SH} is neglected. It is represented by equation (3). The short circuit current I_{SC} is the current at V = 0 and is approximately equal to the light generated current I_L as shown in equation (4).

$$V_{OC} \approx \frac{AkT}{q} ln\left(\frac{I_L}{I_o} + 1\right) \tag{3}$$

$$I_{SC} \approx I_L \tag{4}$$

The maximum power is generated by the solar cell at a point of the current-voltage characteristic where the product *VI* is maximum. This point is known as the MPP and is unique, as can be seen in Figure [2], where the previous points are represented.

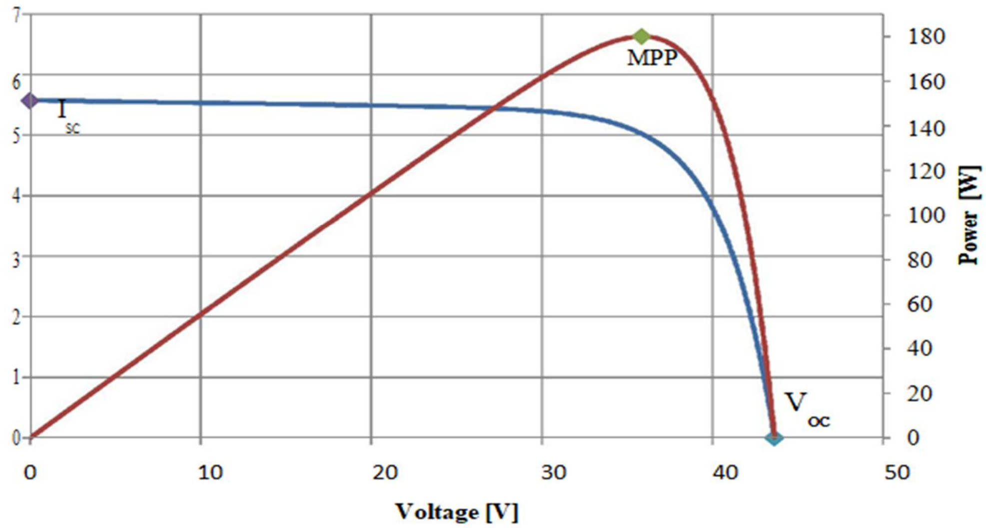

Figure 2. Important points in the characteristic curves of a solar panel.

III. TYPES OF SOLAR CELLS

Over the past decades, silicon has been almost the only material used for manufacturing solar cells. Although other materials and techniques have been developed, silicon is used in more than the 80% of the production [4]. Silicon is so popular because it is one of the most abundant materials in the Earth's crust, in the form of silicon dioxide, and it is not toxic. Monocrystalline and polycrystalline silicon solar cells are the two major types of silicon solar cells. There is a third type, amorphous silicon, but the efficiency is worse than with the previous types so it is less used. Other new solar cells are made of *copper indium gallium (di)selenide* (CIGS) or *cadmium telluride* (CdTe). Much *research and development* (R&D) effort is being made to develop new materials, but nowadays there are no commercial substitutes to the above types of solar cells. In this section these different solar cells are reviewed.

One of the most important characteristics of solar cells is the efficiency, which is the percentage of solar radiation that is transformed into electricity. It is measured under *Standard Test Conditions* (STC), irradiance of 1000 W/m², air mass coefficient (it characterizes the solar spectrum after the solar radiation has travelled through the atmosphere) A.M 1.5, and a cell junction temperature of 25°C. The higher efficiency, the smaller surface is needed for a given power. This is important because in some applications the space is limited and other costs and parameters of the installation depend on the installed PV surface.

A. *Monocrystalline Silicon*

Monocrystalline silicon solar cells are the most efficient ones. They are made from wafers (very thin slices) of single crystals obtained from pure molten silicon. These single crystal wafers have uniform and predictable properties as the structure of the crystal is highly ordered. However the manufacturing process must be really careful and occurs at high temperatures, which is expensive. The efficiency of these cells is around 15-18% and the surface needed to get 1 kW in STC is about 7 m^2.

B. *Polycrystalline Silicon*

These cells are also made from wafers of pure molten silicon. However, the crystal structure is random: as the silicon cools, it crystallizes simultaneously in many different points producing an irregular structure: crystals of random sizes, shapes and orientation. These structures are not as ideal as in the monocrystalline cells so the efficiency is lower, around 11-15% However the manufacturing process is less expensive, so the lower efficiency is compensated in some way. The surface needed to obtain 1 kW in STC is about $8m^2$.

C. Amorphous and thin-film Silicon

Amorphous silicon is the non-crystalline form of the silicon and it can be deposited as thin-films onto different substrates. The deposition can be made at low temperatures. The manufacturing process is simpler, easier and cheaper than in the crystalline cells. The weak point of these cells is their lower efficiency, around 6-8% . This efficiency is measured under STC. However, the performance under weaker or diffuse irradiation, such as that in cloudy days, can be higher than in crystalline cells and their temperature coefficient is smaller . Amorphous silicon is also a better light absorber than crystalline, so despite having low efficiency, the thin film is a competitive and promising technology. The first solar cells were of thin-film technology. They have been used since the 1980s in consumer electronics applications, such as calculators. In recent years it has also begun to be used in high power applications due to the characteristics mentioned above.

D. Other Cells And Materials

As was mention in the introduction of this chapter, there are other materials apart from silicon that can be used for manufacturing solar cells. These compounds are also thin-film deposited, so they have the same advantages as the silicon thin film solar cells but with a better efficiency. Among these compounds, two are already used in commercial solar cells. They are CIGS and CdTe. The efficiency is around 10-13% and it will rise in the following years as the technologies are improved. It is commonly said that thin film technology is the way to achieve the grid parity, i.e. the point at which the cost of generating electricity is equal, or cheaper than grid power .

E. PV Modules

are made from solar cells connected in series and parallel to obtain the desired current and voltage levels. Solar cells are encapsulated as they have to be weatherproofed and electric connections also have to be robust and corrosion free. The typical construction of a PV module can be seen in Figure [3].

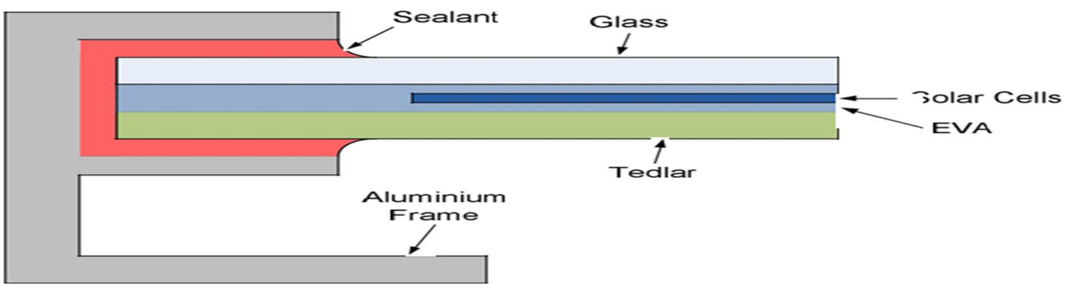

Figure 3. PV Module typical construction.

IV. MAXIMUM POWER POINT TRACKING ALGORITHMS

As was previously explained, MPPT algorithms are necessary in PV applications because the MPP of a solar panel varies with the irradiation and temperature, so the use of MPPT algorithms is required in order to obtain the maximum power from a solar array. Over the past decades many methods to find the MPP have been developed and published. These techniques differ in many aspects such as required sensors, complexity, cost, range of effectiveness, convergence speed, correct tracking when irradiation and/or temperature change, hardware needed for the implementation or popularity. Among these techniques, the P&O and the InCond algorithms are the most common. These techniques have the advantage of an easy implementation but they also have drawbacks, as will be shown later. Most of these methods yield a local maximum and some, like the fractional open circuit voltage or short circuit current, give an approximated MPP, not the exact one. In normal conditions the V-P curve has only one maximum, so it is not a problem. However, if the PV array is partially shaded, there are multiple maxima in these curves. In order to relieve this problem, some algorithms have been implemented as in . In the next section the most popular MPPT techniques are discussed.

A. Hill-Climbing Techniques

Both P&O and InCond algorithms are based on the “hill-climbing” principle, which consists of moving the operation point of the PV array in the direction in which power increases .Hill-climbing techniques are the most popular MPPT methods due to their ease of implementation and good performance when the irradiation is constant . The advantages of both methods are the simplicity and low computational.

1) *Perturb and Observe:* The P&O algorithm is also called "hill-climbing", but both names refer to the same algorithm depending on how it is implemented. Hill-climbing involves a perturbation on the duty cycle of the power converter and P&O a perturbation in the operating voltage of the DC link between the PV array and the power converter . In the case of the Hill-climbing, perturbing the duty cycle of the power converter implies modifying the voltage of the DC link between the PV array and the power converter, so both names refer to the same technique. In this method, the sign of the last perturbation and the sign of the last increment in the power are used to decide what the next perturbation should be. On the left of the MPP incrementing the voltage increases the power whereas on the right decrementing the voltage increases the power. This problem is common also to the InCond method, as was mention earlier. A scheme of the algorithm is shown in Figure [4].

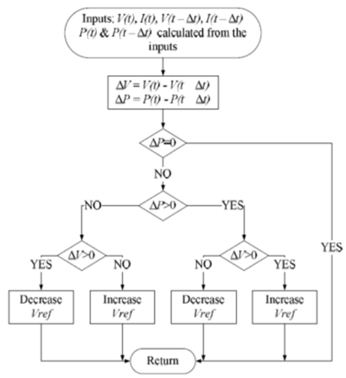

Figure 4. The flowchart of the P&O Algorithm.

2) *Incremental Conductance:* The incremental conductance algorithm is based on the fact that the slope of the curve power vs. voltage (current) of the PV module is zero at the MPP, positive (negative) on the left of it and negative (positive) on the right, as can be seen in Figure 11:

$V\ P = 0$ ($I\ P = 0$) at the MPP $V\ P > 0$ ($I\ P < 0$) on the left $V\ P < 0$ ($I\ P > 0$)
on the right

By comparing the increment of the power vs. the increment of the voltage (current) between two consecutives samples, the change in the MPP voltage can be determined. A scheme of the algorithm is shown in Figure 5.

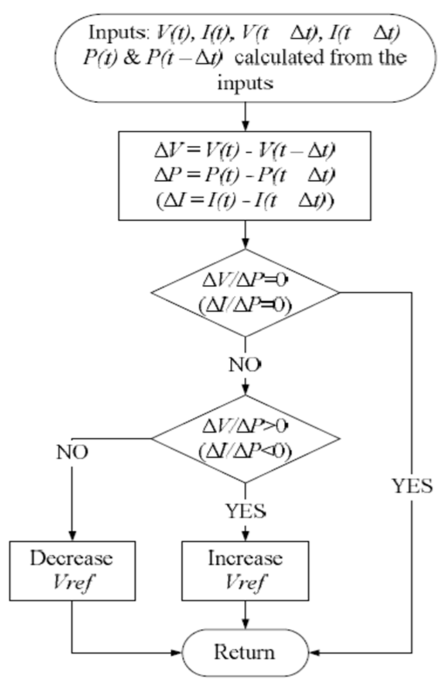

Figure 5. Incremental Conductance algorithm.

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V. MAXIMUM POWER POINT TRACKING ALGORITHMS EFFICIENCY TESTS

A. Simulation Model

One of the objectives of this thesis is to develop a model to test the dynamic performance of different MPPT algorithms independently of the converter used. Detailed models of the PV system with the switching model of the power converter are computationally very heavy and the time that can be simulated in a normal computer is only a few seconds. However the simulation time required for testing the system with the irradiation profiles proposed in [9] can be up to several minutes, which can be difficult or impossible to achieve on a PC, if a complete model of the PV system is used, because the computer runs out of memory after some seconds are simulated.The model proposed here was developed in Matlab®/Simulink® and consists of a model of the PV array, the DC-link capacitor and a controlled current source, which replaces the power converter. The MPPT Control block generates the reference voltage using the MPPT algorithm under test. This model is depicted Shown Fig[6].

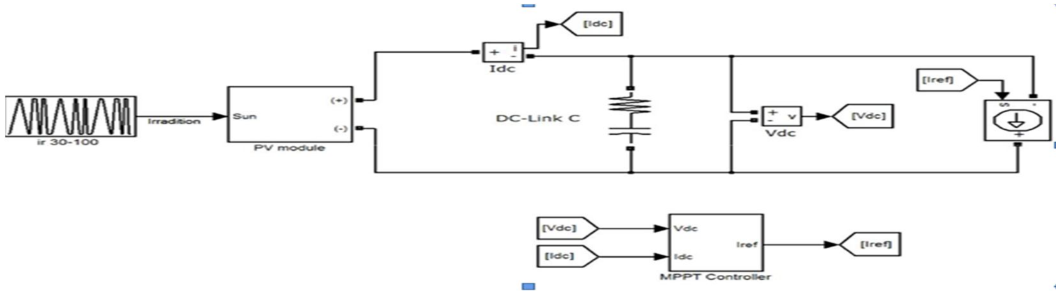

Figure 6. Model used for simulations

The reference voltage generated by the MPPT Control block is shown in Figure [7].

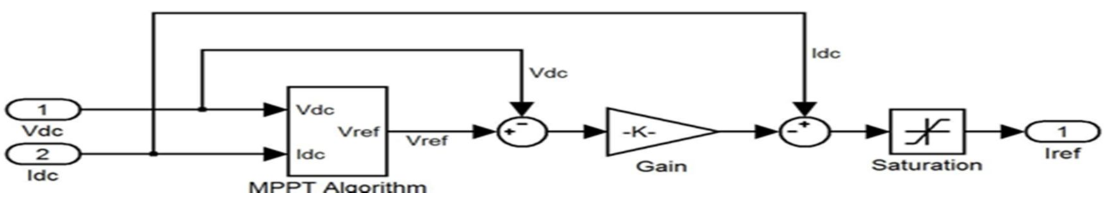

Figure 7. MPPT Controller.

B. Perturb And Observe

The algorithm shown in Figure 12 is implemented in the MPPT Algorithm block shown in Figure 7. Two different rates of change of the reference voltage (V_{ref}) are considered. The first slope has a gradient of 20 $W/m^2/s$ and the second one of 100 $W/m^2/s$. Figure 19 illustrates the results of the test.

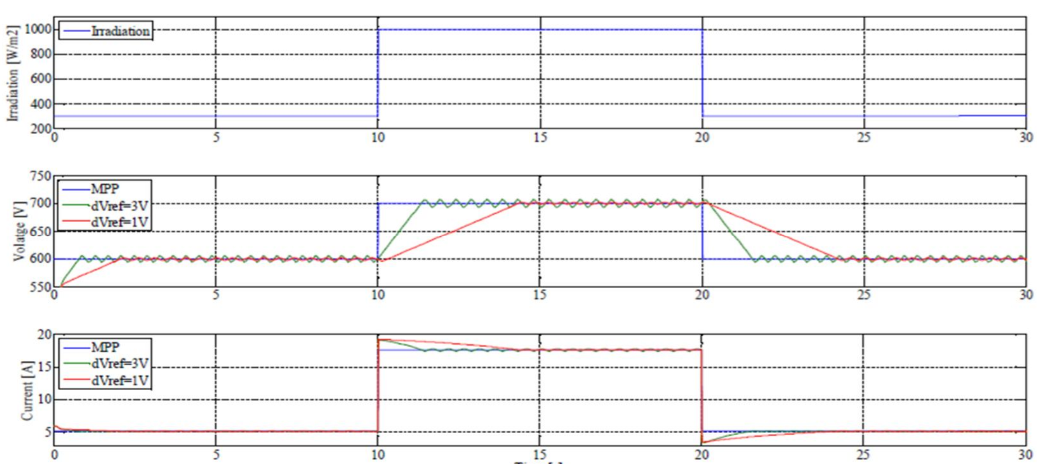

Figure 8. Performance of the P&O original algorithm under slopes of 20 and 100 $W/m^2/s$. The MPP values are shown in blue whereas the real values corresponding to the two cases studied, V_{ref} set to 3 and 1 V, are shown in green and red respectively.

C. Modified Algorithms

From the results of the previous tests under irradiation slopes, it is obvious that with both algorithms the voltage from the PV panel is far from the MPP voltage. Moreover, the algorithms may even move the DC voltage in the wrong direction. Interestingly, the current tracks closely the MPP current and in the correct direction. The same can be said about the power, as can be seen in Figure 9. The new flowchart is depicted in Figure 10.

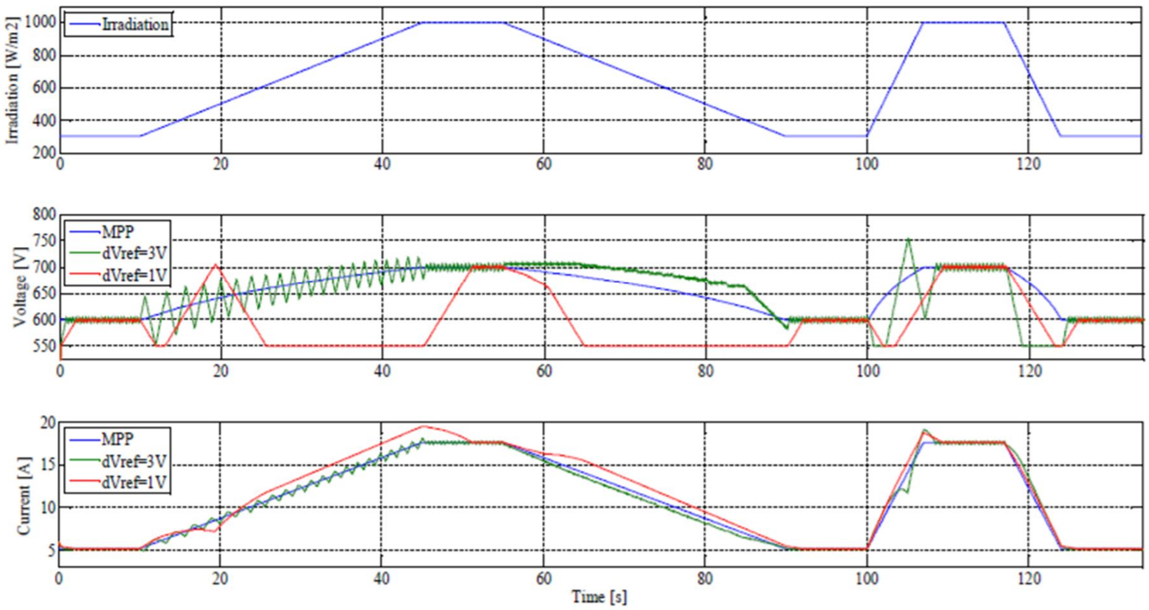

Figure 9. Voltage, current and power under irradiation ramps.

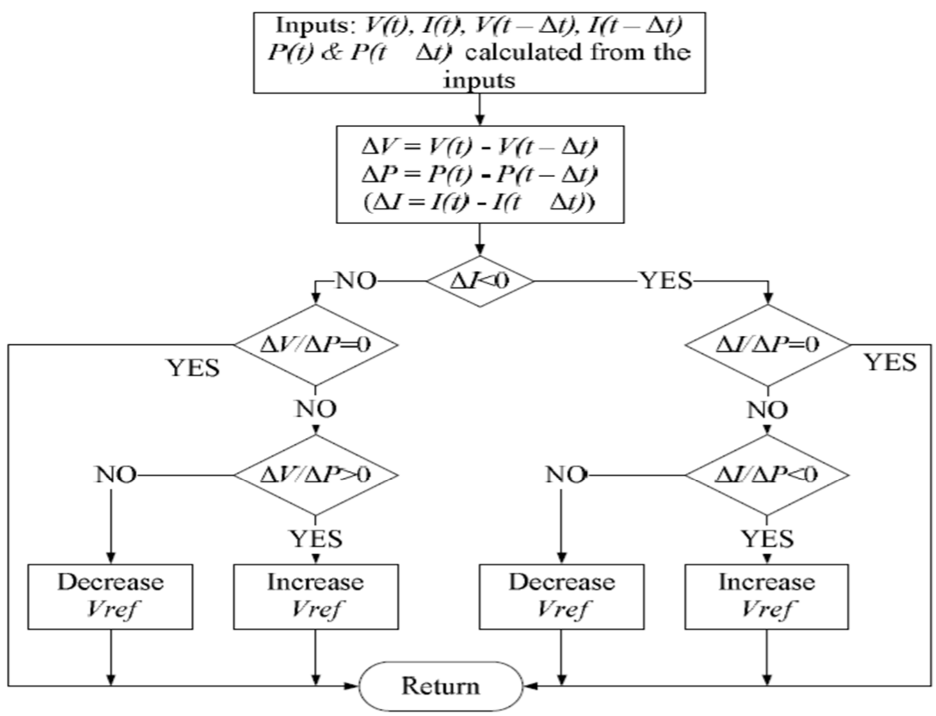

Fig. 10 New flowchart of the InCond algorithm.

VI. RESULTS AND DISCUSSION

A. Results Comparison

Comparing the performances of the different algorithms considered in this chapter, it can be said that the best results have been obtained with the modified InCond and P&O methods. The dynamic efficiency when using the irradiation slopes in Table III is over 99.4%. Furthermore, the P&O and InCond algorithms track the MPP under all ramps in Table II with even better efficiencies, as seen in Figure [11]. The efficiency was 99.6531% and the irradiance varied from 100 to 500 W/m^2 following a slope with a gradient of 1 W/m^2/s. In contrast, using the FLC the efficiencies are good with the slopes from Table III but when the gradients are smaller, then the tracking gets bad because the controller does not detect the change in the irradiation and the reference voltage is kept constant. This leads to a severe drop in the power obtained from the PV array because the MPP is not tracked. Another disadvantage of the FLC is that it is more difficult to tune because all MFs have to be customized for the PV array used in the system. The efficiency of the controller depends greatly on designer's expertise in proposing a suitable FIS for the FLC. The reason is that there are no general rules how to select the MFs or which error should be chosen. In contrast, in the case of the modified hill-climbing techniques, the design steps are well defined.

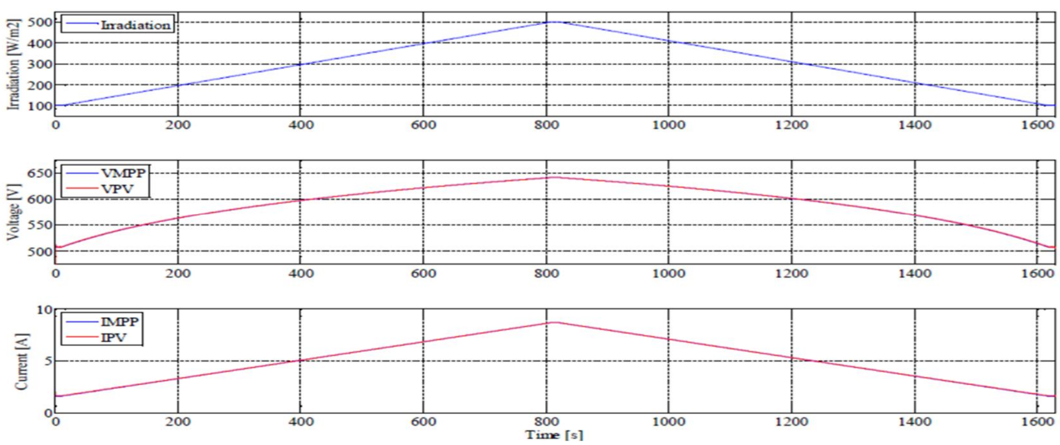

Figure 11 . MPPT tracking with a slope of 1 W/m^2/s from 100 to 500 W/m^2 and the InCond algorithm in the core of the modified scheme

VII. CONCLUSIONS

In this thesis, most of the MPPT algorithms which can find the real MPP were reviewed. For simplicity and effectiveness reasons, P&O and InCond were selected for further analysis. Their performance and dynamic MPPT efficiencies were studied according to the European Standard EN 50530. The tests confirmed the problems of P&O and InCond algorithms as reported in the literature. For testing purposes, a simplified model of the PV system was developed. In this model, the power converter was replaced with a controlled current source. This allowed long enough simulations so that the dynamic MPPT efficiency can be tested. Modifications to the traditional P&O and InCond algorithms were proposed, which allow the hill-climbing algorithms to track the MPP even under changing irradiation and adapt the increment in the reference voltage to the operating point, as the variation of the MPP voltage is not linear. The dynamic efficiency measured according the standard was above 99.4 %. After, taking into account all the results, it can be concluded that the best algorithm is the modified P&O. Its dynamic MPPT efficiency is similar to that of the modified InCond, but the P&O algorithm is simpler. The above conclusions are based on simulations and the reported results in the literature. No experimental validation could be done and that should be the next step to confirm the results from the simulations.

VIII. ACKNOWLEDGEMENT

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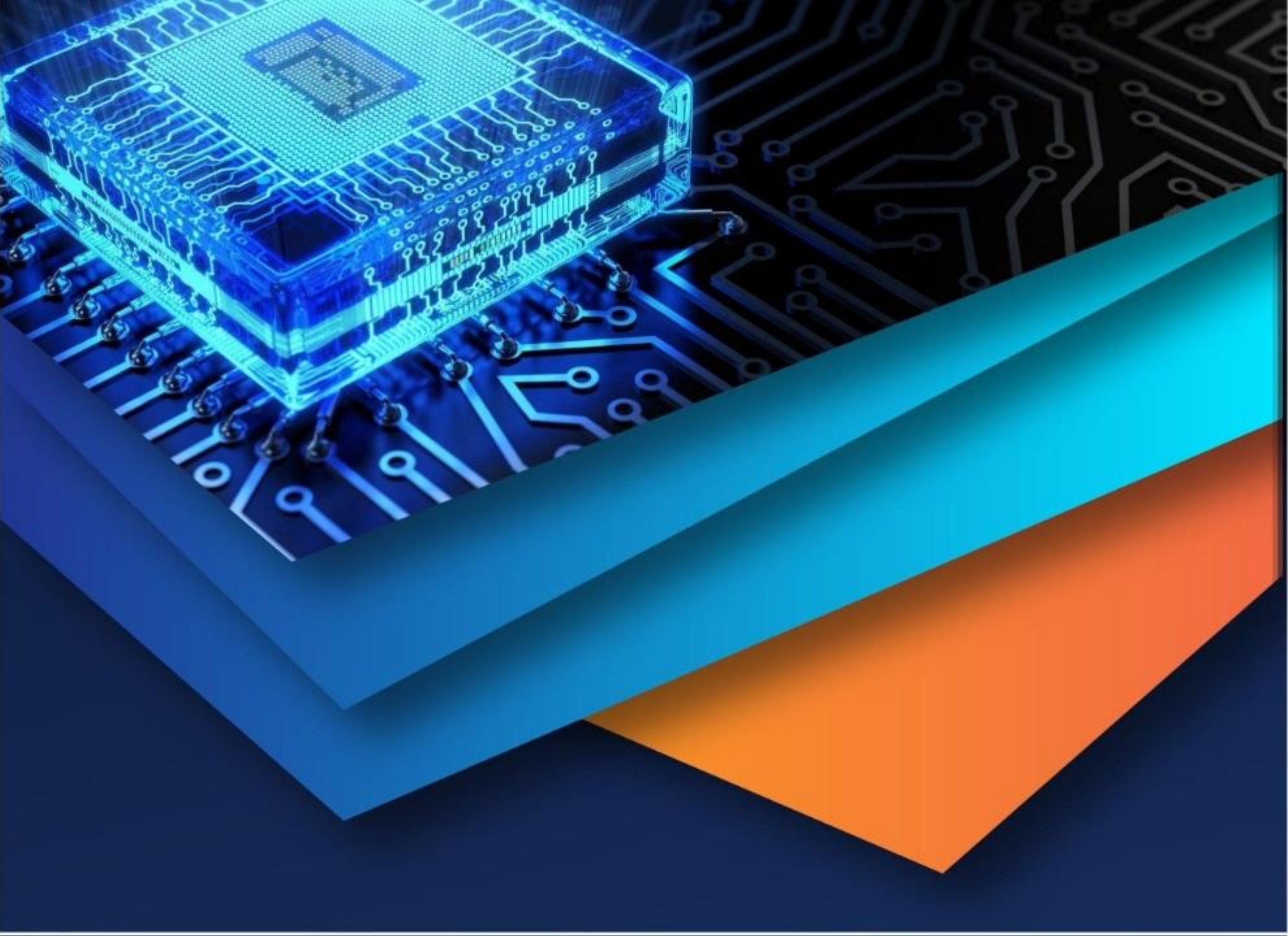

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