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MPPT and Effect of Partial Shading

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Abstract

This thesis presents the Maximum Power Point Tracking(MPPT) controller for solving partial shading problems in photovoltaic (PV) system. Initially the characteristics of the photovoltaic cell has been simulated along with various configurations of their connection and the effects due to the temperature has been considered. The phenomena of partial shading has been studied and simulations of different patterns of insolation have been done in MATLAB-Simulink in order to study the behavior of the PV array.

The boost converter in continuous and discontinuous mode (CCM/DCM) has been simulated. The converter is able to draw maximum power from the PV system for a given irradiation level by adjusting its duty cycle. A PV system is built in MATLAB-SimPowerSystem and the performance of the Perturbation and Observation (P&O) algorithm has been analyzed. It has shown the limits of its performance and the case in which it fails to track the MPP.

A review of the solutions about Partial Shading problem presented by the researchers so far has been performed. Two new algorithms have been proposed and developed in MATLAB-SimPowerSystem and the results are commented and compared with each other in terms of efficiency. The results are validated by testing the PV circuit in Real-Time Simulator Opal-RT.

Moreover, a general study about the PLL-Inverter has been done and it is developed in MATLAB-SimPowerSystem. The effectiveness of the solution proposed has been verified by the Real-Time Simulator Opal-RT.

1 Introduction

1.1 Introduction

The current levels of dependence on fossil fuels, carbon emissions associated with energy and the concerns about global warming yield to develop a new innovative technology sector, making photovoltaics increasingly attractive. Among the renawable energy resources, the Photovoltaic energy can be considered the most important due to the abundance and sustainability of solar radiant energy.

Photovoltaic cells offer numerous benefits:

- PV operates cleanly. There are no emissions associated with the use of solar cells. (There are environmental impacts from the manufacture of PV cells, but these are considered relatively small).
- Photovoltaics provide a highly reliable system. Once PV cells are in place and providing electricity, they are very low-cost and low maintenance.
- Modular PV panels can be used in a wide variety of sizes and configurations, as stand alone sources of electricity or connected to the grid in residential, commercial, or institutional building.
- Photovoltaics is increasingly cost-competitive with alternative sources of electricity, such as oil, natural gas, coal or nuclear, the PV costs are coming down rapidly.
- PV cells allow greater independence and freedom of choice. Individual users can generate power away from the electricity grid. Nations can reduce the need to import fuels to generate electricity.

1.2 Objective of the thesis:

- To develop detail model of PV cells including along with series parallel combination.
- Devolop the I-V & P-V characteristics and identify the maximum power point (MPP)
- Investigate the effect of PS and a Multi String PV array.
- Compare different algorithms for MPPT under Partial Shading (PS).
- Design and develop a full PV System with boost converter and an inverter for power transfer from DC to AC.

2 Characteristic of Photovoltaic cell

2.1 Introduction to a photovoltaic cell

A simple equivalent circuit of a photovoltaic cell is given from a current generator driven by sunlight in parallel with a diode [Figure 2.1].

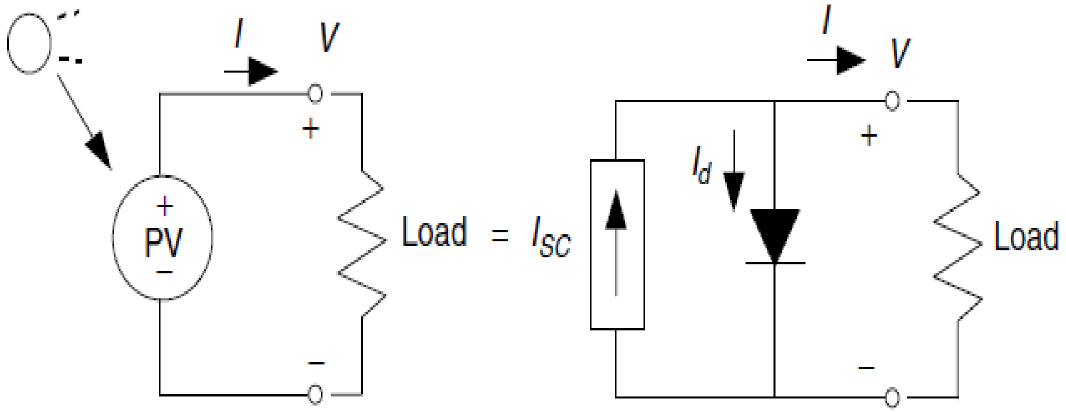


Figure 2.1

The most important parameters in a photovoltaic cell is the short circuit current (I_{SC}) and the voltage open circuit (V_{OC}) [Figure 2.2].

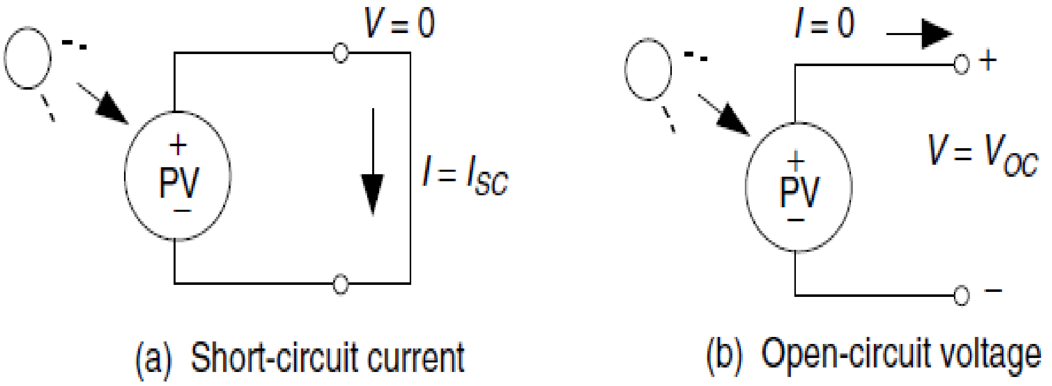


Figure 2.2

The I_{SC} is obtained by leaving the terminals of the PV cell shorted together and measuring the correspondent current, vice versa, the V_{OC} is the voltage measure across the cell when the terminals of the cell are kept disconnect.
It's obviously that I_{SC} represents the current generator and the V_{OC} the voltage across the diode when the all current I_{SC} flows through it.

The output current of the PC cell is given by the follow equation:

$$I = I_{SC} - I_d \tag{2.1}$$

and, substituting the equation of the diode

$$I = I_{SC} - I_0 \left(e^{\left(\frac{qV}{kT}\right)} - 1\right) \tag{2.2}$$

It is possible to derive the value of V_{OC} by the assumption of I=0.

$$V_{OC} = \frac{kT}{q} \ln\left(\frac{I_{SC}}{I_0} + 1\right) \tag{2.3}$$

We can note that a plot of the current cell is just the value of I_{SC} added to the diode curve turned upside-down.
The current I_{SC} is directly proportional to the value of insolation. As can be seen from the Figure 2.3, two curves of the characteristic of a cell are obtained in different condition of insolation, with light and dark [1].

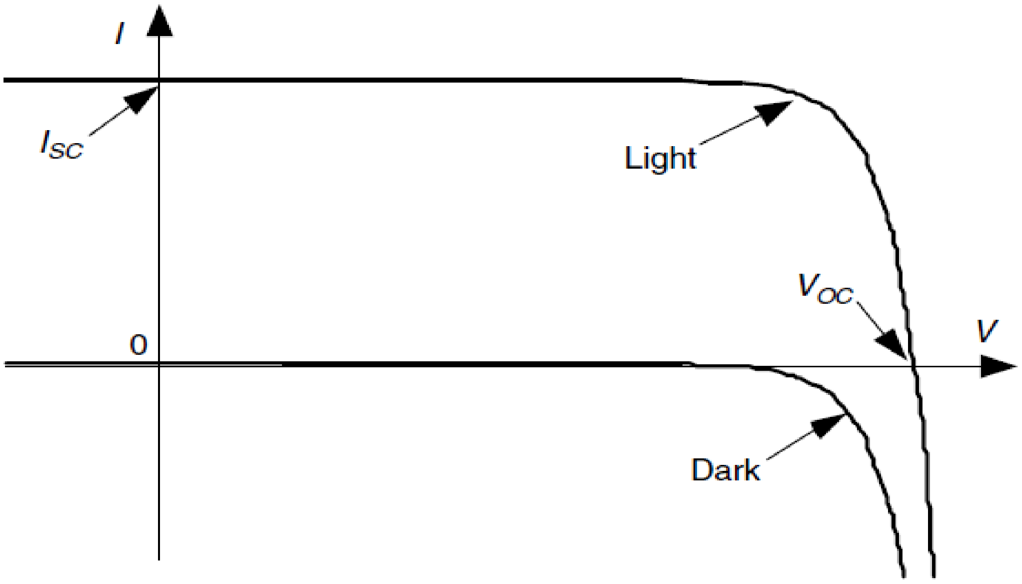


Figure 2.3 [1]

A more accurate circuit of a PV cell takes into account a parallel leakage resistance R_P (Figure 2.4). Therefore, the current of generator flows through the diode, the parallel resistance and the load

$$I = (I_{SC} - I_d) - \frac{V}{R_p} \tag{2.4}$$

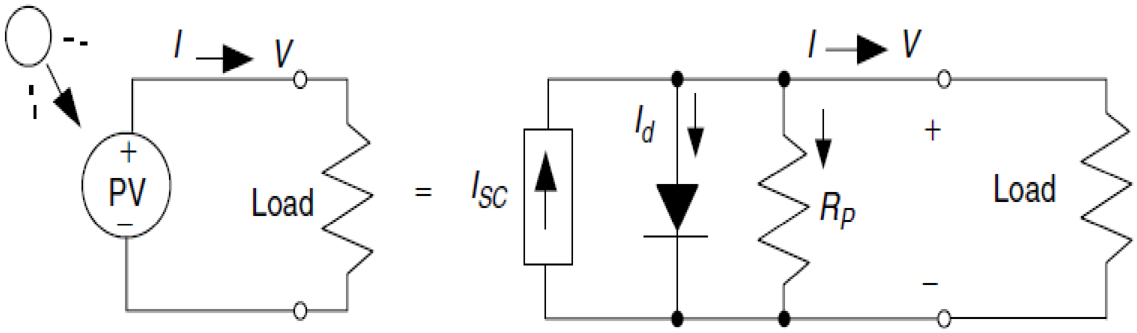


Figure 2.4

The influence of resistance R_P on the Current-Voltage characteristic can be seen from the following picture (Figure 2.5).

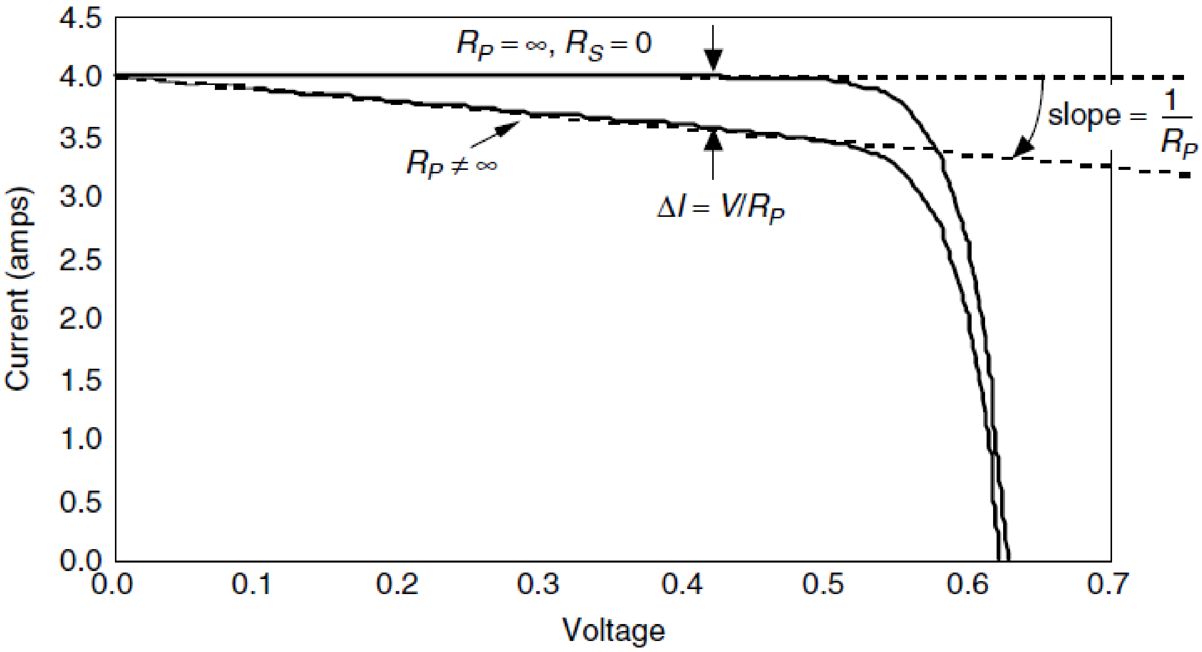


Figure 2.5

On the other hand, a better circuit model should take into account the effects of the contacts resistance associated with the bond, wires and the resistance of the semiconductor. These could be represented with a series resistance as shown in Figure 2.6, whose effects on the Current-Voltage characteristic are shown in Figure 2.7.

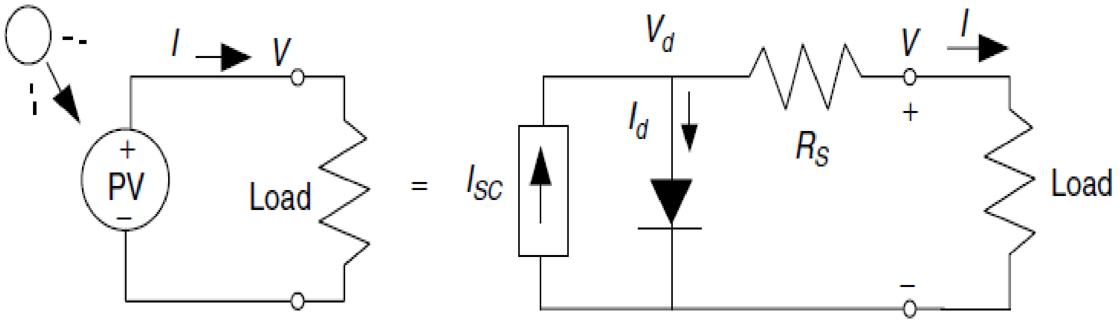


Figure 2.6

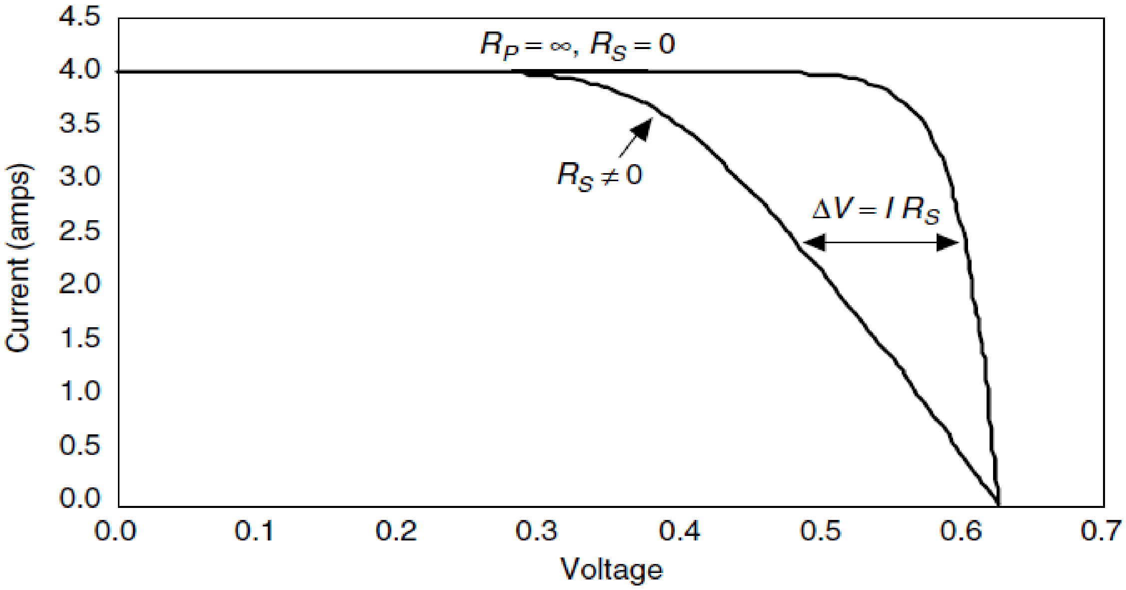


Figure 2.7

Therefore the equivalent electric circuit of PV cell is shown in Figure 2.8.

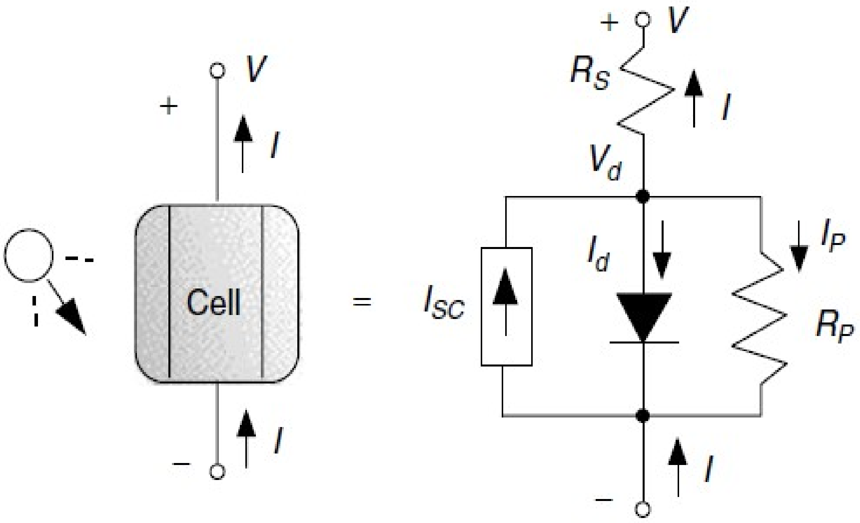


Figure 2.8

The behaviour of the cell, under the assumption of 25 °C, is ruled by the following equation:

$$I = I_{SC} - I_0\left(e^{(38.9V_d)} - 1\right) - \frac{v_d}{R_p} \tag{2.5}$$

2.2 Series and parallel connection of cells

Moreover, the application in which the solar cells are used, required to work with high value of voltage. Since the voltage produces by a single cell is around 0.5 Volt, it becomes obviously that we have to organise the cells in module, which cells are connected together in order to reach an acceptable value of voltage, 12 Volt or 24 Volt for the most common application (Figure 2.9). Such combination of modules connected in series is called string and the parallel connection of string which composes the whole PV panel is called array (Figure 2.10).

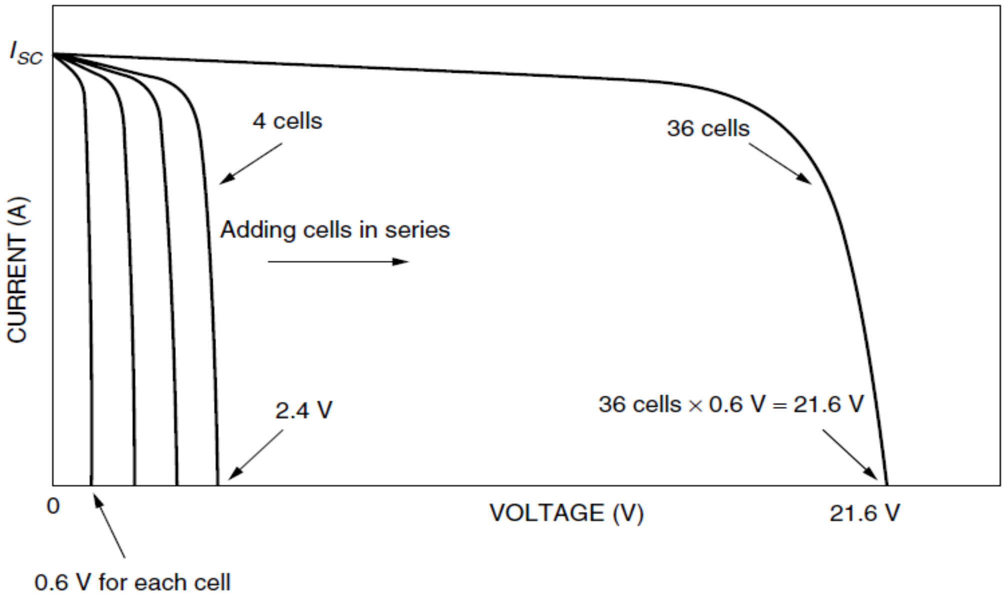


Figure 2.9

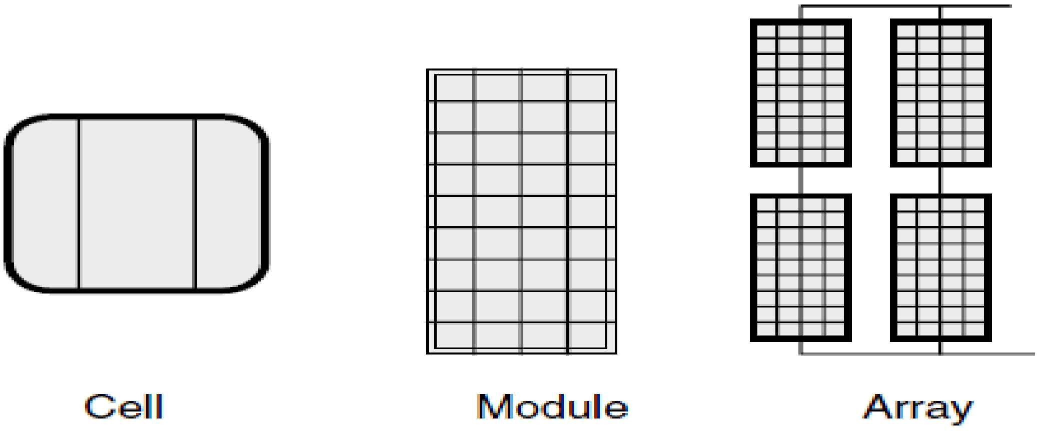


Figure 2.10

To increase the voltage and the current of the photovoltaic system, multiple modules are wired together in series and parallel to reach the exact value of voltage and power that are required. The modules connected in series increase the voltage of the whole system, and the parallel connection increases the current delivered (Figure 2.11 and 2.12) .

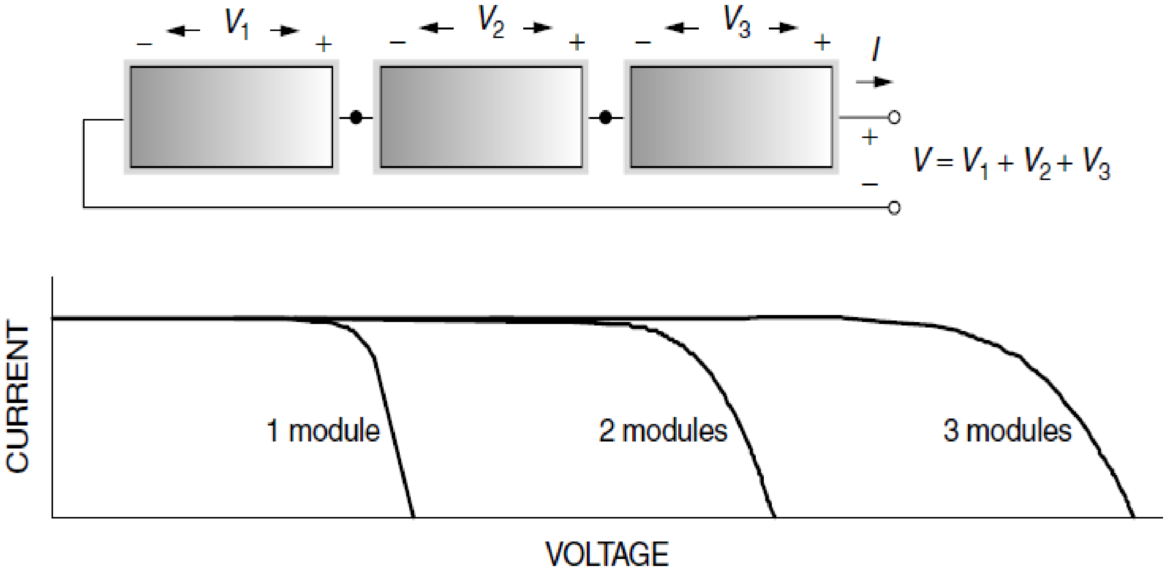


Figure 2.11

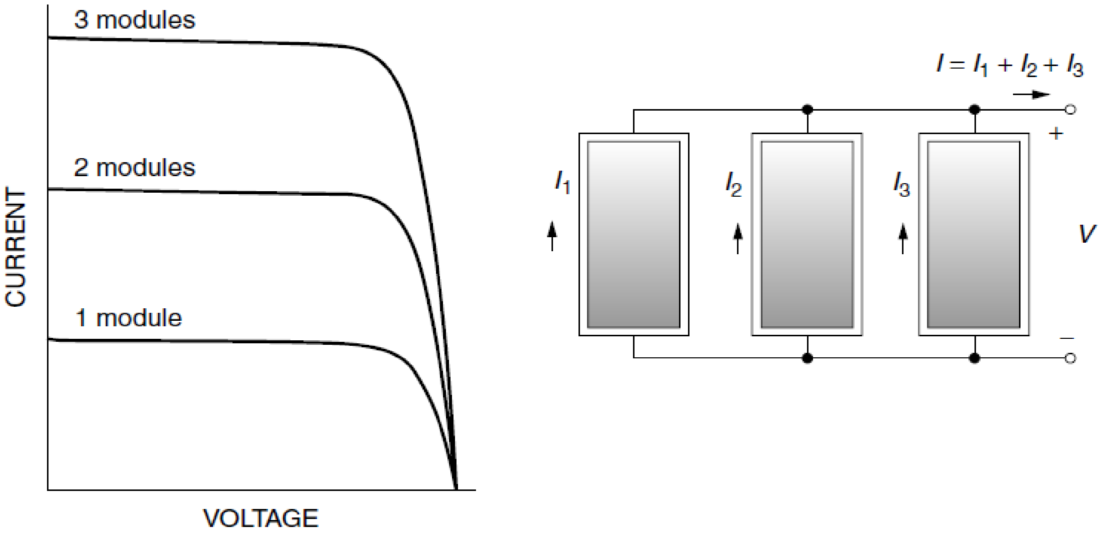


Figure 2.12

If the only constraint is the value of power, it is preferable to connect the modules in parallel instead of series. The reason is because if an entire string is removed from service for maintenance or other reason, the overall current will decrease but the system can still deliver energy, which is not the case all the modules are connected in series.

One of the main interesting factor about a PV panel is the power that it can deliver. As we can see, when the terminals are left either disconnected or shorted together, the current or the voltage are zero and thus, the power delivered results to be zero. When a load is connected to the panel, some combination of current and voltage will result and the power will be delivered.

In Figure 2.13 is shown the Current-Voltage and Power-Voltage curves of a generic photovoltaic panel.

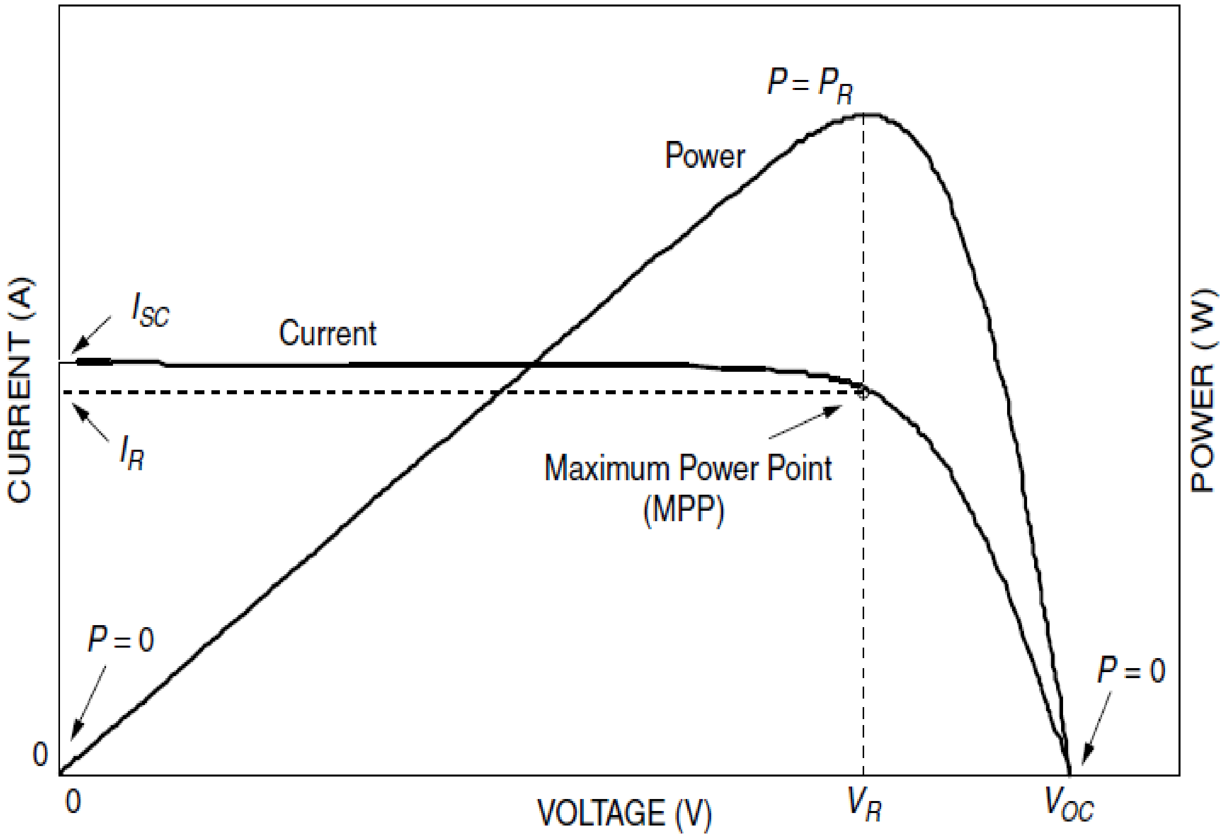


Figure 2.13

The maximum power point (MPP) is the point in which the product of current and voltage results to be maximum, the spot near the knee of the Current-Voltage curve. In the MPP the voltage and current are design as Vm and Im.

Another method is used to find out what is the maximum power point. It corresponds to maximize the rectangle that could fit better inside the I-V curve (Figure 2.14).

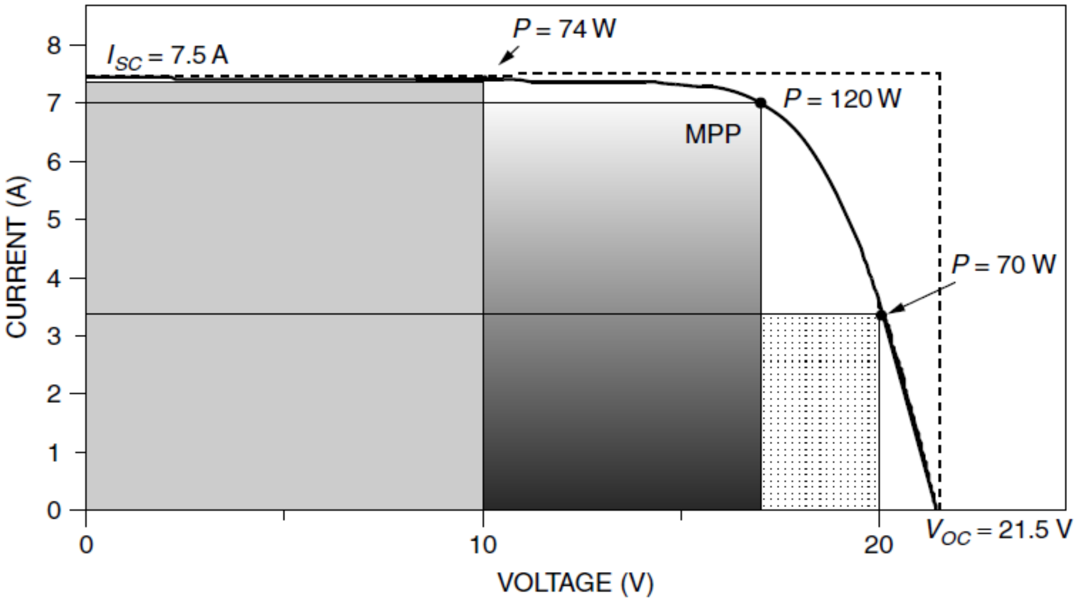


Figure 2.14

The intersection between the sides and the axes determine the value of current and voltage that characterize the rectangle and thus, its area is the power delivered by the PV panel.
In this contest its important the fill factor (FF) which gives the ratio between power extracted from the panel and the power given by the multiplication between Voc and Isc.

$$Fill\ factor\,(FF) = \frac{Power\ at\ the\ maximum\ power\ point}{V_{OC} I_{SC}} = \frac{V_R I_R}{V_{OC} I_{SC}} \qquad (2.6)$$

The I-V curve as well as the P-V curves are effected of several parameters such as insolation, temperature and so on. Therefore it becomes important to find a way to compare the performance of different PV panels. A set of condition has been established in order to let to make fair comparison.
The test is called “Standard Test Condition” (STC) and is characterize by the following parameters:

- solar insolation 1kW/m^2
- air mass of 1.5 (AM 1.5)
- cell temperature 25 °C

2.3 Effects of temperature and insolation on I-V curves

As we can see in Figure 2.15, the temperature and insolation change the characteristic I-V of a photovoltaic panel.

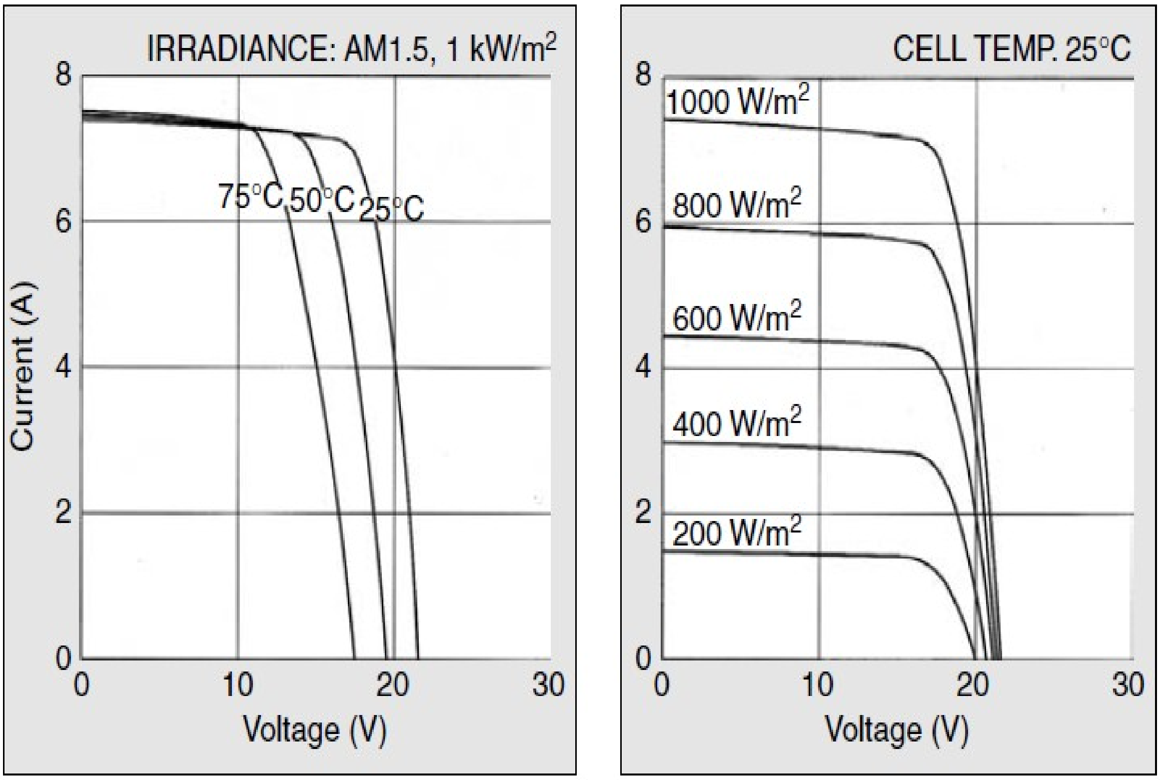


Figure 2.15

If the insolation drops down, the short circuit current will be decreased in direct proportion. It means that if the insolation will be decrease in half, the short circuit current will be cut in half. Its effects influence also the open circuit voltage which will decrease but following logarithm equation, and its changes will be very modest.

In Figure 2.15 can also be seen the effects of the temperature on the PV module. As the temperature increase, the voltage open circuit will decrease substantially and the short circuit current will slightly increase. Therefore, when the temperature increases the MPP will move toward left and thus, the power extract from the PV module will be less.

Hence, a PV module results to perform better on cold and clear days then in hot ones.

However, the cell's temperature is not only due to the temperature of environment in which the cell is placed. Just a small part of the insolation that hit a cell will effectively convert in current, the other part will contribute to increase the overall temperature of the PV cell. Therefore, the manufactures provides a indicator NOCT that help the designers to take into account the effects of the temperature.

The term NOCT stands for “nominal operating cell temperature” and represents the cell temperature in a module when ambient is 20 °C, solar irradiation is 0.8 kW/m^2 and wind speed is 1 m/s. It's also provide a formula that help the designers of circuits to take into account the effects of the factors on the overall cell's temperature:

$$T_{cell}=T_{amb}+\left(\frac{NOCT-20^{o}}{0.8}\right)S \tag{2.6}$$

where “T_{cell}” is cell temperature °C, “T_{amb}” is ambient temperature °C and “S” is solar insolation (kW/m^2).

3 Partial Shading

3.1 Partial Shading condition

One of the most important aspects in photovoltaic field is the behaviour of the PV system under partial shading condition. It's possible to distinguish two kind of partial shading [2]:

- near shadings
- far shadings

In the "far partial shadings" the obstacles is sufficiently far for considering that it acts globally on the PV panel (Figure 4.1).
In the other case, the near shadings is due to near objects which produce visible shading on the PV system. It could be get shaded by passing clouds, neighbouring buildings and towers, trees, and utility and telephone poles.
The overall I-V characteristic of an array is given by adding the voltage of the modules connected in series and the current of the strings connected in parallel. Thus, when one or more modules are shaded the characteristic change its shape due to the different value of currents and voltages provided by the modules.
It is useful to compare the characteristic at the Maximum Power Point of an array under normal insolation and under partial shading condition. To do this, a full determination of the I-V characteristic is required, including negative voltages. For this quadrant it is supposed that the current increase quadratic moving towards higher negative voltage, until the diode Zener avalanche reach its breakdown value. In a real case this point it will never reach because the cell is destroyed by the temperature due to the power consumption. Anyway the model is sufficiently accurate to study the behaviour of the array under partial shaded condition.

3.2 HOT SPOT and BY-PASS DIODE

In Figure 3.1 is reported the case of 1 cell shaded at 80%, so its I_{SC} is 20% of the short circuit current of a cell under normal insolation. The dotted line represents the characteristic of the others 35 cells under normal insolation The reverse characteristic of the shaded cell starts from the value of I_{SC} current and it increases quadratically with the reverse voltage due to the energy absorbed from the external circuit.
As it can be seen, the shaded cell absorbs the power produced by the other cells in the module and it effects in a negative way the overall characteristic of the module.
The resulting I-V curve for the module will be the sum of the voltages of each cell. The short circuit current of the module is measured and its temperature reach about 127 °C. The power results to decrease dramatically and the efficiency of the overall module is going down.

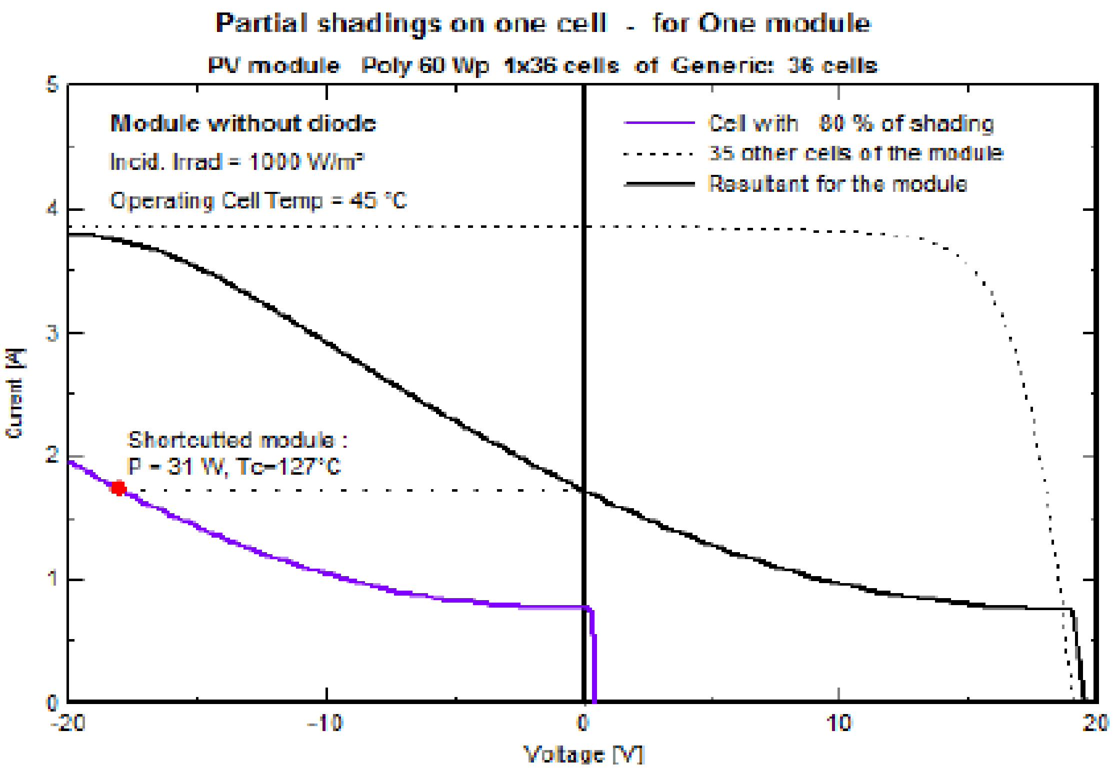


Figure 3.1

When the cell is integrated in a string (Figure 3.2), the unshaded cells try to increase the current of the whole series and thus, the current will flow through the leakage resistance in parallel of the shaded cell. Therefore, in the case of high value of current, it could lead to a high temperature of the shaded cell with the creation of the phenomena called “hot spot” and the destruction of the module.

In order to avoid that condition, the manufactures have to put a by-pass diode in parallel to each module which will derive the current when the voltage becomes negative (Figure 3.5). The function of the diode is to limit the energy dissipated on the shaded module.

In the picture (Figure 3.3) is shown the same condition treated before with a by-pass diode added to each sub-modules. In this case, the power consumption across each module results to be too high and thus it needs to split the module in two sub-module in which a by-pass diode is added. Therefore the consumption of power will reduce from 31W in the case of one diode for each module to 10W for a diode for each sub-modules.

The case represented in picture (Figure 3.1) is a worst case in which just one module is shaded along the whole string. If more modules are shaded in the same string, the consumption of power will be shared by the shaded modules and thus, decrease the stress of the shaded modules.

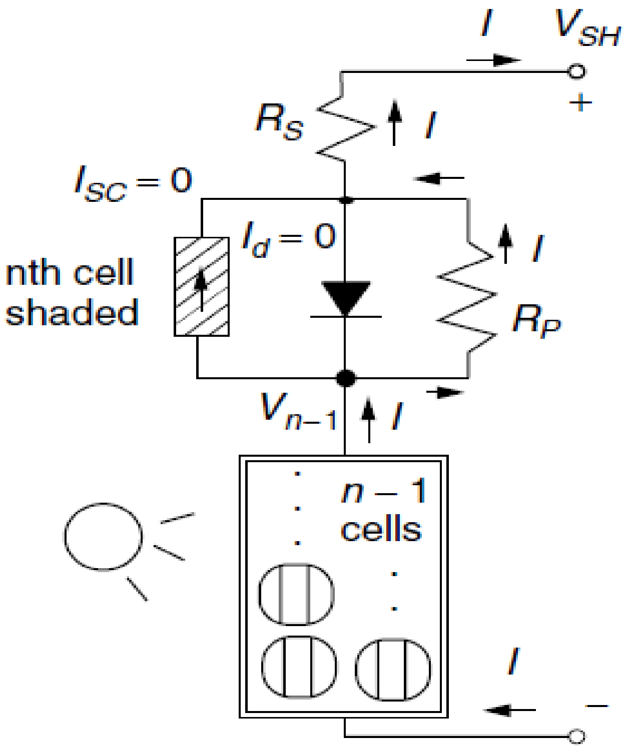


Figure 3.2

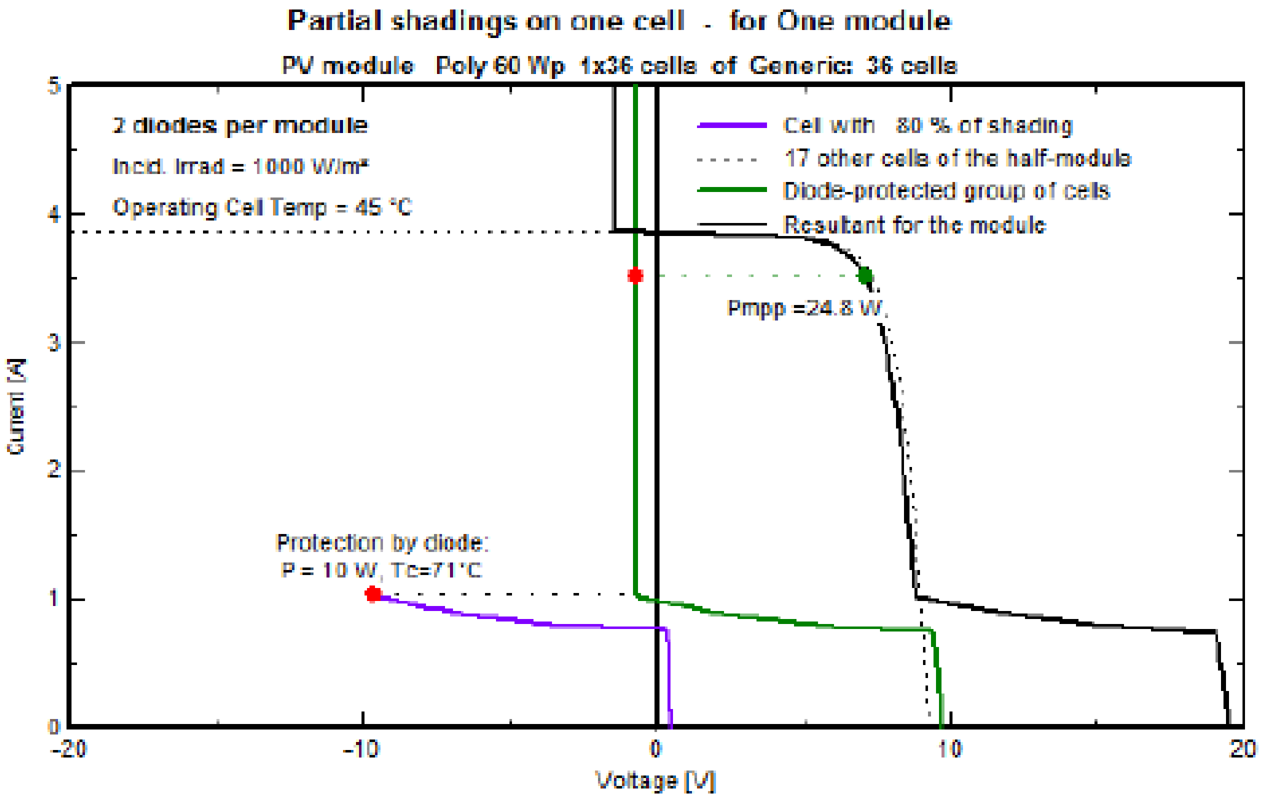


Figure 3.3

3.3 Evaluation of the consumption power of a shaded cell in an array

To understand how much the phenomena of partial shading can affect the performance of the whole PV system, a picture (Figure 3.4) is reported in which a loss due to one shaded cell is shown as function of the number of modules connected in series.

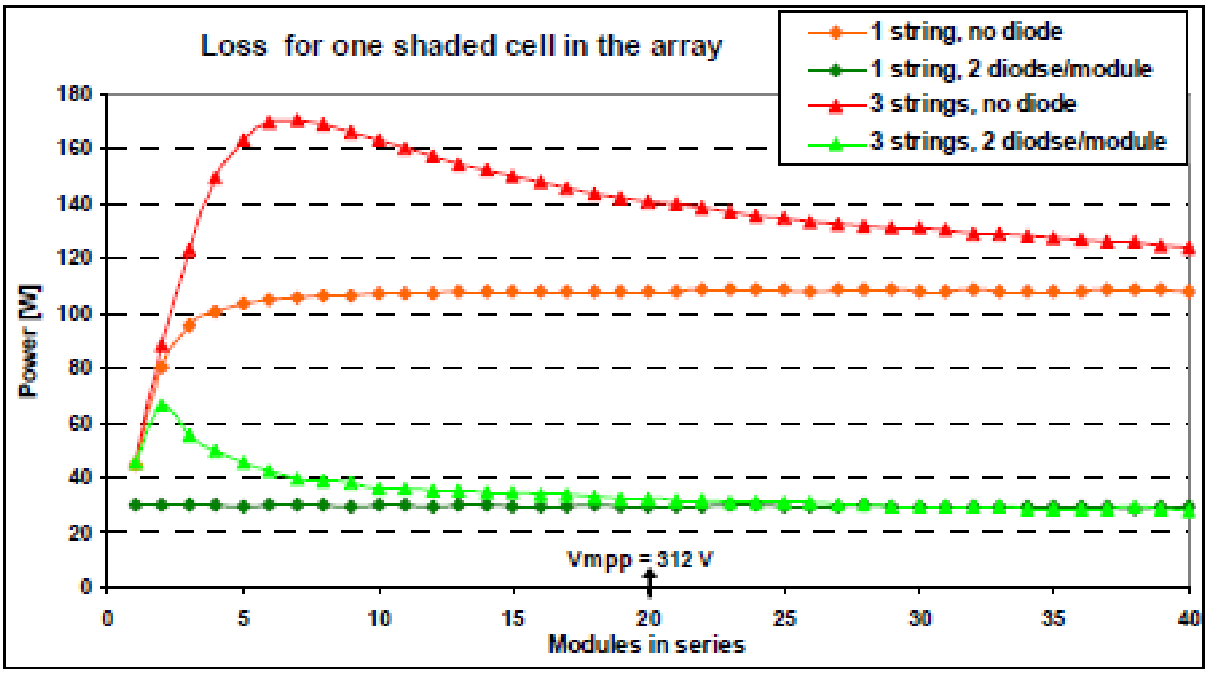


Figure 3.4

The experiment has been done with module that gives 55 W under uniform insolation (1000 W/m^2) and a temperature of 45 °C. The cell has been shaded for 85% and the results of the simulation shown that using the by-pass diode the loss would be much less than in other condition. In a PV system composed of several string connected in parallel, is common to add to each string a "blocking diode" (Figure 3.5). This diode is very important because its function is to avoid that, in circumstance of one or more modules of its string is shaded, the current of the other string will flow across the string affected by partial shading that generate less voltage.

The main effect of partial shading phenomena is that the P-V curve will have more local maximum, and thus, it becomes important to develop some techniques in order find the maximum point of power and let the system to extract the maximum power (Figure 3.6), which is the main objective of the thesis.

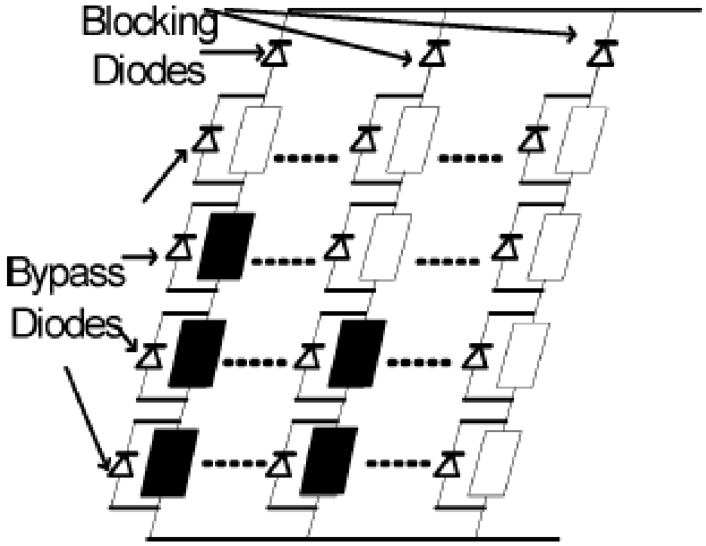


Figure 3.5

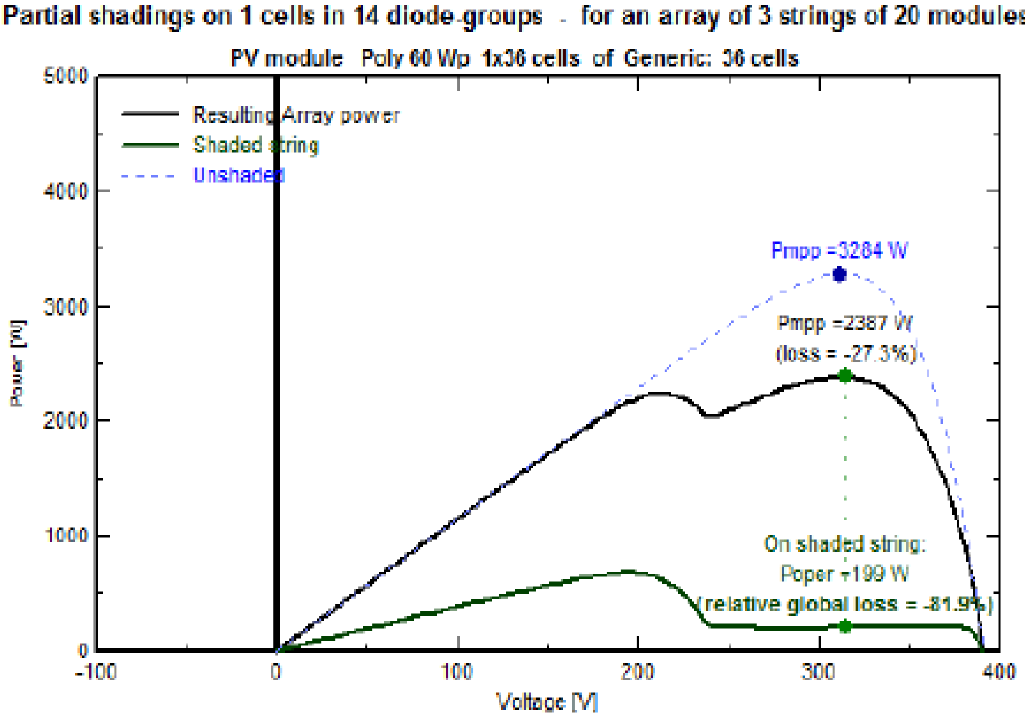


Figure 3.6

The shape of the P-V characteristic is due to several factors: size of the array, number of modules in series and parallel. In Figure 3.7 is reported the picture of an array with different value of insolation.

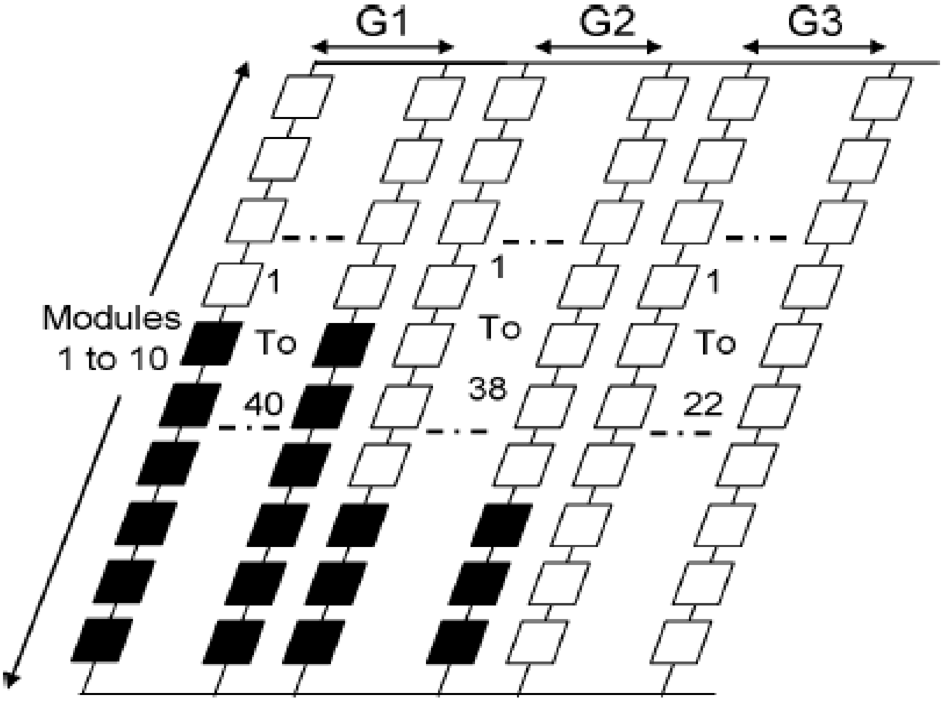


Figure 3.7

A “sub-assembly” is called a set of modules connected in series which receive the same value of insolation.
Several series-connected with different insolation form a “series assembly”. The “series assembly” with the same pattern of insolation, connected in parallel, form a “group”. In Figure 3.7 is possible to note the different groups which composed the array.
In [3] an experiment to study the effect of the shading pattern on the P-V output has been studied. Considering the array composed of three groups with different configuration (Figure 3.8), the results of the different curves has plotted in Figure 3.9.

Curve	G1			G2			G3			Array configuration
	U	S	N_S	U	S	N_S	U	S	N_S	
1	26	4	**3**	24	6	**5**	30	0	**2**	30 x **10**
2	21	4	**3**	19	6	**5**	25	0	**4**	25 x **12**
3	16	4	**3**	14	6	**5**	20	0	**7**	20 x **15**
4	11	4	**3**	9	6	**5**	15	0	**12**	15 x **20**
5	8	4	**3**	6	6	**5**	12	0	**17**	12 x **25**
6	6	4	**3**	4	6	**5**	10	0	**22**	10 x **30**

U: Number of unshaded modules in a series assembly; S: Number of shaded modules in a series assembly; N_S: Number of series assemblies in a group.

Figure 3.8

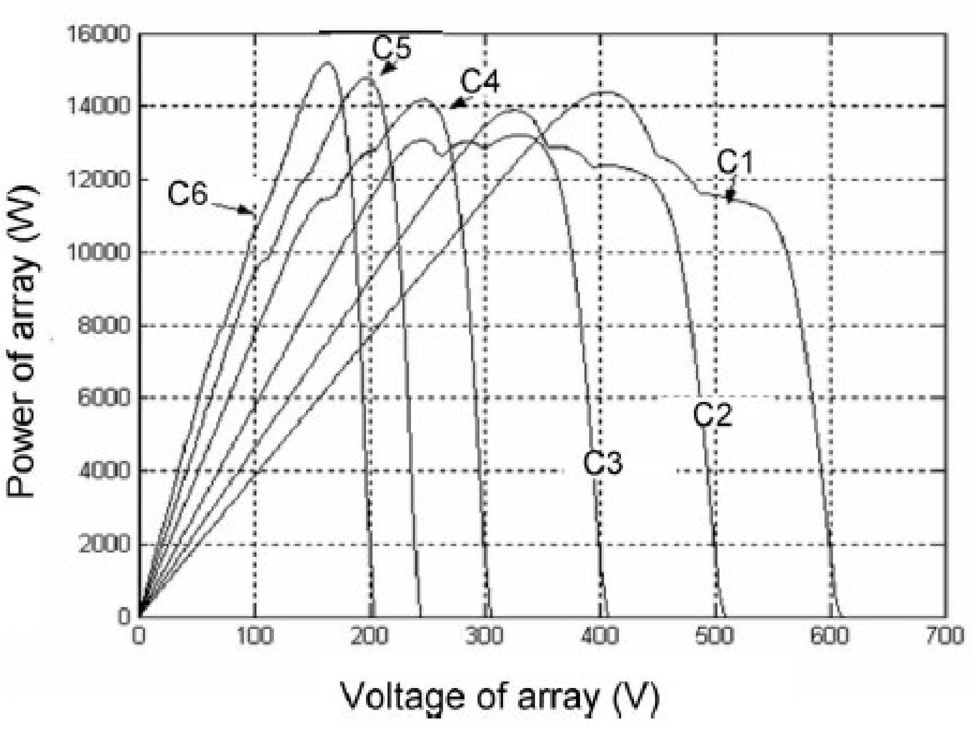


Figure 3.9

The Figure 3.9 shows that the peak of the power in non uniform insolation is dependent on the shading pattern of the array. In this case, the maximum power is obtained in the curve C6, which array is composed by 30 series assemblies, each with 10 series-connected modules. It means that it is preferable to use configuration of array with a lot of string connected in parallel with each string composed with few modules. On the other hand, another important consideration lies on the fact that the number of local maximum is equal to the number of different shading patterns on the PV array.

3.4 Simulation of PV panel using MATLAB-Simulink environment

If we consider the circuit shown in Figure 3.10, in which the PV panel is connected to a resistance, the operative point will be the intersection between the two characteristic. Remembering the equation of the resistor,

$$V = R \cdot I \qquad \text{or} \qquad I = \left(\frac{1}{R}\right) V \tag{3.1}$$

it means that, when it will be plotted on the I-V axes, it will result in straight line will slope 1/R (Figure 3.11).

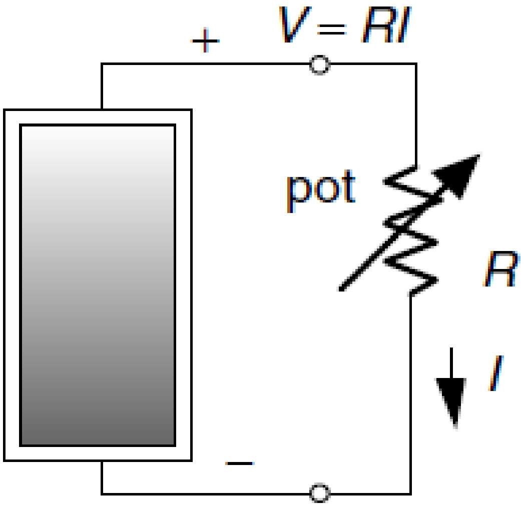


Figure 3.10

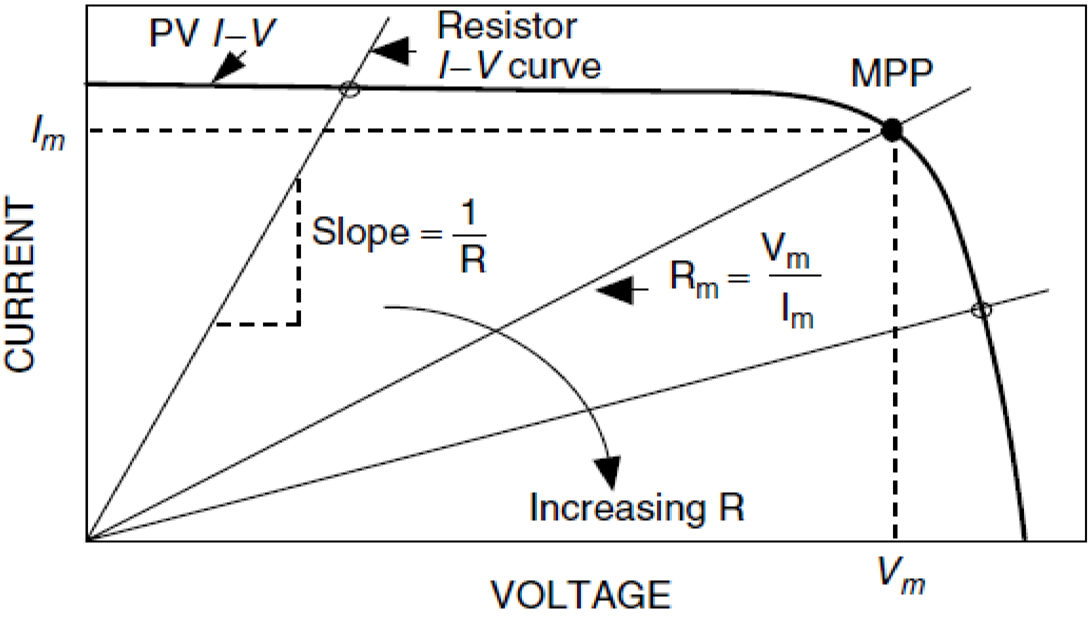


Figure 3.11

As can be seen in Figure 3.11, the operating point will move along the PV characteristic as the value of the resistance will change. Therefore, in order to scan the I-V characteristic of the array we need to connect the PV array to a potentiometer and change its value of resistance from zero to infinite.

The value of resistance R_m corresponds to the MPP where I_m and V_m stand for voltage and current at the maximum power point (MPP).

In Figure 3.12 is reported the picture about the circuit used to simulate the characteristic of the panel.

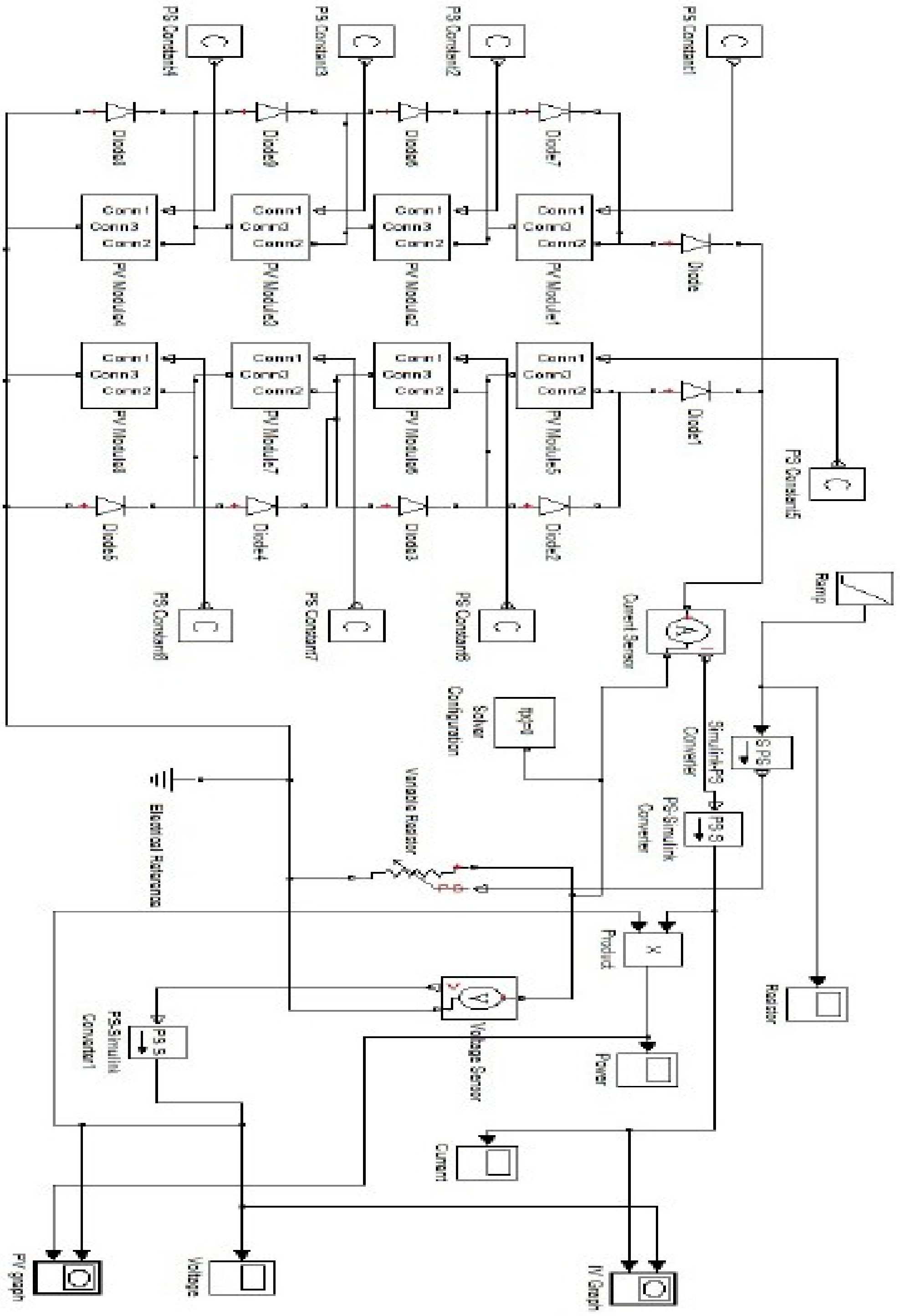


Figure 3.12

4 Maximum Power Point (MPP)

4.1 Characteristic of Maximum Power Point (MPP)

As can be seen, the maximum value of the power can change its position on the curve I-V and thus, the system needs to track the MPP under any operative condition of working in order to maintain a good efficiency. In Figure 4.1 is reported the effect of “far shading” in which the overall irradiation decreases uniformly. The operative point will move towards the left side as the insolation drop down.

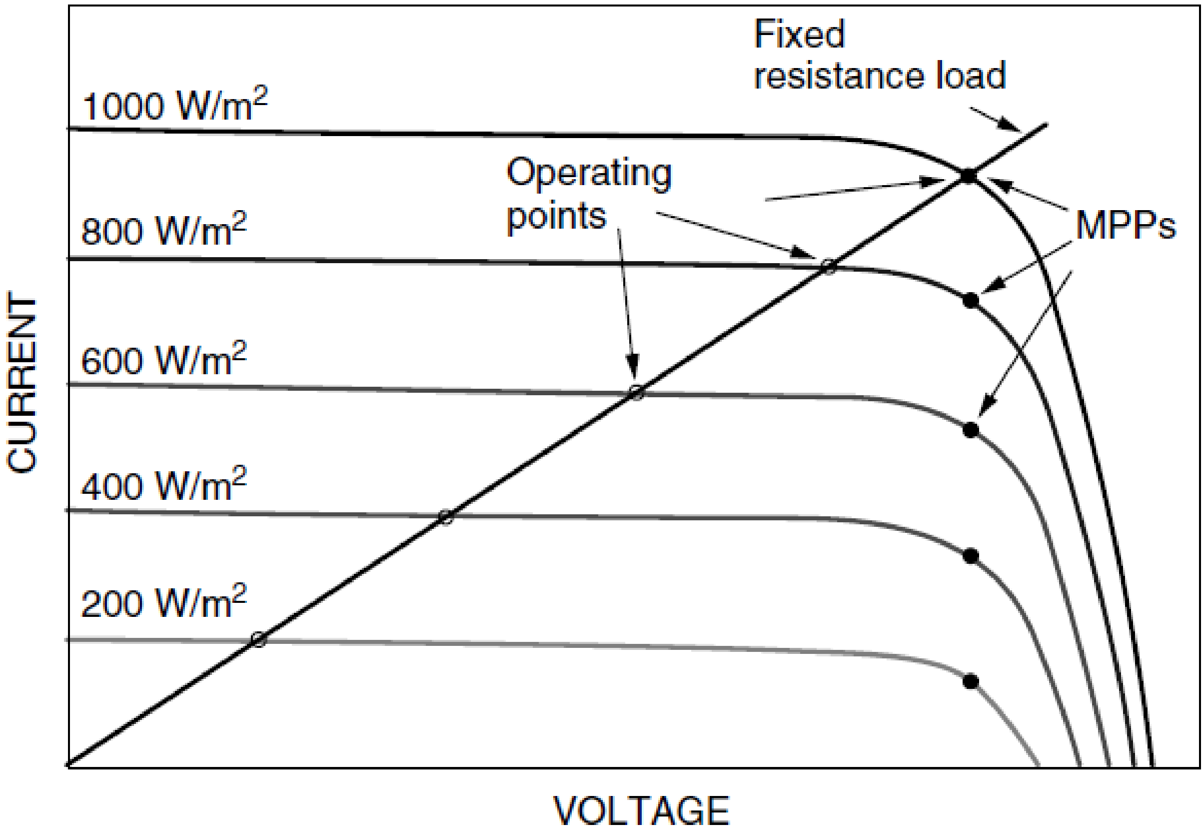


Figure 4.1

In this case, the P-V curve results to have just one local maximum which value decreases proportionally to the drop down of the insolation. On the other hand, in case of “near shading”, the P-V curve presents several local maximum and thus it could be not obviously for the system to detect and track the global one instead to be trapped in a local maximum.

4.2 Boost converter

The most commercial applications of the MPPT are implemented by using a boost converter (Figure 4.2). The MPPT block checks the voltage and current in output of the PV panel and then, it controls the duty cycle to find the MPP.

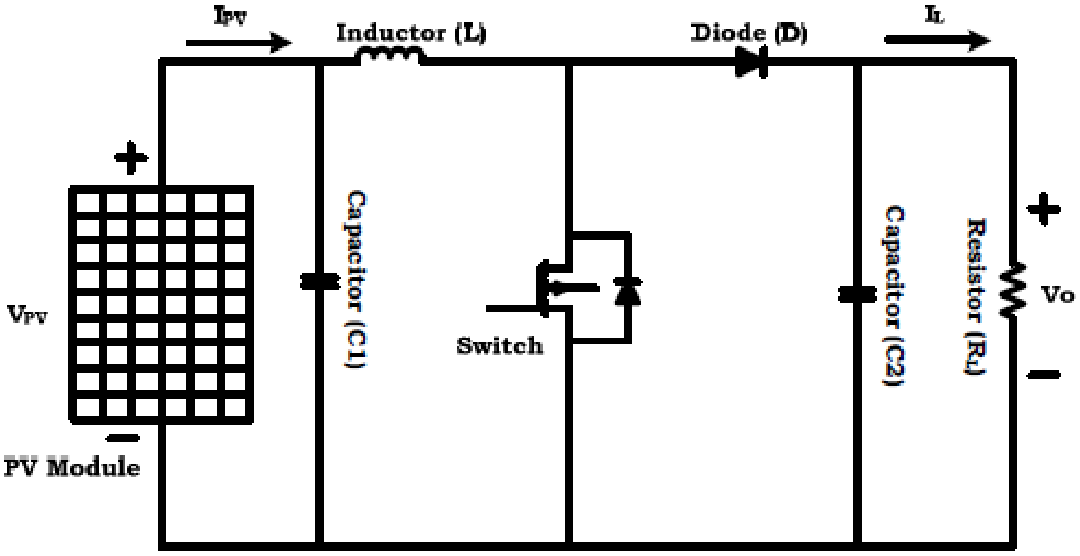


Figure 4.2

In order to understand how it works the circuits we have to analyse first the behaviour of the boost converter.

4.3 Boost Converter in continuous mode (CM)

For the analyzation we make the assumptions of ideal boost converter:

- U_i and U_o constant
- L and C ideals
- Switch and diode ideal
- Steady State working point

We can individualize two main phases:

Powering phase

In this phase the switch is closed. The diode will be reverse biased and all current will flow through the switch. The voltage in input of the boost will drop across the inductor, and current will start to raise according to the following equation:

$$i_L(t)=i_L(0)+\frac{1}{L}\int_0^t u_L(\tau)\partial\tau=I_{Lmin}+\frac{U_i}{L}t \tag{4.1}$$

In such phase the amplitude of the current in the inductor results to be:

$$\Delta I_{Lon} = \frac{U_i}{L} t_{on} = \frac{U_i}{f_S L} \delta \tag{4.2}$$

Free-wheeling phase

In this phase the switching is open, the current will force the diode to be in "conduction mode" and thus the current of the source and inductor will flow to the load. In this phase, the voltage drop across the inductor will be U_i-U_0 and the current starts to decrease ($U_i<U_0$) from the maximum point reached in the previous phase.

$$i_L(t) = i_L(0) + \frac{1}{L}\int_0^t u_L(\tau)\partial\tau = I_{Lmax} - \frac{U_0 - U_i}{L} t \tag{4.3}$$

Where $i_L(0)$ is the value of the current in the inductor reached at the end of the "powering phase".
The origin of time it's assumed to be starting when the switching is opened.
The ripple of current in the end of this phase will be

$$\Delta I_{Lon} = \frac{U_0 - U_i}{L} t_{off} \tag{4.4}$$

Since in steady state the value of current at the beginning of the powering phase is equal to the current in the end of free-wheeling phase, we can derive the follow equations:

$$\Delta I_{Lon} = \Delta I_{Loff} = \Delta I = \frac{U_i}{L} t_{on} = \frac{U_0 - U_i}{L} t_{off} \tag{4.5}$$

where $t_{off}=T_s-t_{on}$. Therefore, substituting we obtain

$$M = \frac{U_0}{U_i} = \frac{1}{1-\delta} \tag{4.6}$$

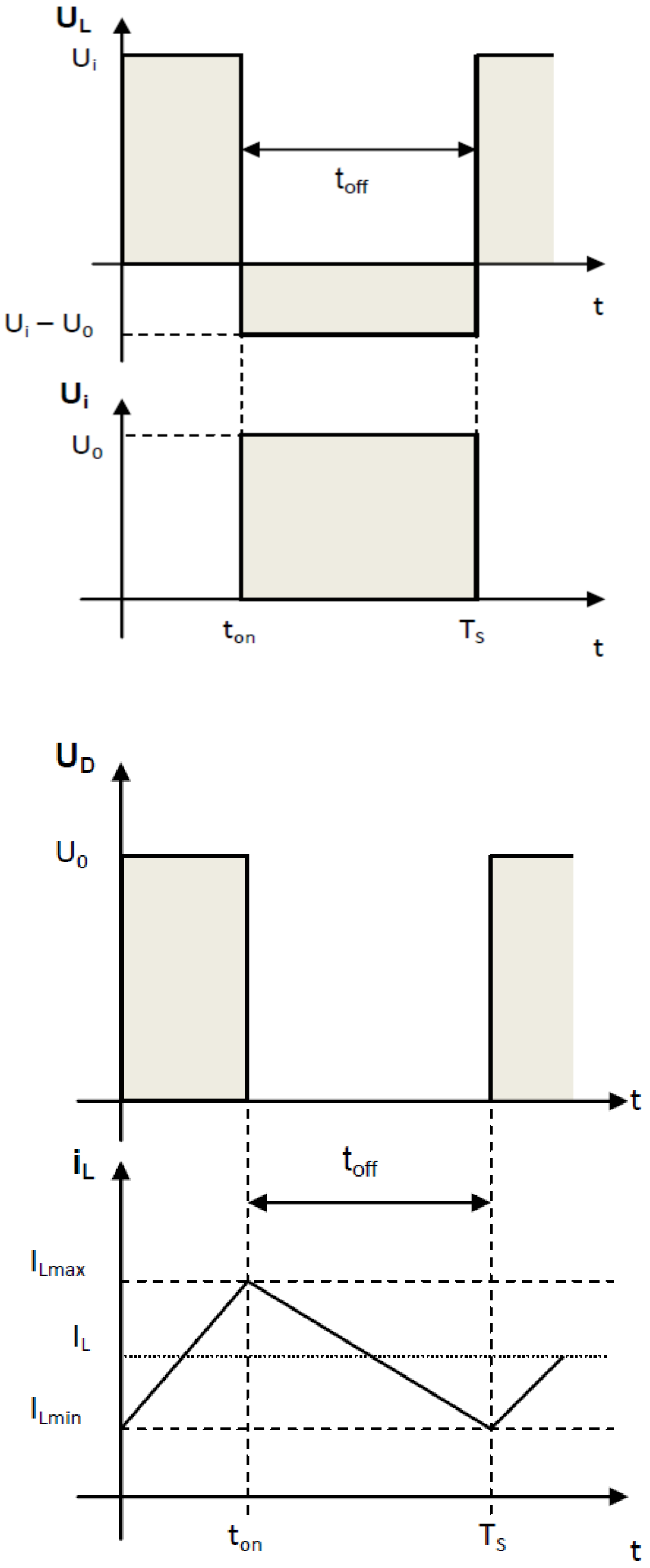

U_L
U_i
t_{off}
t
$U_i - U_o$
U_i
U_o
t_{on}
T_S
t
U_D
U_0
t
i_L
t_{off}
I_{Lmax}
I_L
I_{Lmin}
t_{on}
T_S
t

Figure 4.3

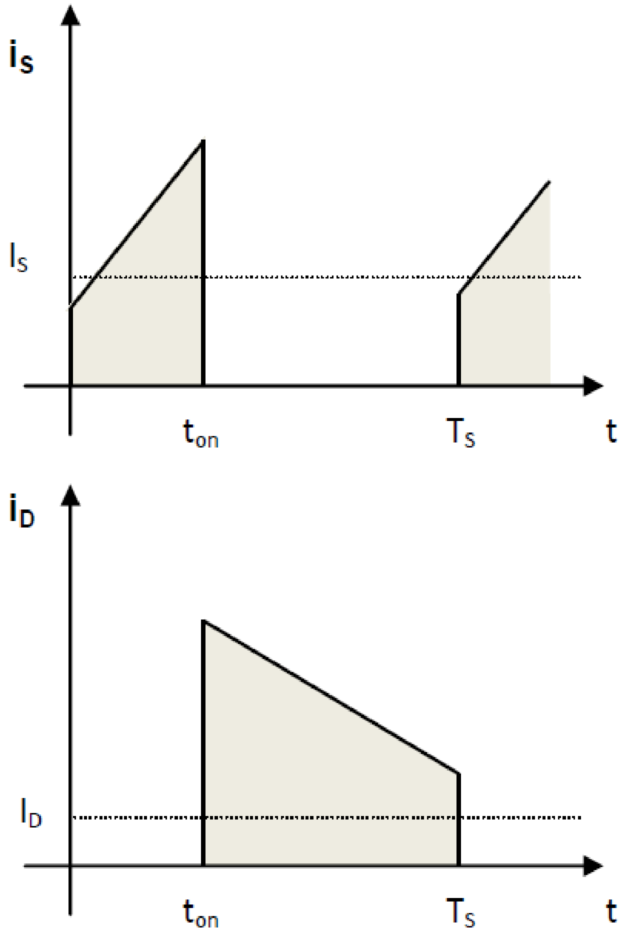


Figure 4.4

The average current is the switching is equal to the average input current and its value is given by the follow equation:

$$I_S = \frac{I_{Lmin} + I_{Lmax}}{2\,T_S} t_{on} = I_L \delta \tag{4.7}$$

and the average current that flow through the diode is:

$$I_D = \frac{I_{Lmax} + I_{Lmin}}{2\mathrm{T}_S} t_{off} = I_L (1 - \delta) \tag{4.8}$$

In steady state the average current in the capacitor is null and thus the average current that flow into the load is the same as the avarage current in the diode. Therefore we can derive:

$$P_i = P_0 \Rightarrow U_i I_i = U_0 I_0 \Rightarrow U_i I_L = U_0 I_D \tag{4.10}$$

and thus,

$$\frac{I_L}{I_D} = \frac{U_0}{U_i} = \frac{1}{1 - \delta} \tag{4.11}$$

In order to find the amplitude of the ripple of the output voltage we have to find the value of the current that flow across the capacitor. It's given by the follow equation:

$$i_C = i_D - I_0 = i_D - I_D \tag{4.12}$$

and its shape it's reported in Figure 4.5.

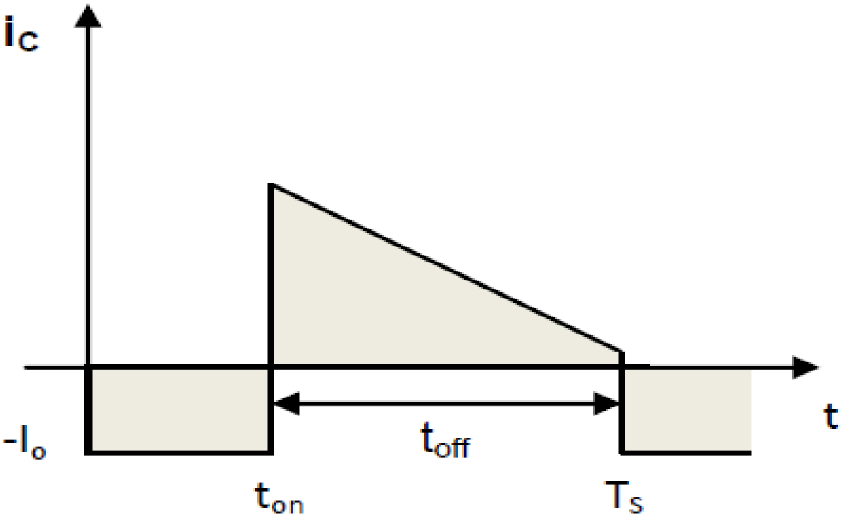


Figure 4.5

The value of the ripple is given by the follow equation,

$$|\Delta U_0| = \frac{1}{C} \int_0^{t_{on}} i_C \partial t = \frac{1}{C} \int_0^{t_{on}} I_0 \partial t = \frac{I_0 t_{ton}}{C} = \frac{I_0 \delta}{f_S C} \tag{4.13}$$

4.4 Boost Converter in discontinuous mode (DM)

If the load current decrease, the current through the inductor will decrease as well. It means that during the interval in which the switch is OFF, the current through the inductor will be null and thus, it will lead the diode to be interdicted.
The value limit of current that indicate the condition work in discontinuous mode is given by the equation:

$$I_{Lmin} = \frac{\Delta I_L}{2} \tag{4.14}$$

The curves of voltage and current in the inductor during this phase are reported in Figure 4.16.

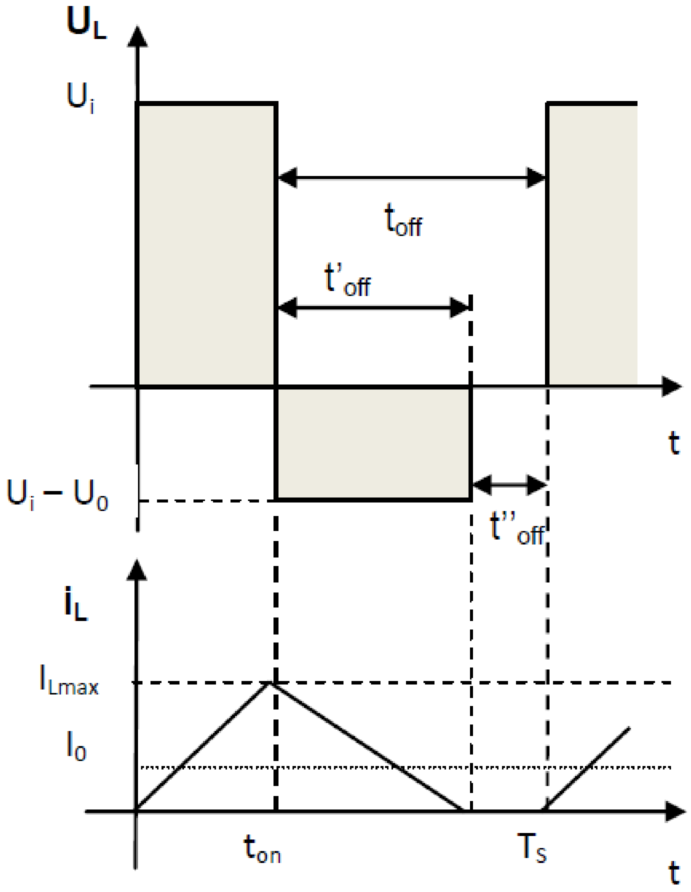


Figure 4.6

Looking the shape of the voltage across the inductor we can write:

$$U_i t_{on} = (U_0 - U_i) t'_{off} \tag{4.15}$$

This equation doesn't let to calculate the rapport of conversion M because of the presence of the incognito t'_{off}. Therefore we use the relation $I_D = I_0$ which derives from the condition in steady state:

$$I_0 = I_D = I_{Lmax} \frac{t'_{off}}{2T_S} \tag{4.16}$$

$$I_{Lmax} = \frac{U_i}{L} t_{on} \tag{4.17}$$

From the three last equations (4.15-4.16-4.17) we can calculate the rapport of conversion M in discontinuous mode:

$$M=\frac{U_0}{U_i}=1+\delta^2\frac{U_i}{2f_S L I_0} \tag{4.18}$$

in this condition we can note how the rapport of conversion depends not only from the duty cycle "δ" but also from the current absorbed by the load I_0. Moreover, compared with the case in continuous mode, the rapport of conversion in DCM results to be higher than in CCM.

4.5 Input state of the Boost Converter

As we have seen, the current in inductor is affected by ripple. This factor can influence the characteristic of PV panel to which the boost is connected. Therefore, once the MPP is reached, the ripple in the inductor implies that the I_{PV} current has an alternative component of current and thus, creates difficulty to achieve and maintain the MPP.
For this reason, the designers of PV system place a capacitor which interface the PV panel with the dc converter (Figure 4.7).

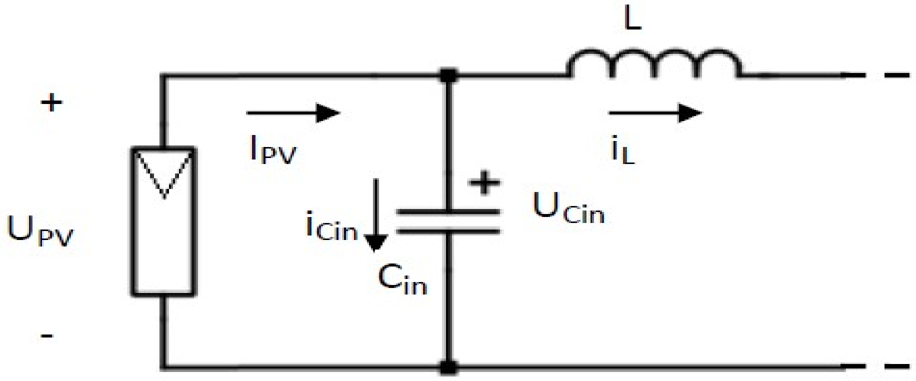


Figure 4.7

This capacitor has the function to absorb the ripple of the current from the inductor.
The capacitor doesn't affect the continue component of the current from the panel. It means that the average current from the panel I_{PV} is equal to the average current in the inductor I_L.
The ΔI_L current will be absorb by the capacitor (Figure 4.8).

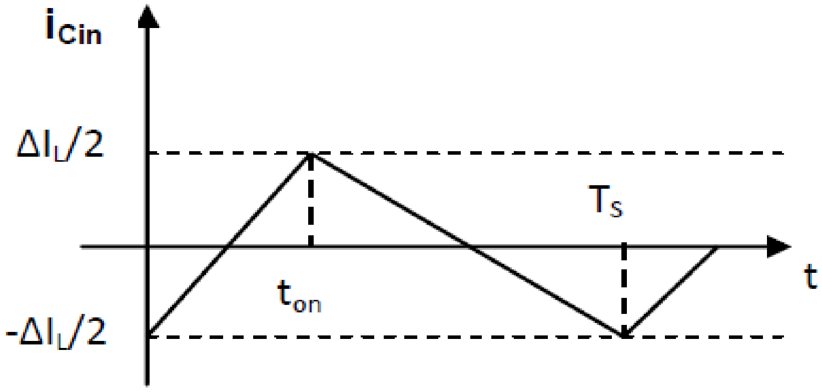


Figure 4.8

and thus, the ripple is related to the capacitor's value from the follow relation:

$$|\Delta U_{Cin}|=\frac{1}{C_{input}}\int_{0}^{t} i_{Cin}\,\partial t=\frac{1}{C_{input}}\left(\frac{\Delta I_L}{2}\left(\frac{t_{on}}{2}+\frac{t_{off}}{2}\right)\frac{1}{2}\right)=\frac{\Delta I_L T_S}{8C_{input}} \tag{4.19}$$

5 Boost parameter and set-up circuit

5.1 Calculation of the Boost parameters

In order to figure out which are the parameters of the boost, we need to keep in consideration the characteristic of the PV panel used in the simulation.
The PV panel used to simulate the efficiency of the algorithms is made up of two strings connected in parallel. Each string is composed of four modules connected in series and each module is made up of seventy-two cells connected in series.
The equation used to simulate the cell is

$$I = I_{PV} - I_S\left(e^{\frac{V+I R_S}{N V_T}} - 1\right) - I_{S2}\left(e^{\frac{V+I R_S}{N_2 V_T}} - 1\right) - \frac{V + I R_S}{R_P} \tag{5.1}$$

and the parameter of the cell used in the panel are reported in Figure 5.1.

Short-circuit current, I_{SC}:	5,61	A
Open-circuit voltage, V_{OC}:	0,7166	V
Irradiance used for measurements, I_{R0}:	1000	$\frac{W}{m^2}$
Quality factor, N:	1,5	
Series resistance, R_S:	0,006	Ohm
First order temperature coefficient for I_{PV}, TIPH1:	0	$\frac{1}{K}$
Energy gap, E_G:	1,11	eV
Temperature exponent for I_S, TXIS1:	3	
Temperature exponent for R_S, TRS1:	0	
Parameter extraction temperature, T_{meas}:	25	C
Fixed circuit temperature, TFIXED:	25	C

Figure 5.1

In condition of uniform insolation the details of the whole array (Figure 5.2) are given as follow:

- Voltage open circuit (Voc) : 205.4 Voltage
- Current short circuit (Isc) : 11.22 Ampere
- Insolation values: PSConstant1=PSConstant2=...=PSConstant8=1000 $\frac{W}{m^2}$

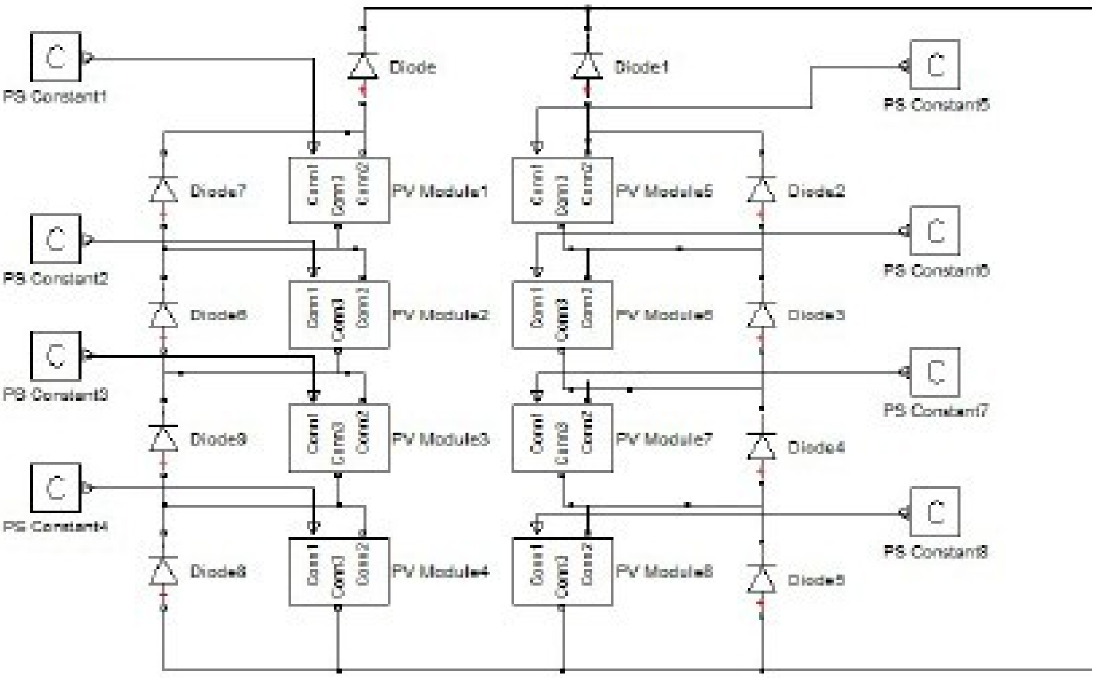


Figure 5.2

The follow pictures (Figure 5.3-5.4) show the characteristics of Power (Watt)-Voltage (Volt) and Current (Amper)-Voltage(Volt) under condition of uniform insolation.

Power (Watt)- Voltage (Volt)

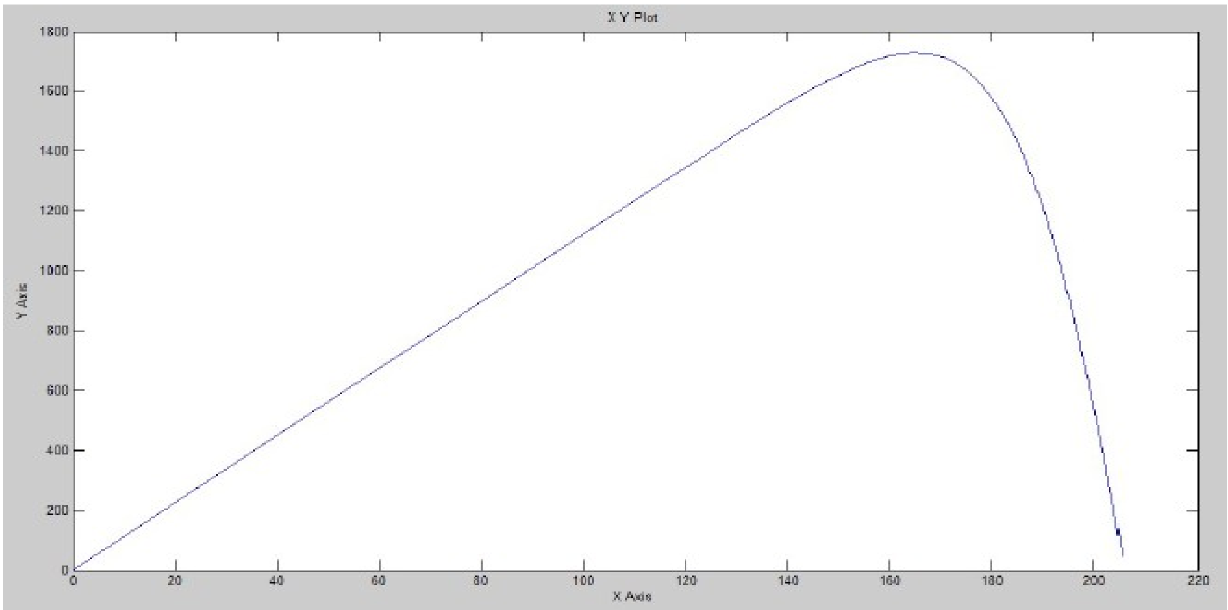


Figure 5.3

Current (ampere)-Voltage (Volt)

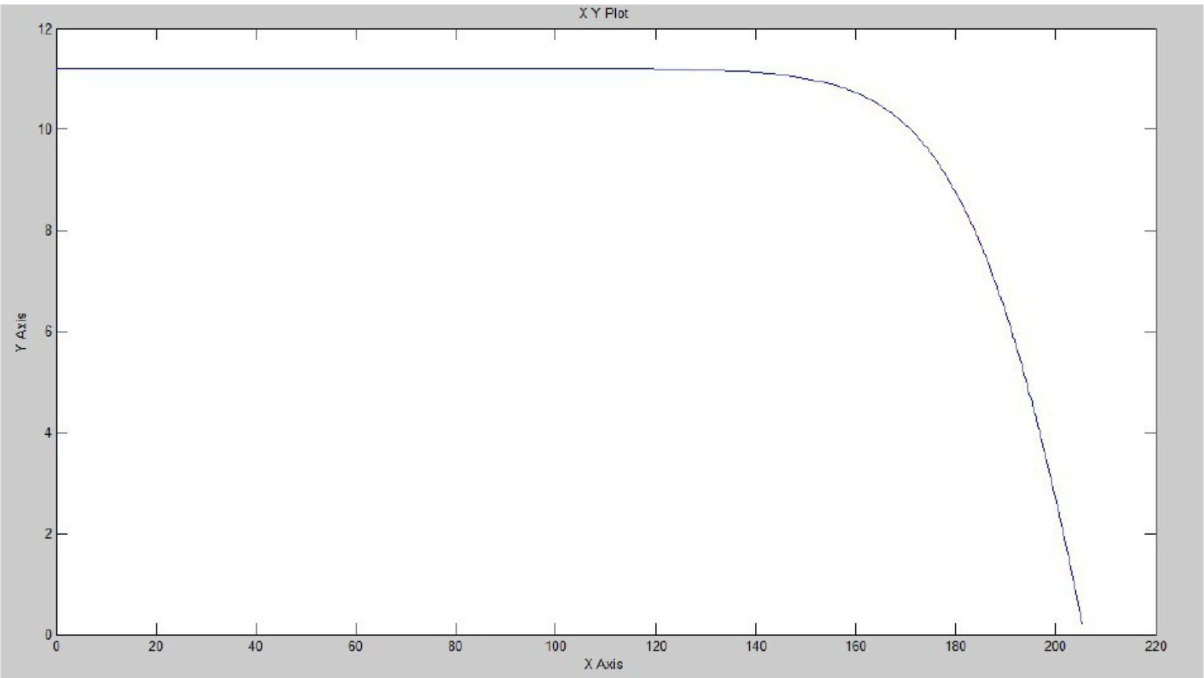


Figure 5.4

Characteristic:

- $V_{MaxPowerPoint}$ (V_{MPP})=165 Volt
- $I_{MaxPowerPoint}$ (I_{MPP})=10.55 Ampere
- $P_{MaxPowerPoint}$ (P_{MPP})=1740 Watt

As it is well known, the operating point of work is determined by the intersection between the P-V curve and the load line given by the resistance seen from the PV panel.
The MPPT changes the value of the input resistance of the boost by acting to the duty-cycle.
Remembering the equation of the boost in continuous mode (CM) we can derive:

$$M=\frac{V_{out}}{V_{input}}=\frac{1}{1-dutycycle} \tag{5.2}$$

and,

$$V_{out}=I_{out}\times R_{load} \tag{5.3}$$

$$V_{input}=I_{input}\times R_{input} \tag{5.4}$$

substituting we derive the value of R_{input},

$$\frac{I_{out}\times R_{load}}{I_{input}\times R_{input}}=\frac{1}{1-dutycycle}\Rightarrow R_{input}=(1-dutycycle)\times(\frac{I_{out}\times R_{load}}{I_{input}}) \tag{5.5}$$

but

$$P_{input} = P_{out} \Rightarrow M = \frac{I_{input}}{I_{out}} = \frac{1}{1 - dutycycle} \tag{5.6}$$

so, substituting we have the final relation

$$R_{input} = (1 - dutycycle)^2 \times R_{load} \tag{5.7}$$

It means that, once the R_{load} is chosen, it's always $R_{input}<R_{load}$ because 0<dutycycle<1.
Therefore the maximum value of R_{input} is obtained for dutycycle=0 and it will be equal to R_{load}, thus remembering the I-V curve with the intersection of the load line (Figure 3.11), if the dutycycle increases the operating point will move towards the left side. It is important to ensure that exist a value of dutycycle for which the MPP could be reached. Thus, noting from the I-V curve that the MPP is at V_{MPP}=165 Volt and I_{MPP}=10.55 Ampere we can derive the value of the minimum resistance:

$$R_{inputmin}=R_{load}=165/10.55=15.64 \text{ ohm} \tag{5.8}$$

In order to make large the interval of working of the boost, also for the purpose to detect the right peak in condition of partial shading, is better to choose a value of resistance a bit higher.

$$R_{inputmin}=R_{load}=60 \text{ ohm} \tag{5.9}$$

From simulation it is easy to see that at this value of resistance the correspondent intersection with the I-V and P-V curves is given at these values:

V=198.54 Volt
I=3.3 Ampere
P=657 Watt

Booster is important to step up the voltage so we can change the point of work and increase the power delivered by the PV panel. The value of the capacities chosen are C_{input}=200 µF and in output of the booster the capacitor's value is C_{out}=2 mF.

The boost has the follow parameters:
Inductor=1 mH, Frequency of Switching=10 KHz and a Diode.
The reason because i chose a high frequency was to be sure that the booster works in continuous mode for every value of dutycycle. The equations provide the value that has to be satisfied to work in CM:

$$L > \frac{R_{load} \cdot DutyCycle \cdot (1 - DutyCycle)^2}{2 \cdot f_{switch}} \tag{5.10}$$

where R_{load} is the resistance in output and its value is 60 ohm as discussed before.

The final circuit used in the simulation is reported in Figure 5.5.

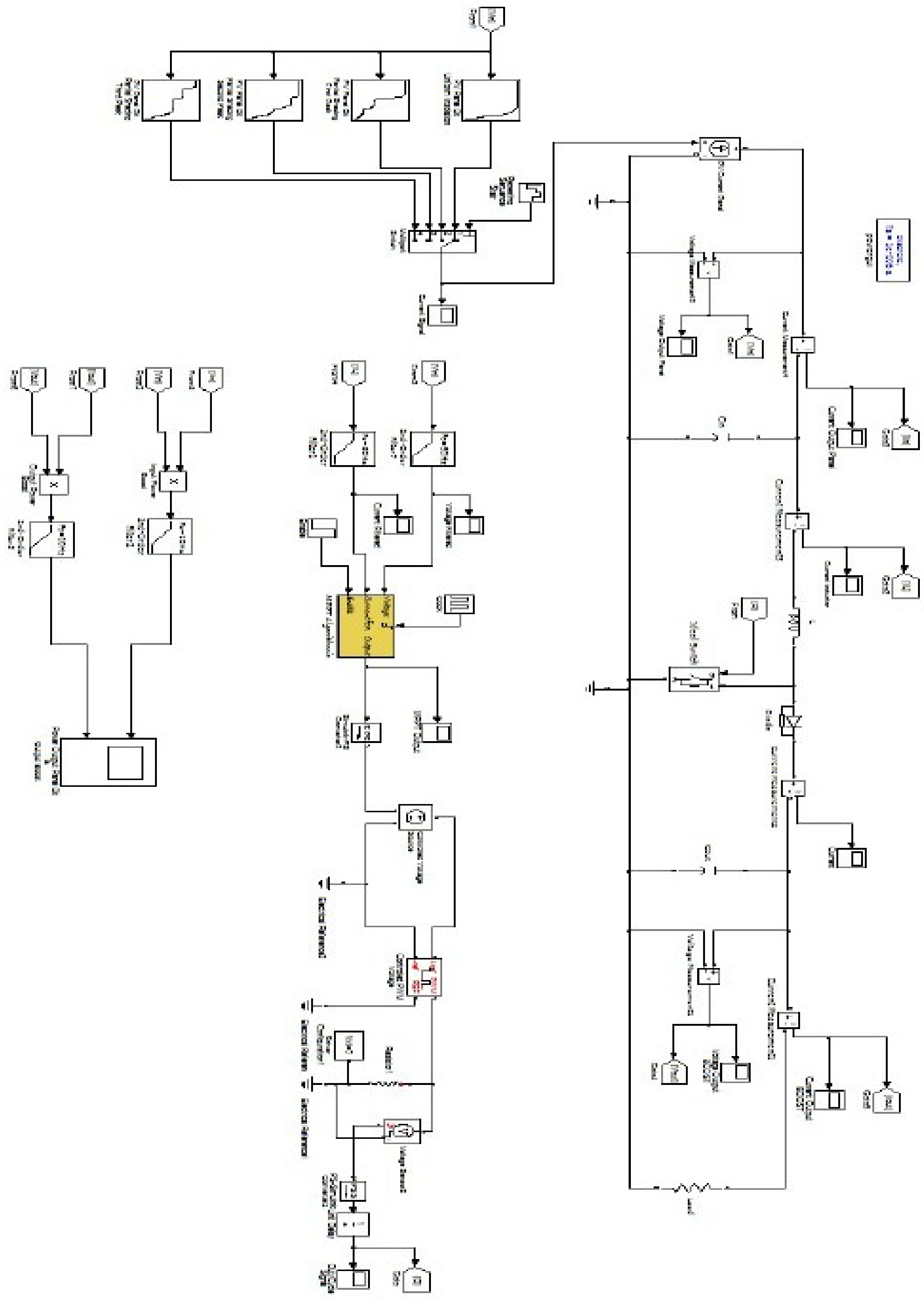


Figure 5.5

5.2 Set-up circuit for testing algorithms

As can be seen in Figure 5.5, the MPPT checks the value of current and voltage in output of the panel and in its output it provides the duty cycle that commands the switch. The aim of the MPPT is to let the circuit to work in the maximum point of power and thus increase the efficiency of the whole system.
The MPPT block has the following input:

- Voltage
- Current
- Enable: it is a signal that enables the algorithm to start working after 0.1 sec. That choice is because initially the signal is not stable, it changes rapidly so it's better to wait at least 0.1 sec.
- Pulse: this input is important because the algorithmic works in discrete time and it's easier to calculate the difference between two different instant of time and understand if the condition of partial shading is verified. Otherwise if we use continuous time the difference calculated between two different instant of time is very small and it becomes difficult to verify when the condition of partial shading is occurred.

The duty cycle is provided to the switching by a block called PWM (Pulse-Width Modulated).
It converts an input voltage in a range from 0Volt to 100Volt to a square wave with a duty-cycle that can change from 0% to 100%.
Every algorithm was tested in different panel's configurations with different values of insolation. Initially every circuit is under condition of uniform insolation and after a certain time a condition of partial shading is verified in order to check the performances about the algorithm to achieve the maximum point of power.
The simulations have been done under SimPowerSystem environment, to reduce the time required for the simulation and make it simpler to manage.
To let the system work in SimPowerSystem I had to recreate the PV panel because the prebuilt model doesn't exist in the tool box. To do this I used a look-up table with the values of voltages and currents of the real PV panel.
As we can see in the Figure 5.6, the value of the voltage measured across the current generator goes to select the right value of current into the look-up table that will command the generator of current.

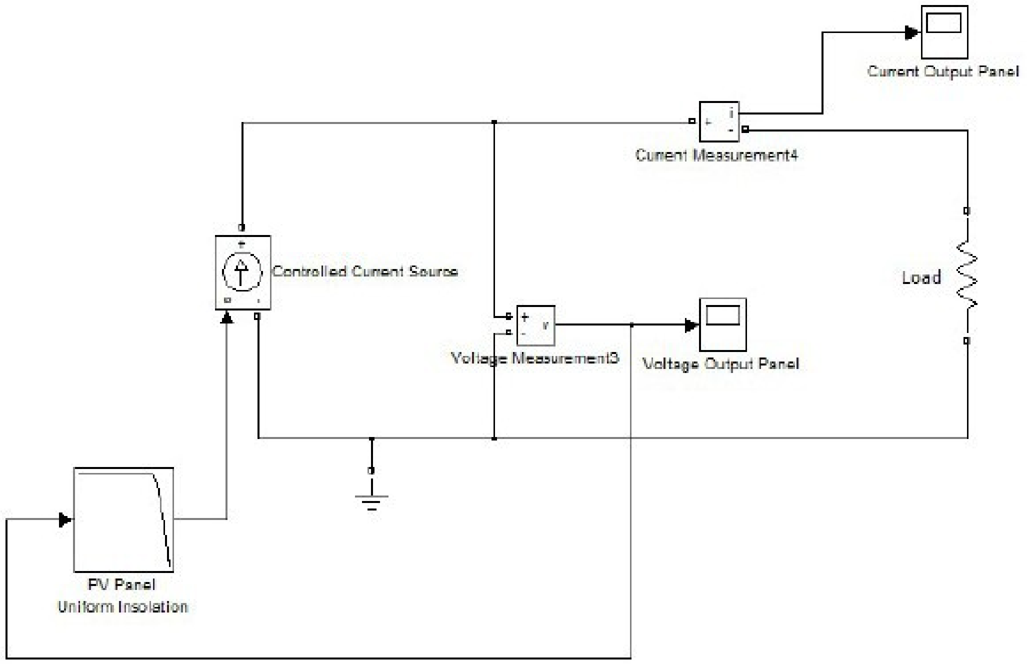


Figure 5.6

From the picture of the circuit, the condition of partial shading is recreated by shifting from one look-up table to another one at a certain time, the signal that command the selection is provided from the block “Repeating Sequence Stairs” to the “Multi-port Switch”.
In order to let the algorithm to work in stable condition the input signals of current and voltage have been filtered before going to the MPPT block.

6 Perturbation and Observation (P&O) Algorithm

6.1 Structure of the P&O algorithm

The method P&O is one of the most common algorithm used in commercial application due to its simplicity and robustness. It's very easy to develop and very accurate under condition of uniform insolation. The algorithm works perturbing the system by changing the value of duty cycle in its output. After one perturb is performed, the current power is evaluated and compared with the previous value in order to determine the change of power ΔP. If ΔP>0, then the operation continues in the same direction of the perturbation. Otherwise the operation will be in the reverse direction. A flowchart of the P&O algorithm is reported in Figure 6.1.

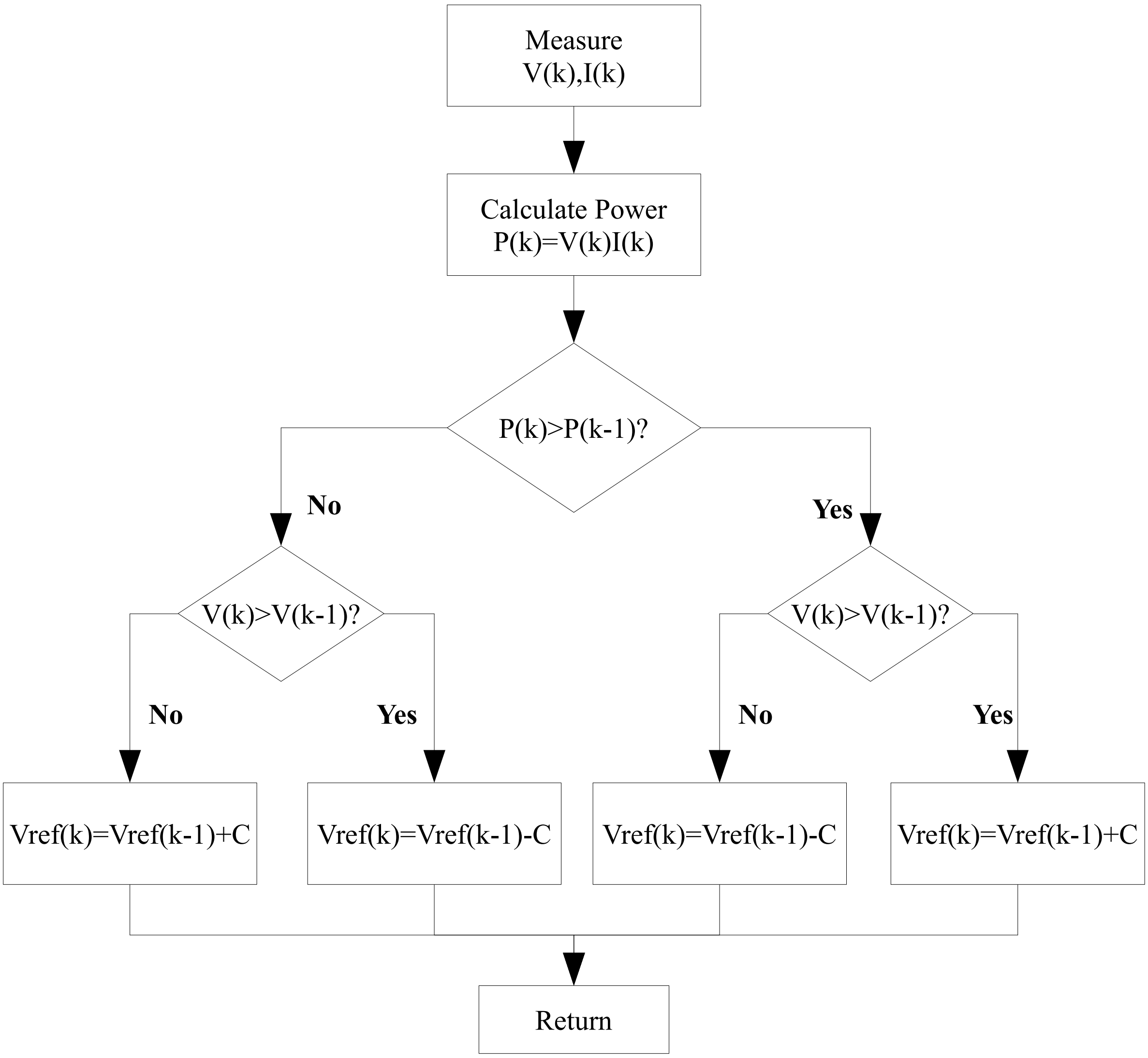


Figure 6.1

Below is reported the main part of the P&O's code used in the algorithm:

```
if (dP ~= 0)
        if dP < 0
          if dV < 0
            DutyCycle=DutyCycle-a;

          else
            DutyCycle=DutyCycle+a;

          end
        else
          if dV < 0
            DutyCycle=DutyCycle+a;

          else
            DutyCycle=DutyCycle-a;

          end
        end

end
```

where the constant “a” determines the increment or decrement of the variable “dutycyle”, “dP” and “dV” are the correspondent variation of power and voltage in two consecutive instant of time.
We can note that the algorithm is able to track the right value of the maximum power under condition characterized by just one peak of power. When it passes from a condition of uniform insolation to another one of partial shading with multiple local peak, it can mistakenly be trapped in a local maximum instead of detecting the maximum global peak.
This failure has been proved by the simulation under MATLAB (Simulink-SimPowerSystem) environment. The circuit is initially tested under condition of uniform insolation (Figure 6.2-6.3) and after 1.5 sec. the system pass under condition of partial shading in which the maximum peak results to be the first local peak (Figure 6.4-6.5).
For the simulations has been taken the details of the PV panel on the roof of DIT. The array has the same configuration of the one in the Figure 5.2 with two string connected in parallel, each one composed of four modules connected in series.

Uniform insolation

Values of insolation: PSConstant1=PSConstant2=...=PSConstant8=1000 $\frac{W}{m^2}$

Power (W)-Voltage (Volt)

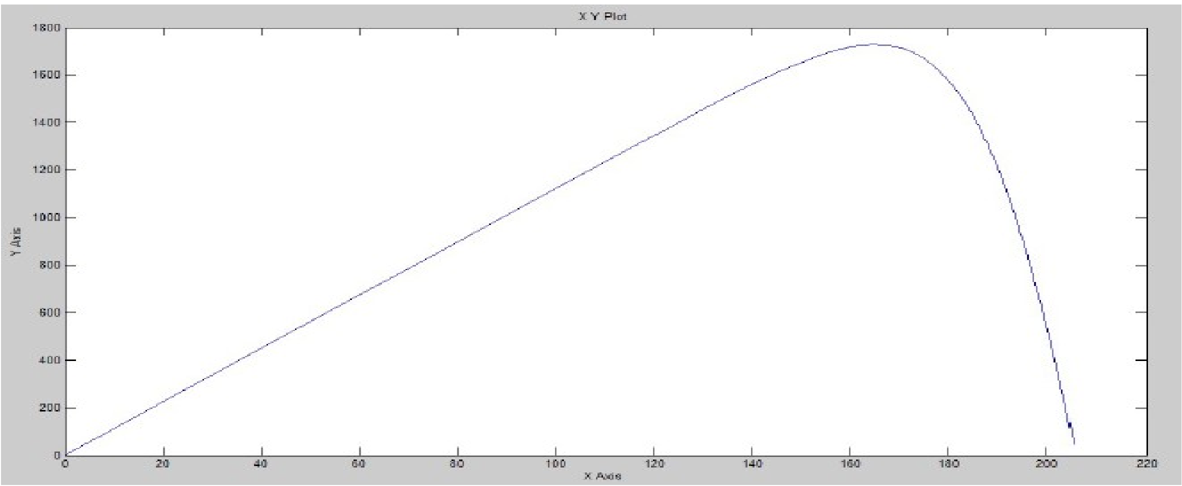


Figure 6.2

Current (Ampere)-Voltage (Volt)

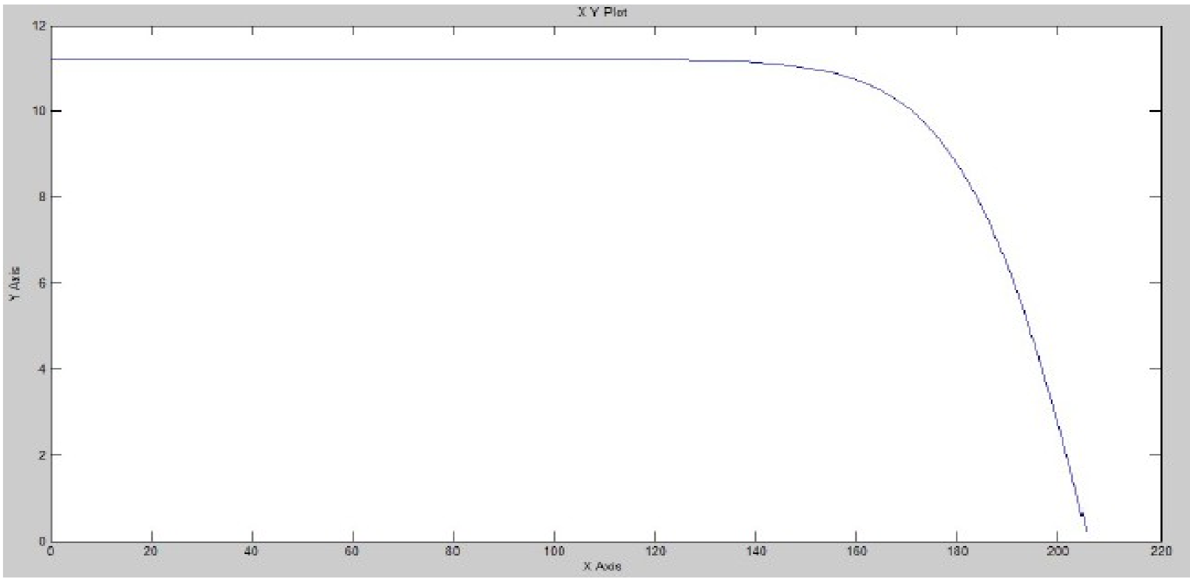


Figure 6.3

Characteristic:

- $V_{MaxPowerPoint}$ (V_{MPP})=165 Volt
- $P_{MaxPowerPoint}$ (P_{MPP})=1740 Watt

Partial Shading-First peak MPP

Values of insolation: PSConstant1=PSConstant2=PSConstant6=PSConstant8=1000 $\frac{W}{m^2}$

PSConstant3=PSConstant4=100, PSConstant5=200 $\frac{W}{m^2}$, PSConstant7=700 $\frac{W}{m^2}$

Power (watt)-Voltage (Volt)

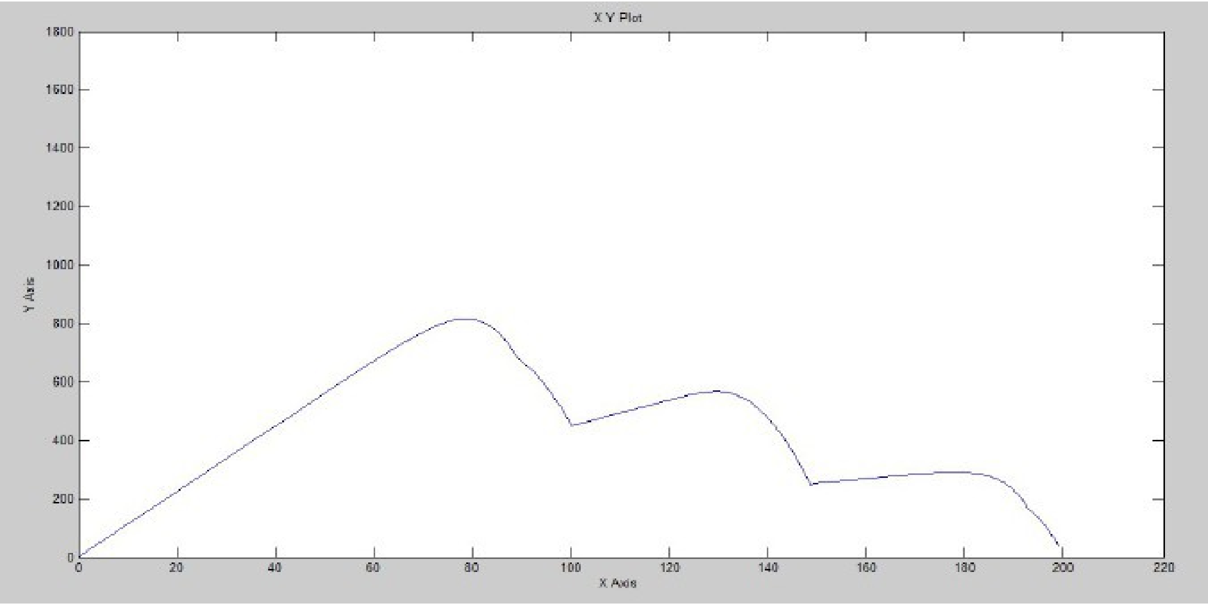


Figure 6.4

Current (Ampere)- Voltage (Volt)

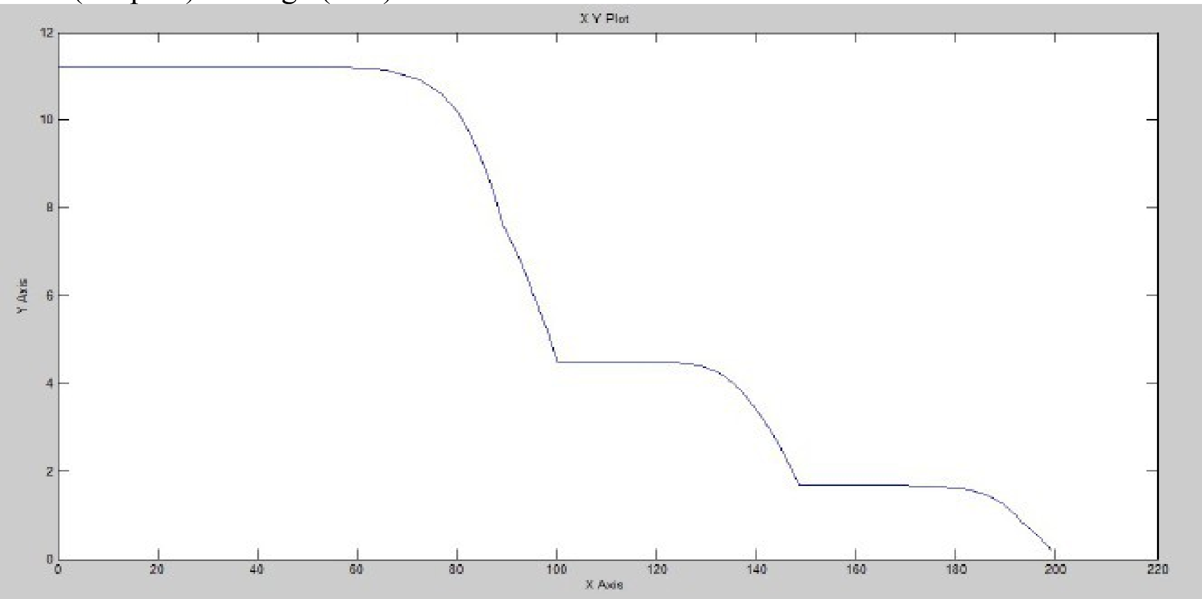


Figure 6.5

Characteristic:

- $V_{MaxPowerPoint}$ (V_{MPP})=78 Volt
- $P_{MaxPowerPoint}$ (P_{MPP})=810 Watt

In the follow are attached the screens resulted from the simulation:

Power (Watt)- Time (s)

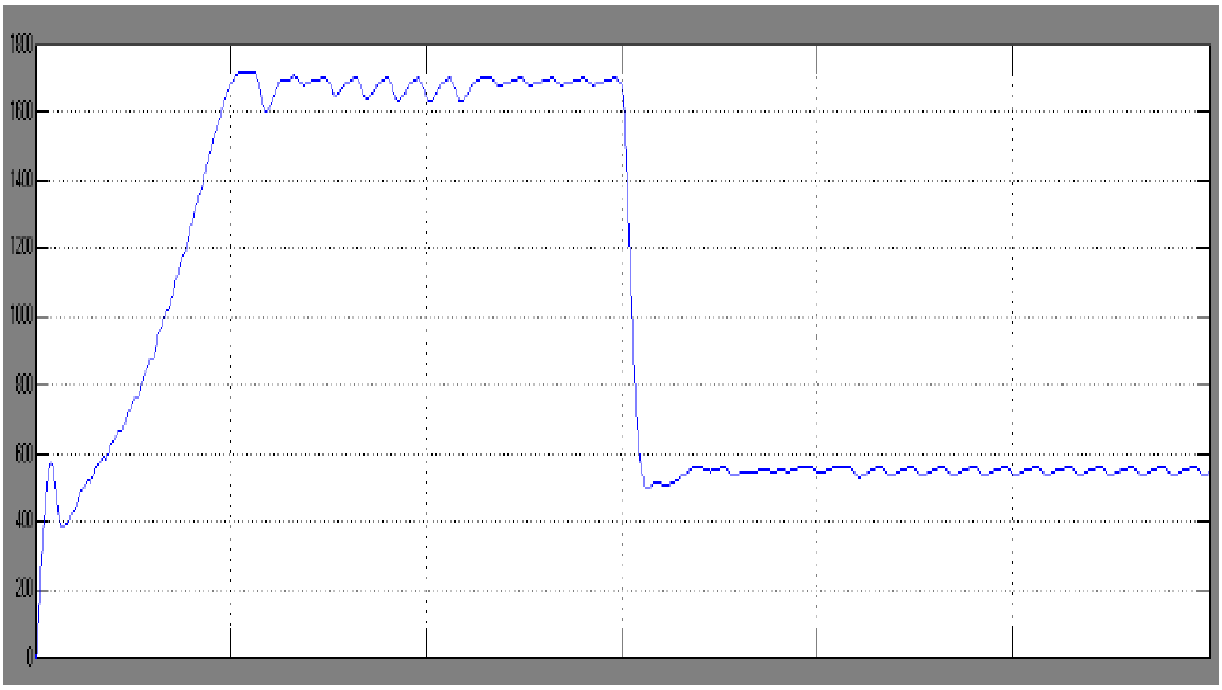


Figure 6.6

Voltage (Volt)- Time (s)

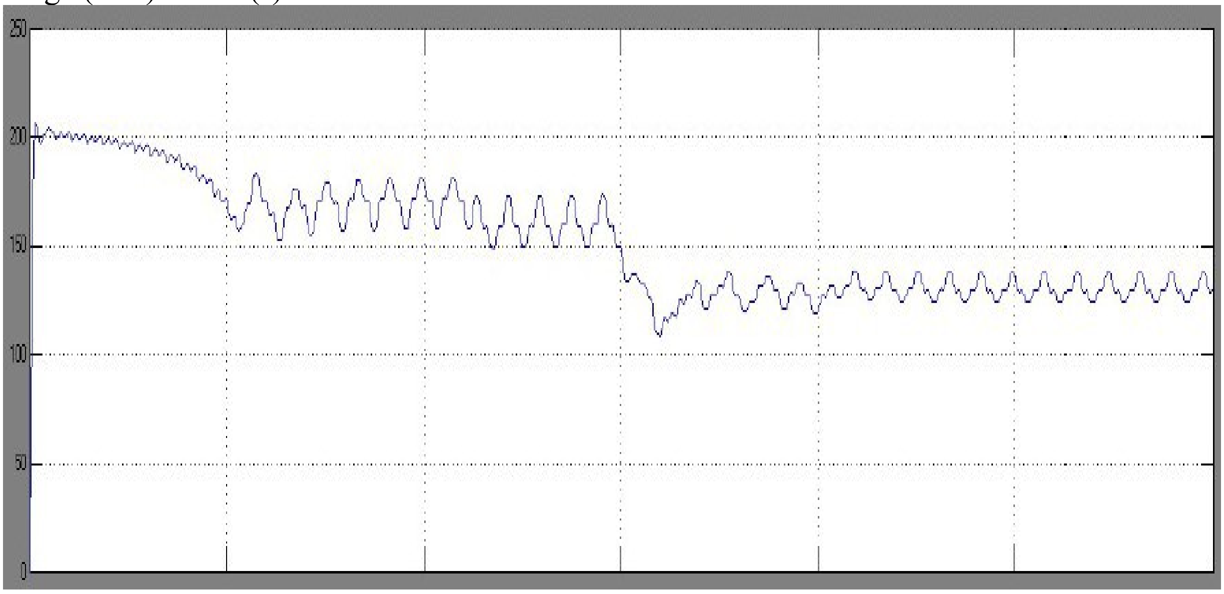


Figure 6.7

Current (Ampere)- Time (s)

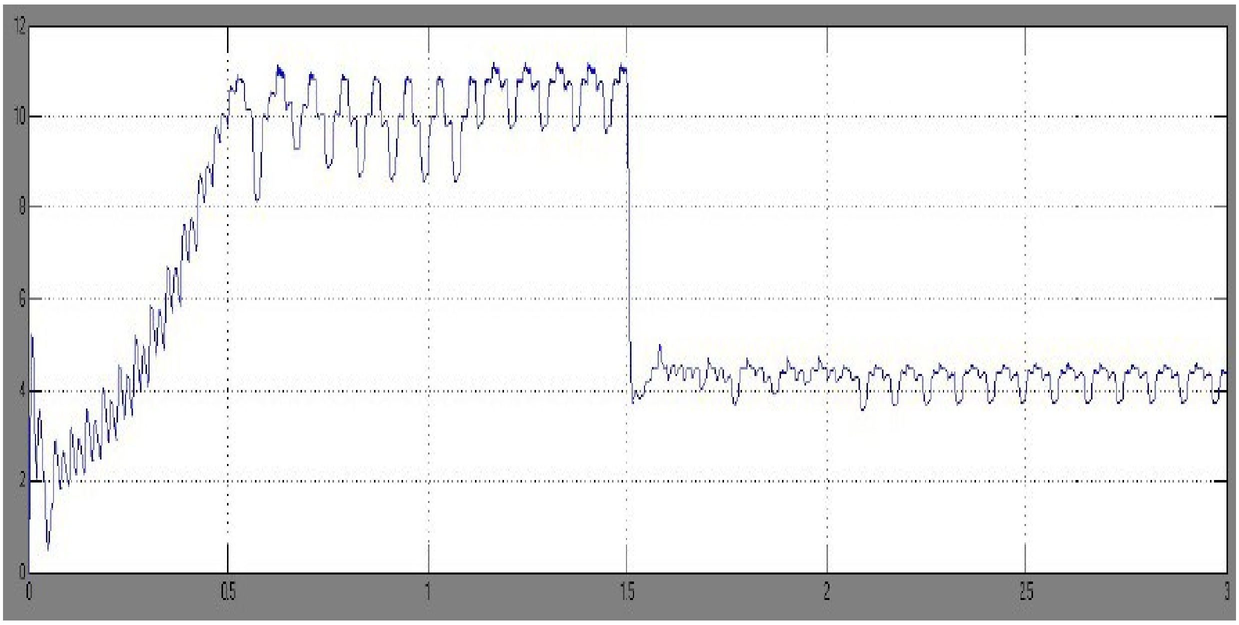


Figure 6.8

As can be noted, under uniform insolation the P-V curve presents just one peak and the P&O can detect it, the power extracted from the panel results to be around 1700 W. After 1.5 s, the condition of partial is verified and in this case, the P&O is trapped in the second local peak with an output power around 560 W, but the global maximum lies on the first peak and its power value is 810 W. Hence the need to find a alternative solution able to track the MPP under any operative condition.

7 Different algorithm to detect Partial Shading problem

7.1 Introduction to the problem of Partial shading

The problem of partial shading is a well known problem and it has attracted the efforts of a lot of researchers. To solve that problem very complex algorithms has been proposed with different solutions. The problem of developing a circuit or an algorithmic able to detect the global maximum at any condition of weather, became important in terms of efficiency of the overall system. Some techniques to detect the maximum point of power are described in the following section.

7.2 Algorithm for Current Balancing of Partial Shaded modules

Sometimes, the power produced by a shaded array could be less the sum of the maximum power that each module could deliver.

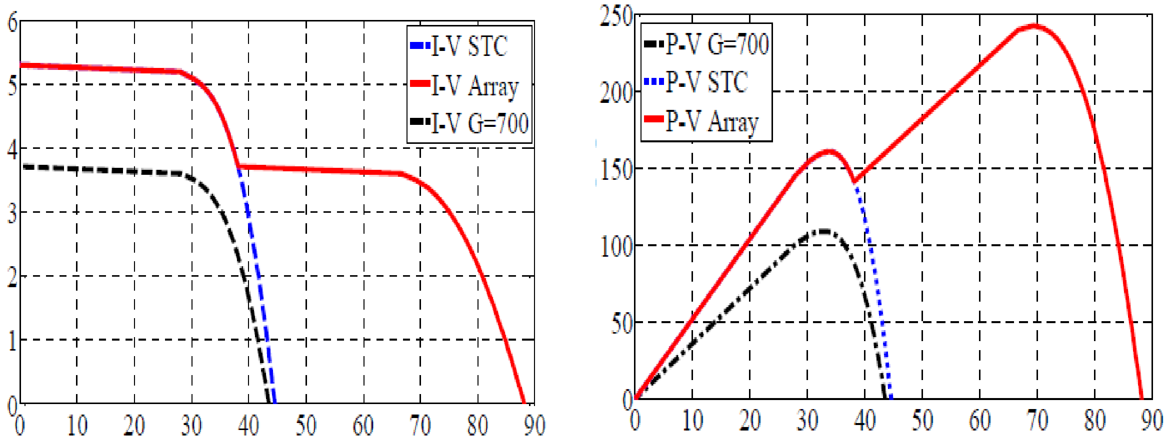


Figure 7.1

As we can see in figure 7.1, if we have an array composed of two modules, one unshaded that can deliver 165W and the other one shaded that delivers 115W, the maximum power that we can extract from the array is 234W, less than the some of the power of each module.
A solution for this problem has been proposed in [5], where a circuit is able to extract different value of power and current for each module and so to extract more power from the whole PV panel.
The effect of this solution is reported in Figure 7.2, with a power that presents just one maximum with the control applied to each module, instead of a normal boost converter in which the characteristic presents more local maximum.

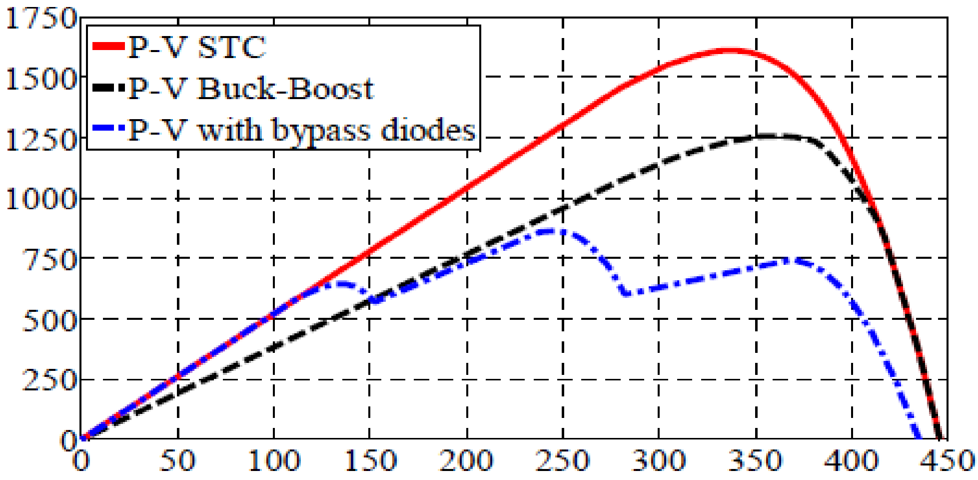


Figure 7.2

The circuit of the solution proposed in [5] is reported in Figure 7.3 and it uses buck-boost converters.

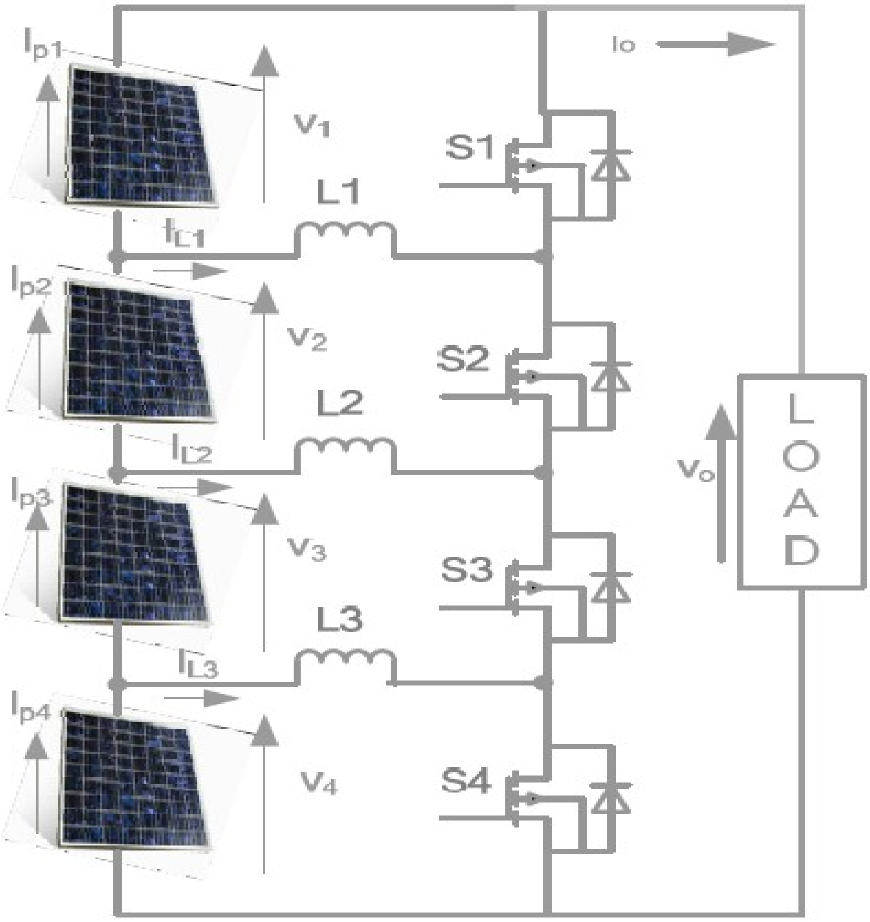


Figure 7.3

The algorithm is based on a Moore machine and it could be extended to a more modules connected in series. This MPPT employs the load and inductance current as the input variables. The value of inductance current is changed according to the switching condition.
For an array composed of four modules connected in series as shown in Figure 7.3, the state

machine of MPPT algorithm is reported in the following picture Figure 7.4.

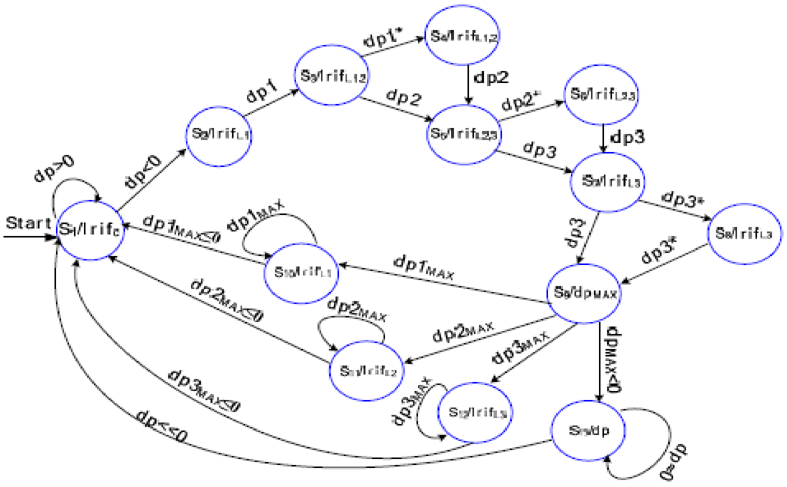


Figure 7.4

Initially the load current is increased step by step until the increment of output power doesn't grow any more. Afterwards a step of current (positive or negative) is applied to each inductor in order to evaluate if a positive variation of output power is occurred. If at the end of this process no positive variations of current is revealed it means that the MPP is reached and a conventional algorithm will be used. Otherwise, the current of the inductor that made the largest variation of output power will be changed until the power variation is positive. This process will start every time a big variation in output power is detected.

Advantages:
-Possibility to extract more power than a normal circuit using a boost converter.
-This solution take into account about different values of temperature and insolations of the modules.

Drawbacks:
-As we can see in the Figure 7.5, this circuit is useful just when the level of insolation of the shaded cell is more than 200W/m^2, otherwise the dissipation along the circuit doesn't let it to work well and a normal boost converter tries to extract more power from the circuit.

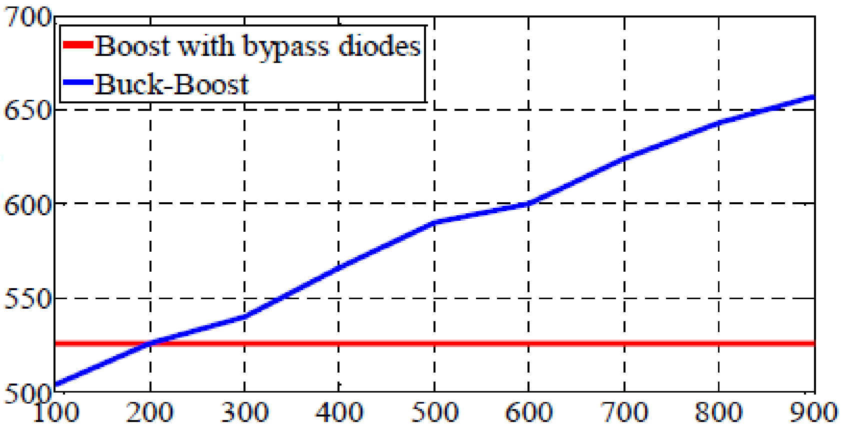


Figure 7.5

-The time required to find the new global maximum is not the best one, due to the several state of Moore machine that the algorithm has to check.
-The circuit needs to use a buck-boost converter for each module and thus the overall solution is going to be very expensive.

7.3 Second solution about Partial shading problem

Another solution to the MPPT Algorithm is proposed in the paper [6]. This MPPT is based on the well-know increment of conductance (IncCond) with a step size that can change depending on the slope of the P-V characteristic. The algorithm uses the block diagram reported in Figure 7.6.

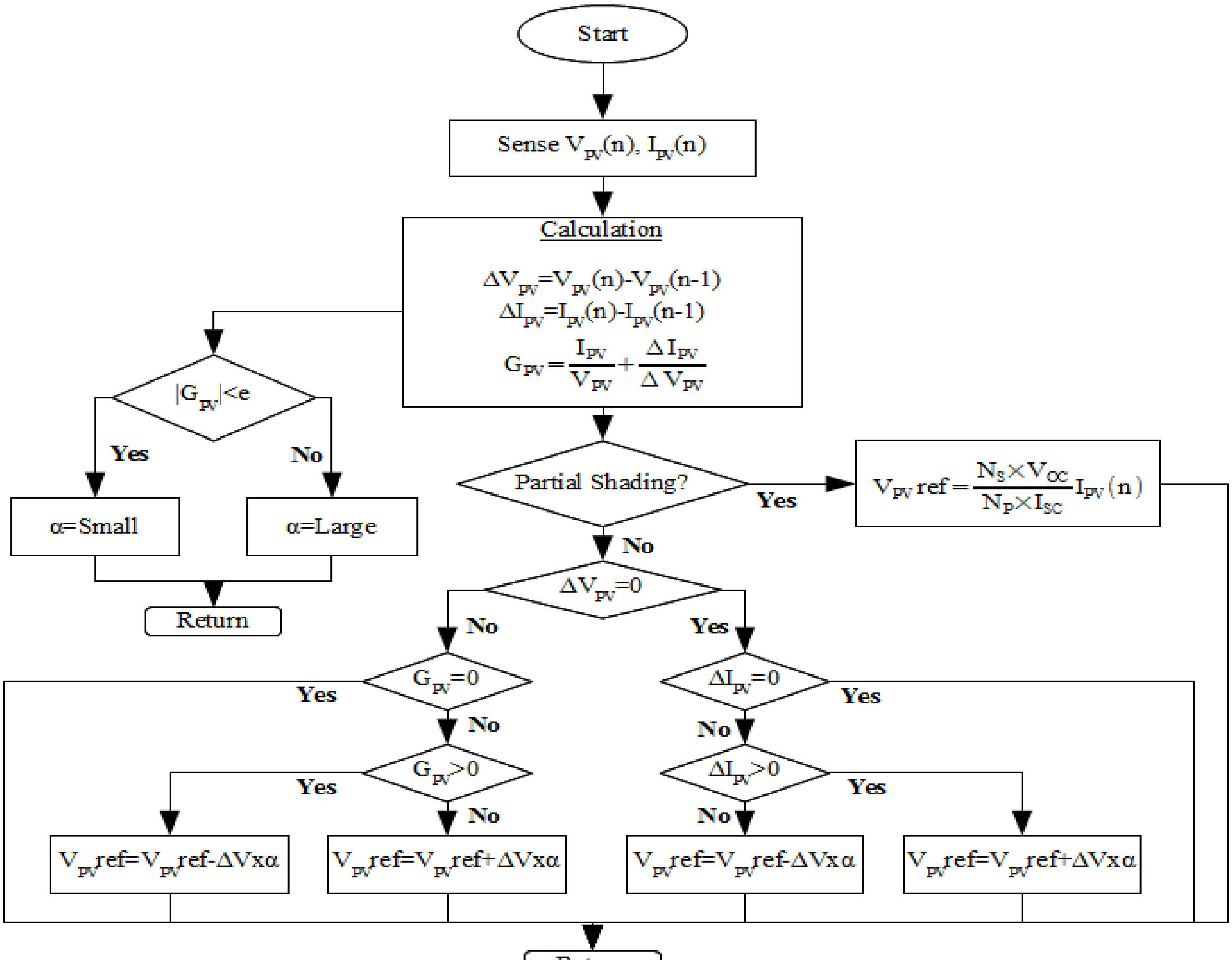


Figure 7.6

As we can see, the condition of partial shading is verified when the following two equations are satisfied:

$$\Delta V_{pv}=V_{pv}[n]-V_{pv}[n-1]<\Delta V_{SET} \qquad (7.1)$$

$$\frac{\Delta I_{pv}}{I_{pv}[n-1]}=\frac{I_{pv}[n]-I_{pv}[n-1]}{I_{pv}[n-1]}<-\Delta I_{SET}=\frac{-I_{pv}[n]}{N_{pM}} \qquad (7.2)$$

where N_{pM} is the number of array connected in parallel.

The condition is satisfied when it occurs both a negative step of current and voltage. The negative step of voltage is usually very small and the step of current has to be very high.
The following picture helps to understand what happens in partial shading condition.

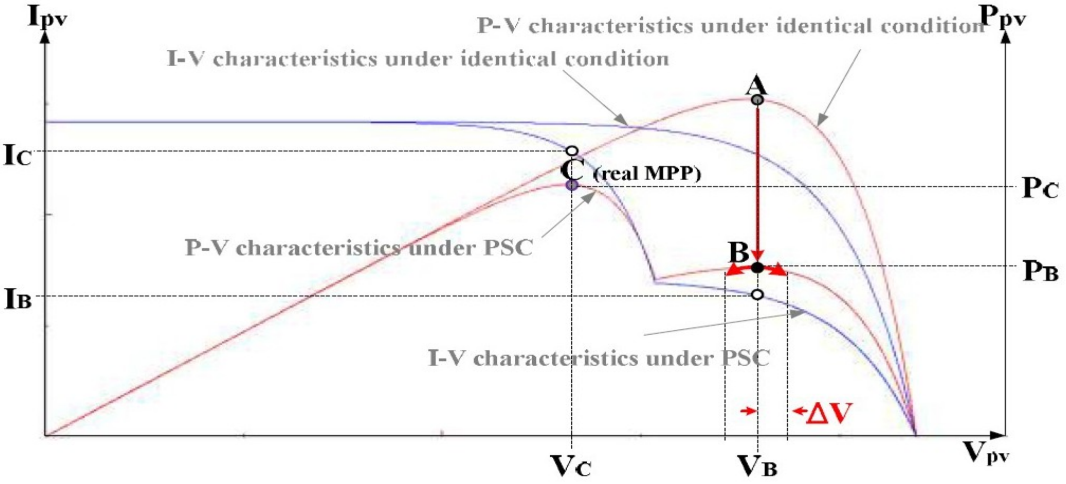


Figure 7.7

When the equations (7.1) and (7.2) are satisfied the value of duty cycle provides to the PWM block has to change.

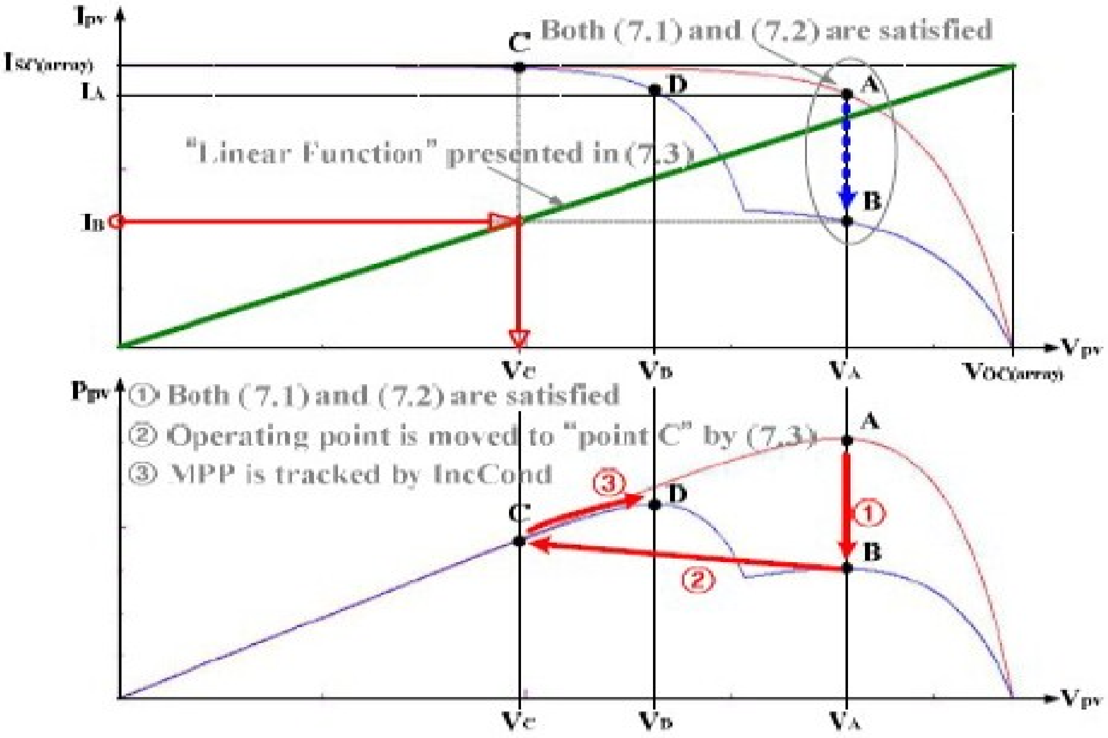


Figure 7.8

As it is shown in the picture above, when the condition of partial shading occurs the voltage has to move towards the point C and then it will start again to try to catch the maximum point of power by using the increment of conductance.
The value of voltage required to move to the point C is

$$V_{pv}^{x} = \left(\frac{N_{sM} \times V_{ocM}}{N_{pM} \times I_{scM}}\right) \times I_{pv}[n] \tag{7.3}$$

After moving towards point C the algorithm will start another time to search the maximum, but this time it will be the global maximum.
Following three cases are reported with different configuration of partial shading that are useful to understand how the algorithm works.
In the first example we can see how the algorithmic pass from the condition of uniform insolation to partial shading condition where the global maximum is the first peak of power.

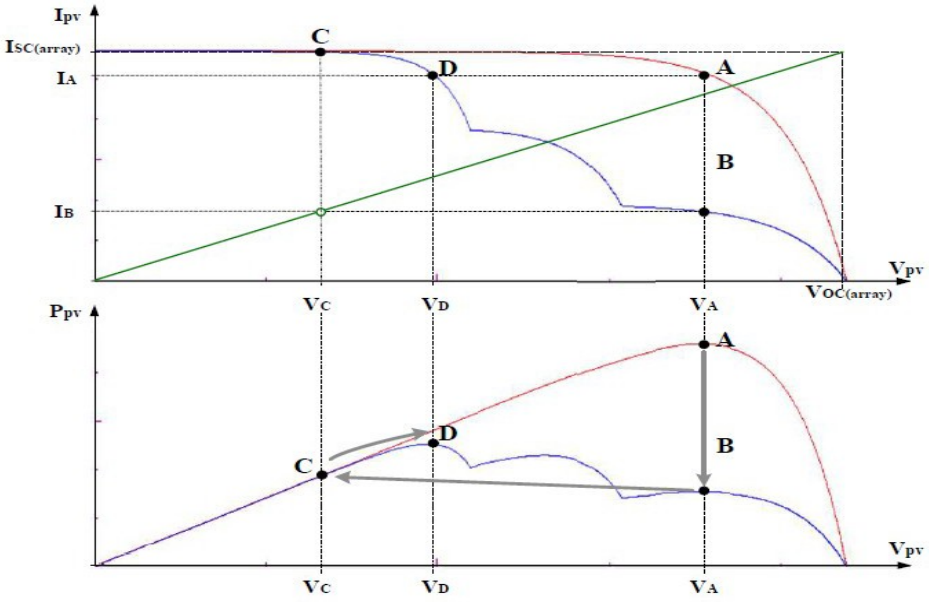


Figure 7.9

In the next example the peak of maximum power under condition of partial shading is the second one.

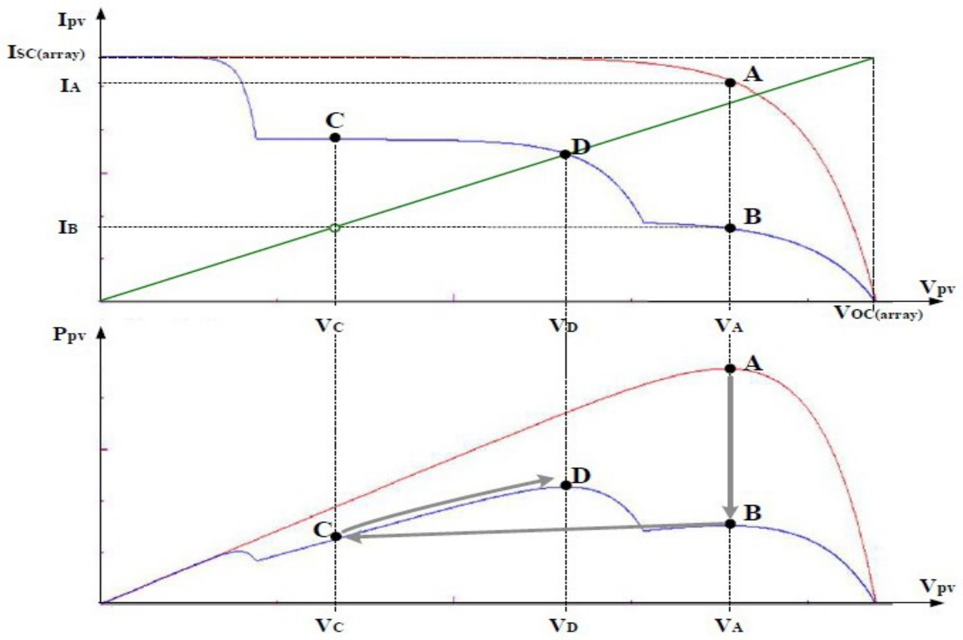


Figure 7.10

In the last example shown with the condition of partial shading the peak is the third one towards high voltage.

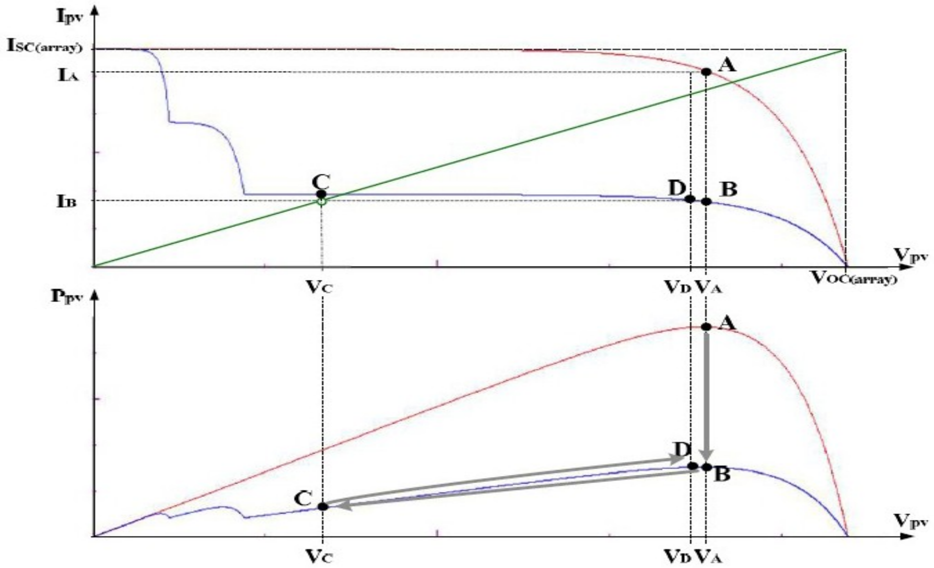


Figure 7.11

The paper implements a circuit with a boost converter in which the algorithm is used with some PI controller (Figure 7.12).

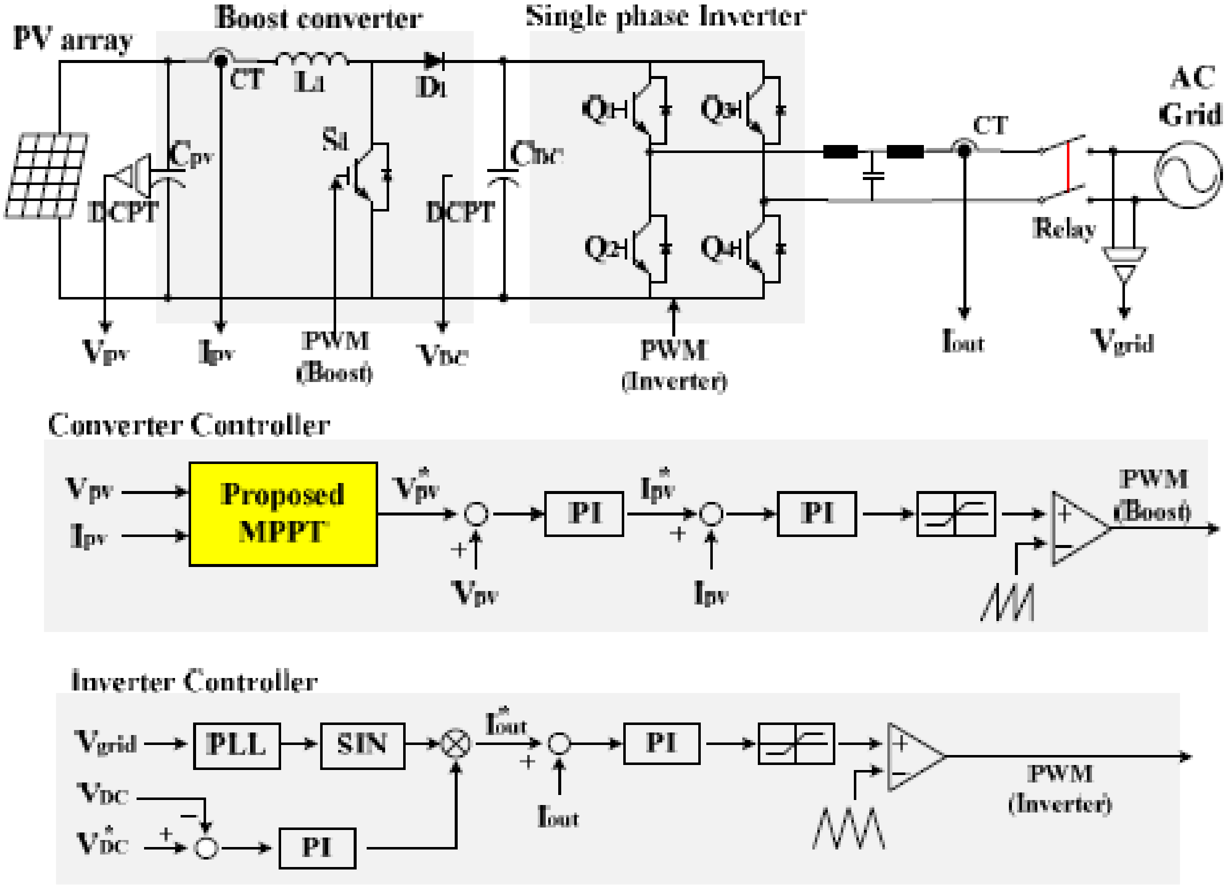
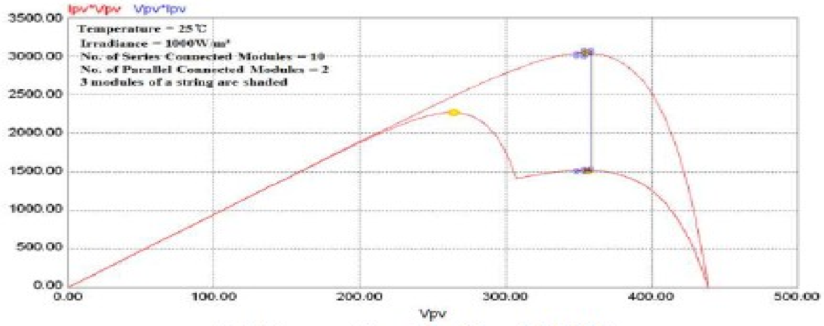


Figure 7.12

To confirm the validation of the algorithm a simple example of partial shading in which the conventional algorithm fails to track the new maximum is reported in the following picture (Figure 7.13).



(a) Conventional IncCond MPPT

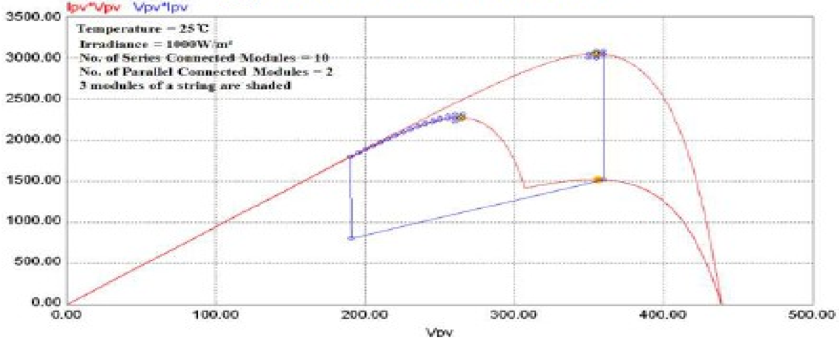
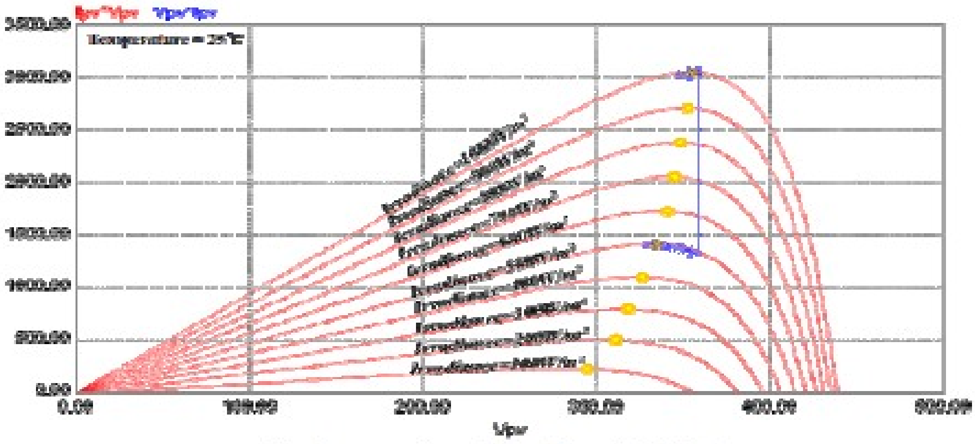


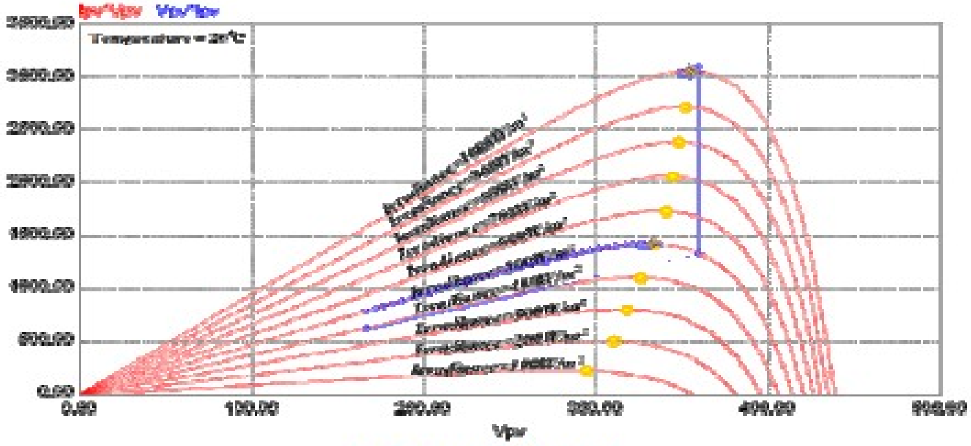
Figure 7.13

Advantages:
-the proposed algorithm can track in every condition of insolation the maximum point of power.
-this MPPT, using the reference voltage to calculate the new operative point of work after a partial shading condition is occurred, allows to achieve the new maximum very quickly.

Drawbacks:
-when the overall insolation of a panel is uniform rapidly changing, the overall characteristic P-V still have just one maximum point, but with the conditions of partial shading the operative point will move and then, it will reach the maximum. It means under that condition a normal method based on increment of conductance has better performance (Figure 7.14).
-the conditions of partial shading is calculated making the difference between two consecutive instant of time. If the two instants of time are not very close it means that the algorithm is not able to react in a very short time in case of a condition of partial shading occurred. On the other hand, if the two instants of time are very close to each other, in the case the insolation changes very slowly over time, the condition of partial shading will not be detected.



(a) Conventional IncCond MPPT



(b) Proposed MPPT

Figure 7.14

7.4 Algorithm based on Increment of Conductance Method

Another solution based on load-line approach is explained following [11]. The load-line can be calculated as the ratio of the V_{MPP} and I_{MPP}. These values can be obtained from the following estimation:

$$V_{MPP} = 0.8\%\ V_{OC}$$
$$I_{MPP} = 0.9\%\ I_{SC}$$

where V_{OC} and I_{SC} are the voltage open circuit and current short circuit evaluated under condition of uniform insolation.

In case of partial shading, the operative point moves close to the intersection between the I-V characteristic and the load-line. Thus, applying a conventional increment of conductance method the MPP can be tracked (Figure 7.15).

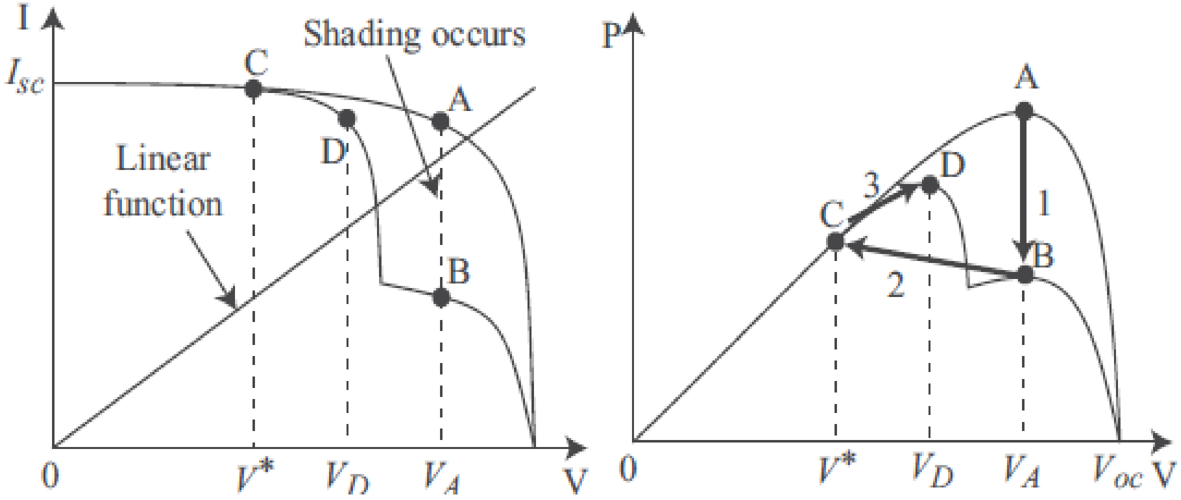


Figure 7.15

The condition of maximum power point is obtained when the following equation is verified:

$$\frac{\delta P}{\delta V} = 0 \qquad (7.4)$$

it means:

$$\frac{\delta P}{\delta V} = \frac{\delta (V \cdot I)}{\delta V} = \frac{\delta I}{\delta V} V + I \approx \frac{\Delta I}{\Delta V} V + I \qquad (7.5)$$

then,

$$\frac{\Delta V}{\Delta I} = \frac{-V}{I} \qquad (7.6)$$

is satisfied when the operating point is actually in maximum power point. Afterwards, at different instant of time a comparison is done in order to find the MPP. In the following picture the flowchart of the Increment of Conductance Method (Figure 7.16) is reported.

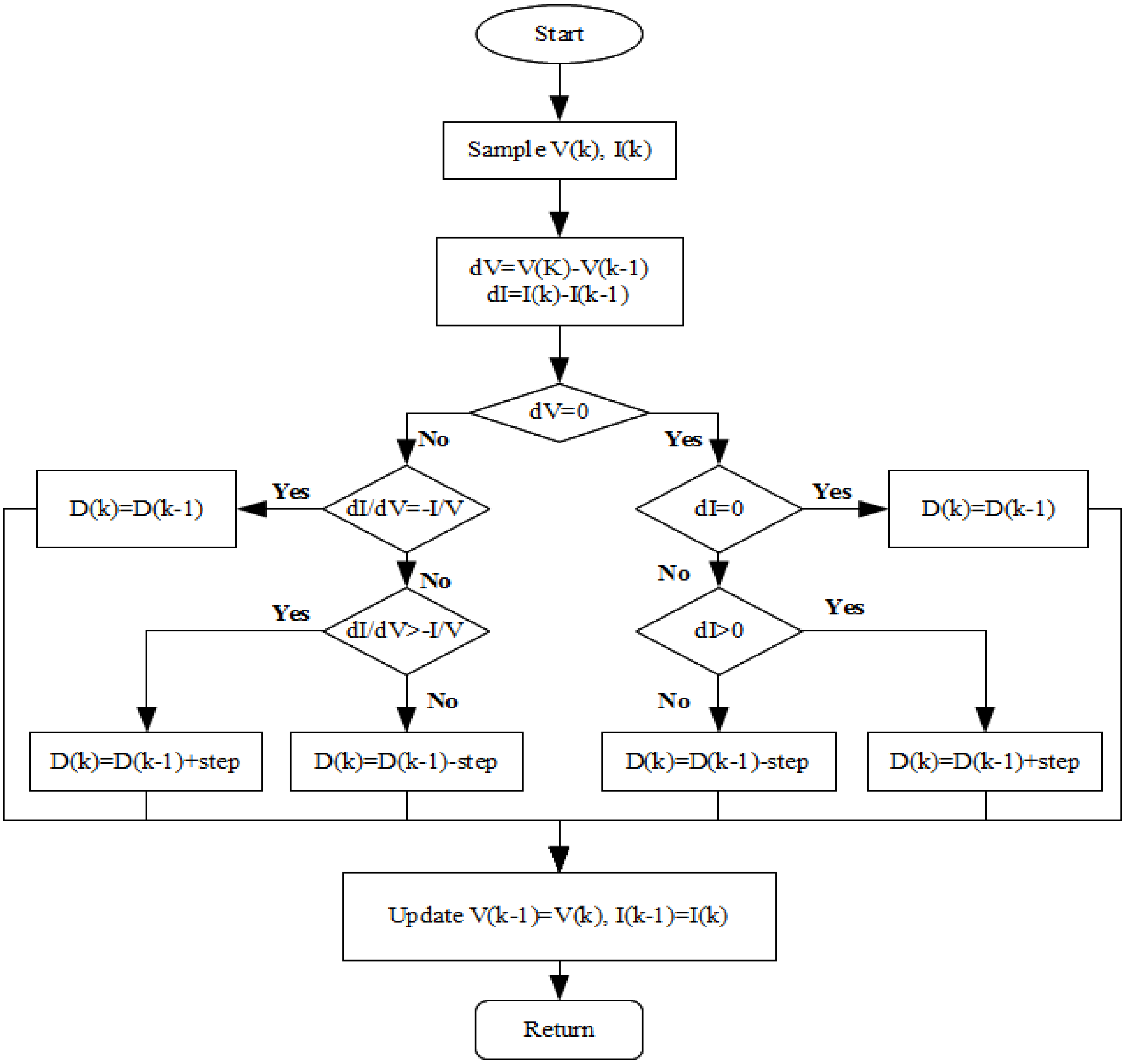


Figure 7.16

Advantages:

-This solution needs an inexpensive microcontroller and a voltage and current sensor to measure V_{OC} and I_{SC}.

-The tracking time of the global MPP is around 0.2-0.3 sec.

Drawbacks:

-The error between the estimated MPP and the real one is around 4.8%.

-The assumption is that global MPP will be close to the intersection between the I-V curve and the load-line. This is not verified for complex partial shading pattern which yields to multi-modal Power-Voltage curves.

7.5 Algorithm based on an extended P&O method

In [7] a new algorithm is proposed to find the global maximum. It uses an extended P&O algorithm and a boost converter coupled to every PV module in order to extract the maximum power. The algorithm has been tested in the circuit reported in Figure 7.17.

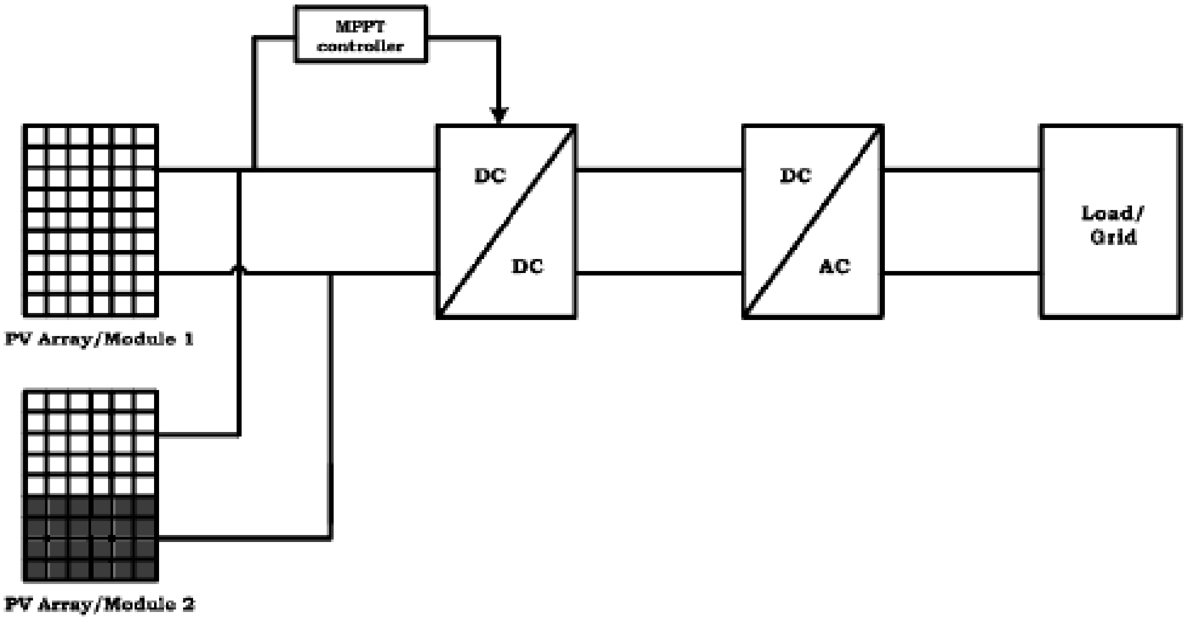


Figure 7.17

In the circuit a couple of voltage and current sensors are used to check the values of voltage and current of every PV module to send to the MPPT block. This solution employs just one MPPT block and thus, it doesn't affect the cost of the overall system.
The flowchart of the algorithm is reported in the following picture (Figure 7.18).

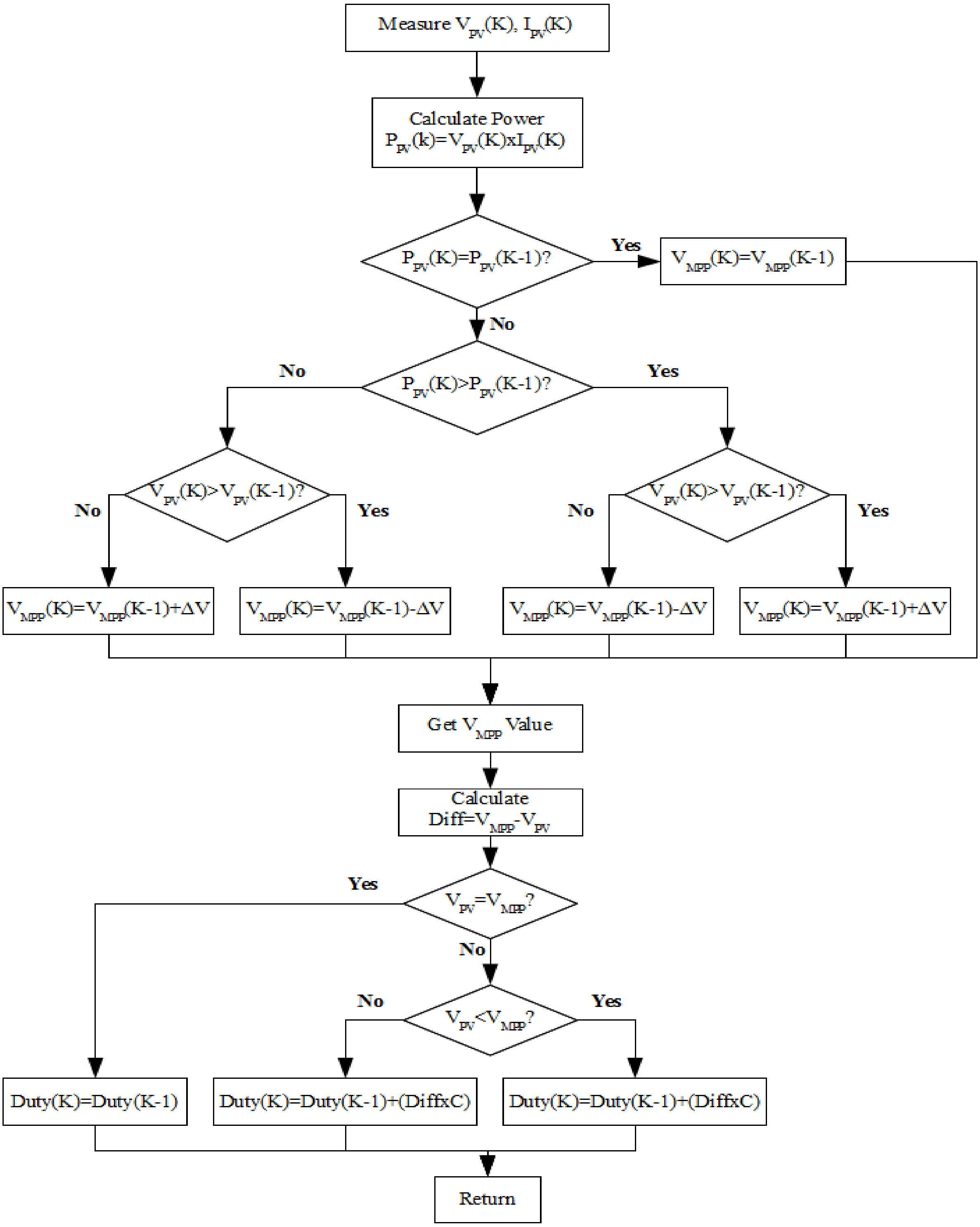


Figure 7.18

For every PV module, after measuring the voltage and current, the PV power is calculated and compared with the power in the previous instant. If the power is the same as before, it means that the system is working in the MPP and the value of the voltage is stored. Otherwise, if the power is bigger than the previous case, it checks if the voltage is increased or not. If yes, V_{MPP} will be increased otherwise it will be decreased.

After obtained the value of V_{MPP}, the difference of V_{MPP} and V_{MODULE} is calculated. If $V_{MPP}=V_{PV}$, then the duty cycle remains the same as it was before. If $V_{MPP}<V_{PV}$ the duty cycle will be decreased

or it will be increased in the case of $V_{MPP}>V_{PV}$.
The power extracted from the PV panel has to go through the boost converter, since the overall efficiency is affected from this term. In the table reported in Figure 7.19, for the configuration of the circuit adopted, the efficiency of the overall circuit for different value of the load power is shown. This system can reach an efficiency of around 99%.

Load (Ω)	PV Module Voltage (V)	PV Module Current (A)	PV Module Power (W)	Load Power (W)	MPPT Efficiency (%) $= \frac{P_{out}(\text{tracked})}{P_{max}(\text{rated})} \times 100$
20	20,26	3,29	66,79	66,47	99,49
40	20,25	3,29	66,79	66,43	99,43
60	20,25	3,29	66,79	66,37	99,34
80	20,26	3,29	66,79	66,31	99,25

Figure 7.19

7.6 Power Increment Technique

Another solution is the one called "Power Increment Technique" shown in the paper [7], where the power converter is controlled by a microcontroller to operate as an adjustable constant input power load.
As we can see in Figure 7.20, starting from the open circuit condition (point B_1), the dc/dc converter is controlled to draw a successively higher amount of power.

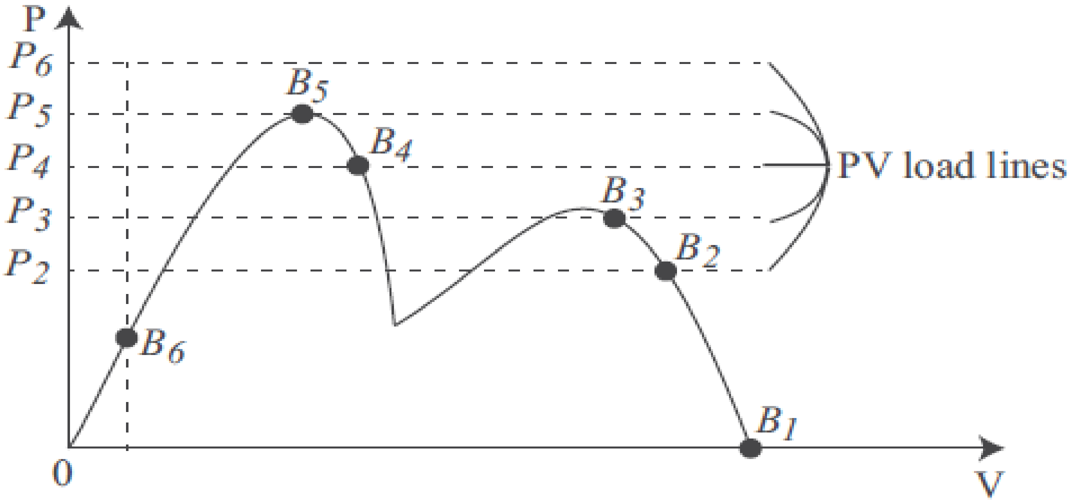


Figure 7.20

At each step the amount of power is increased, moving progressively towards higher output power levels (B_1, B_2, B_3, B_4 and B_5). The corresponding PV voltage is stored by the microcontroller.
After the MPP (point B_5) is achieved, the next increment of power will bring the system to converge to the level of power shown in Figure 7.20 as the point B_6, where the increment of output power is inhibited. This algorithm is able to avoid to be trapped in local maximum (point B_3) and it can detect the global maximum.
Once the system is in the point B_6, this condition means that the previous point was the MPP and the dc-dc converter regulates the output voltage of the PV array at the voltage stored by the microcontroller corresponding to the point B_5. Therefore, the converter operates close to the global MPP and a normal P&O or hill climbing is adopted to reach it.
This process is repeated periodically (in example every 1-15 minutes) and then for the remaining time, P&O or hill climbing is used to track the short variation.
The experimental results show that the energy loss under condition of unshaded PV Panel due to the iterative application of the PV scan, with interval scan of 15 minutes, results in less than 0.06% of maximum energy.
An advantage of this technique is that it doesn't require any information about the characteristics and configurations of the PV modules and the maximum can be detected very accurately. Additionally, the tracking speed of this solution is less than PV curve scanning method.

7.7 Power curve slope

This technique uses the slope of PV curve to detect the global maximum of power. As it is well known, a maximum in the curve correspond $\frac{\Delta P}{\Delta V}=0$, when this condition is verified the value of the power is stored in order to make successive comparison with other maximum [5]. As we can see in Figure 7.21, the presence of another maximum on the left side is detected by changing the slope of the characteristic from positive to negative.

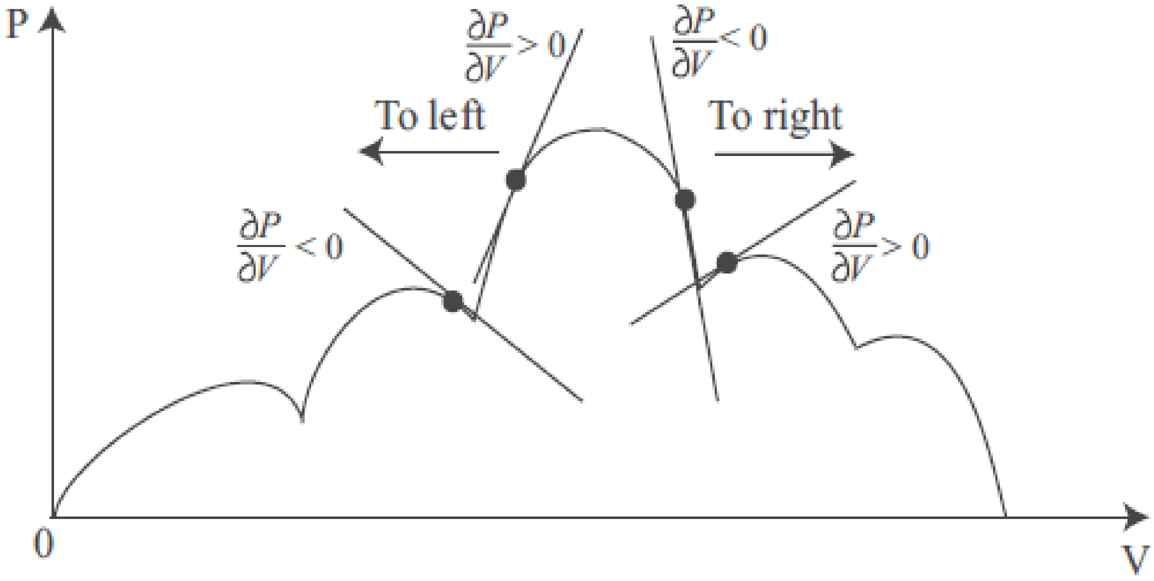


Figure 7.21

On the right side, the slope of PV curve presents a maximum when the slope changes from negative to positive.
The algorithm starts to search the presence of other maximum from the global maximum detected so far. It starts moving from one side, when the slope changes it means the characteristic presents another maximum, it could be a new global or a local maximum. When the condition $\frac{\Delta P}{\Delta V}=0$ will be verified, the value of the power is compared with the previous maximum detected. If this new maximum is greater than the previous one, it will be the new global maximum and the search of other maximum will continue in the same direction. Otherwise, it means that there will be no other higher maximum in that direction, therefore the algorithm will stop searching in that side and will start looking other maximum on the other side of the previous maximum detected.
Once a new local maximum is detected, it means the previous maximum is effectively the global maximum of all the characteristic curve. The fact that the algorithm doesn't search a maximum along the whole curve but just until a local maximum is detected, it reduces the time of tracking the global maximum.

Advantages:
-This solution can be simply implemented by an inexpensive microcontroller and a voltage and current sensor.
-The experiment showed that this technique can detect the maximum with enough accuracy, the difference between the calculated global result and the actual global result is found to be less than 0.5%

Drawbacks:
-This technique is not fast enough for the portable PV applications due to the fast changing of condition of insolation.

7.8 Instantaneous Operating Power Optimization

This technique makes a comparison between the measured power $P_{meas}(t)$ across the PV panel and the instantaneous maximum power reference value, which depends on the p-n junctions temperature T(t) and irradiance E(t).

$$P_{MPP}(t)=P_{MPP}(T(t),E(t)) \tag{7.7}$$

Thus the expression can be written as

$$P_{MPP}(t)=a[T(t)]\cdot b[E(t)] \tag{7.8}$$

where a(T(t)) is the voltage factor and b(E(t)) is the irradiance factor. The irradiance factor determines the value of the current at the maximum point of power $I_{MPP}(E)$. If I_{MPP} is less than a specified threshold, $a(T(t))=a_0$, where a_0 is a constant value. Otherwise the voltage factor will be variable. Usually a level of threshold could be chosen as half value of the maximum current of the panel I_r.
Once a(T(t)) is found, the algorithm continues to compare the measured PV power $P_{meas}(t)$ and the

reference power $P(t)=a(T(t))I_{meas}(t)$, where I_{meas} is the measured current of the PV array [10]. If $P_{meas}(t)<P(t)$, I_{MPP} is tracked by decreasing the measured current as shown in the following equation:

$$I(t)=I_{meas}(t)-\Delta I \tag{7.9}$$

where ΔI is kept constant. In the case of $P_{meas}(t)>P(t)$, I_{MPP} is tracked by changing the value of the current:

$$I(t)=\frac{P_{meas}(t)}{a(T)} \tag{7.10}$$

This procedure will be repeated till the following equation is satisfied:

$$\frac{P_{meas}(t)-a(T)I_{meas}}{P_{meas}(t-1)}<\varepsilon \tag{7.11}$$

where ε is a prefixed error.
The P&O is adopted to assess a(T(t)). In order to optimize the procedure, a preventive assessment of the voltage factor is done and the ratio:

$$K_i=\frac{I_{local}}{I_{MPP}} \tag{7.12}$$

is useful to move rapidly along the characteristic.
Finally, to increase the dynamics, the P&O procedure is used only if the last measured current $I_{meas}(t)$ is far from the current value of P_{MPP} assessed by the last P&O (Ip&o).
In the following picture the flowchart of the algorithm is reported (Figure 7.22).

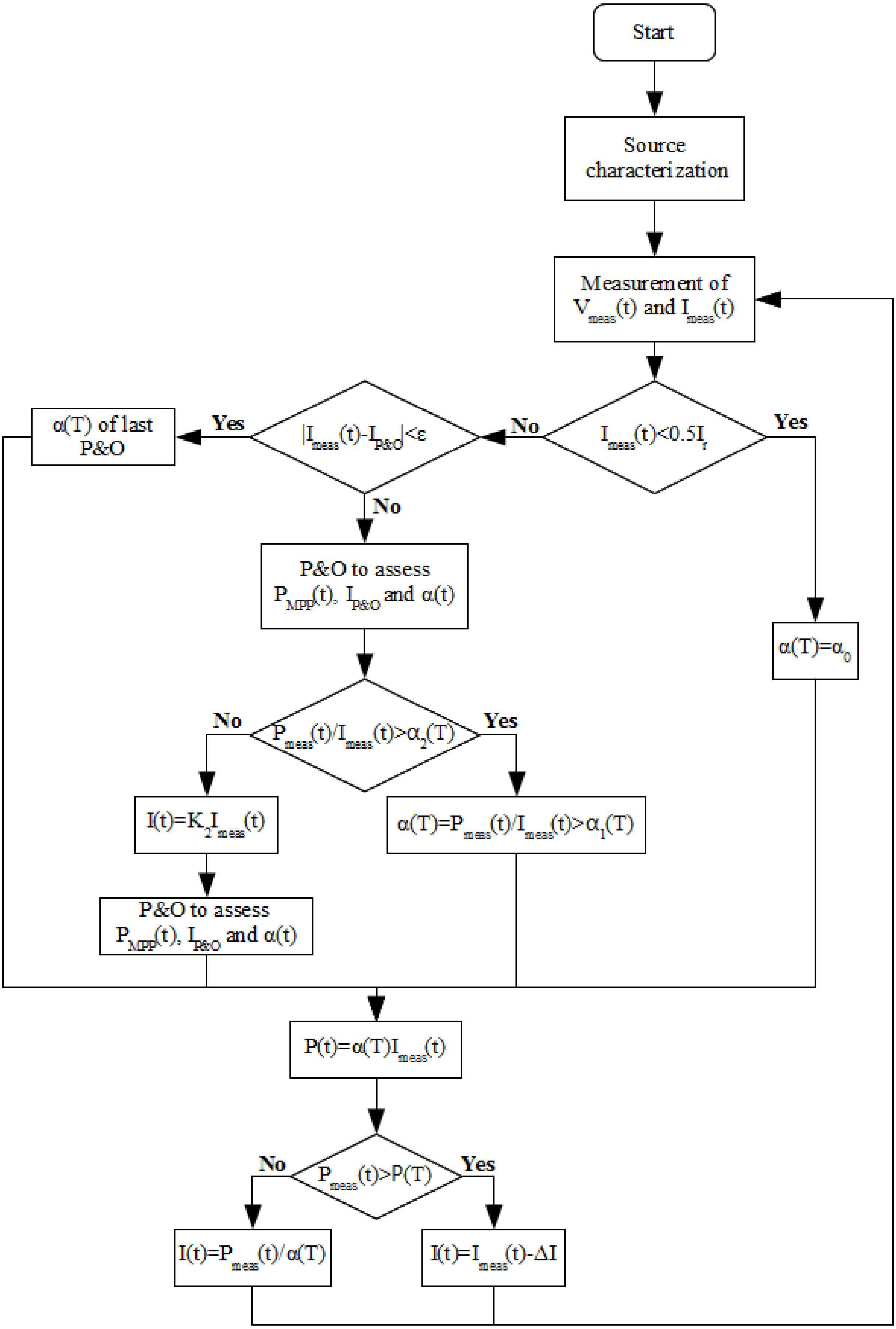

Start
Source characterization
Measurement of $V_{meas}(t)$ and $I_{meas}(t)$
$I_{meas}(t)<0.5I_r$
Yes
No
$|I_{meas}(t)-I_{P\&O}|<\varepsilon$
Yes
$\alpha(T)$ of last P&O
No
$\alpha(T)=\alpha_0$
P&O to assess $P_{MPP}(t)$, $I_{P\&O}$ and $\alpha(t)$
No
$P_{meas}(t)/I_{meas}(t)>\alpha_2(T)$
Yes
$I(t)=K_2I_{meas}(t)$
$\alpha(T)=P_{meas}(t)/I_{meas}(t)>\alpha_1(T)$
P&O to assess $P_{MPP}(t)$, $I_{P\&O}$ and $\alpha(t)$
$P(t)=\alpha(T)I_{meas}(t)$
No
$P_{meas}(t)>P(T)$
Yes
$I(t)=P_{meas}(t)/\alpha(T)$
$I(t)=I_{meas}(t)-\Delta I$

Figure 7.22

Advantages:

-The experimental results show that the maximum can be tracked in less than 0.2 sec.

-The difference between the estimated global maximum and its actual value is less than 1% of the value of the real MPP.

-This solution can be implemented by using an inexpensive microcontroller and with voltage and current sensors.

Drawbacks:

-At the start, a procedure to characterize the PV panel is needed in order to assess the maximum current and then find the value of K_i.

7.9 Fibonacci search

This technique relies on a successive shifting and restricting of the interval in which the maximum is included [13].

The algorithm uses the well known Fibonacci sequence:

$$\begin{gathered} c_0=0 \\ c_1=1 \\ c_n=c_{n-2}+c_{n-1}\,,\; n\geqslant 2 \end{gathered} \tag{7.13}$$

As we can see from the Figure 7.23, at each iteration of the algorithm, the curve is evaluated in two points (ν_1^i, ν_2^i) within the interval search (ν_3^i, ν_4^i) .

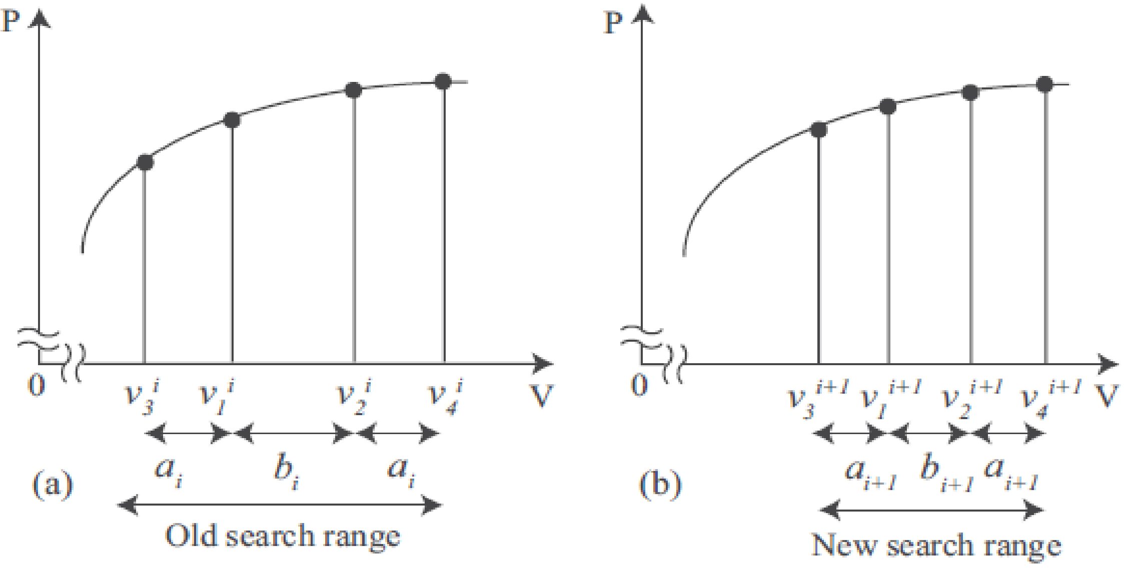


Figure 7.23

The interval search (ν_1^i, ν_2^i) represent the old interval search and on the next iteration it will be reduced as can be noted from the Fibonacci equations:

$$\begin{gathered}\frac{a_{i+1}}{b_{i+1}} = \frac{c_n}{c_{n-1}} \\ \frac{a_i}{b_i} = \frac{c_{n+1}}{c_n} \text{¿¿}\end{gathered} \tag{7.14}$$

where “a$_i$” indicates the distance between the old interval bound and the current interval search and “b$_i$” denotes the amplitude of the interval search.
The interval of searching of the next iteration will be characterized by the rule derived from the following equations:

$$\begin{gathered} if\ P(\nu_1^i) < P(\nu_2^i) \Rightarrow \nu_3^{(i+1)} = \nu_1^i,\ \nu_4^{(i+1)} = \nu_4^i \\ if\ P(\nu_1^i) > P(\nu_2^i) \Rightarrow \nu_3^{(i+1)} = \nu_3^i,\ \nu_4^{(i+1)} = \nu_2^i \end{gathered} \tag{7.15}$$

As can be seen, at each iteration the value of power corresponding to the points on the bound of the interval search are compared. The point on the bound which presents a higher value of power will be kept fixed for the interval of the next iteration and the other one will be reduced by the rule presented above. Thus the step size is variable at each iteration. In this condition the global maximum will always be kept within the interval search. The iterations will end when the following equation will be satisfied:

$$\begin{gathered} |\nu_4^i - \nu_3^i| < \delta \\ |P(\nu_4^i) - P(\nu_3^i)| \leqslant \varepsilon \end{gathered} \tag{7.16}$$

where δ and ε are predetermined tolerances.

Advantages:
-The tracking speed of the global maximum point of power is considered acceptable.
-This solution can be implemented by using an inexpensive microcontroller and voltage and current sensors.

Drawbacks:
-In some simulation this technique fails to track the real global maximum. In case of a complex partial shading pattern, the variable step size rules by the Fibonacci sequence can mistakenly avoid to detect the global maximum and be trapped in a local maximum.

7.10 Fuzzy Logic Control

This technique is composed of three stages: fuzzification, rule base table lookup and defuzzification [14]. In the fuzzification, five linguistic variables are used to convert the numerical input variables:

- -NB (Negative big)
- -NS (Negative small)
- -ZE (Zero)
- -PS (Positive small)
- -PB (Positive big)

In Figure 7.24 is reported a diagram of classification of the numeric variable is reported.

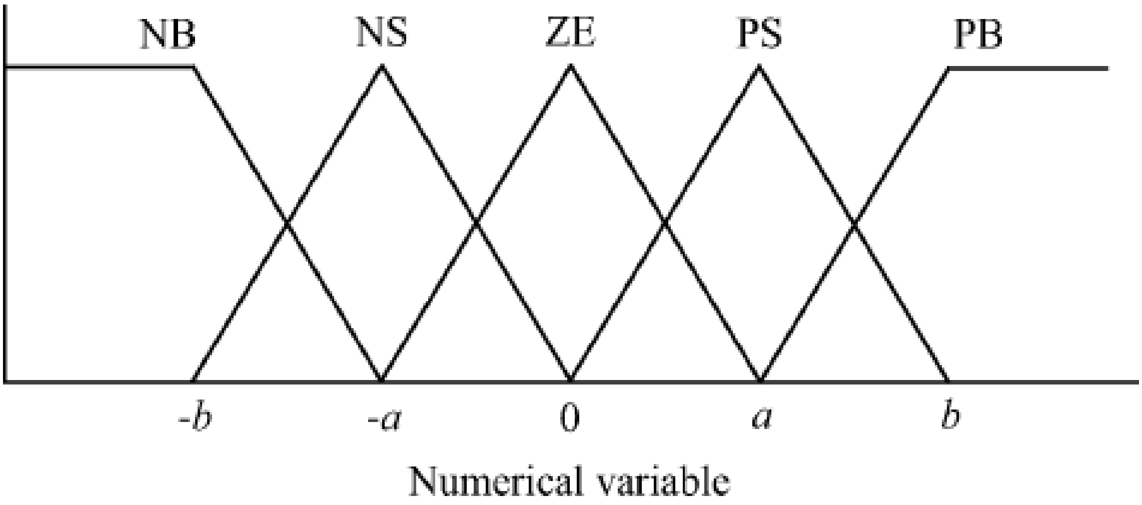


Figure 7.24

At MPP is verified the follow condition:

$$\frac{\delta P}{\delta V}=0 \tag{7.17}$$

Thus, we can define the variables E and ΔE:

$$\begin{gathered} E(n)=\frac{P(n)-P(n-1)}{V(n)-V(n-1)} \\ \Delta E=E(n)-E(n-1) \end{gathered} \tag{7.18}$$

Once E and ΔE are calculated, the algorithm works converting their values in linguistic value (Figure 7.24) and then, they are process through the table reported in Figure 7.25.

ΔE\E	NB	NS	ZE	PS	PB
NB	ZE	ZE	NB	NB	NB
NS	ZE	ZE	NS	NS	NS
ZE	NS	ZE	ZE	ZE	PS
PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

Figure 7.25

The corresponding value matched by E-ΔE results in an output that changes the duty ratio ΔD of the power converter. For example, if the operating point is far to the left of the MPP this implies that E is PB (Positive big) and ΔE is ZE (Zero). Looking up on the table (Figure 7.25), we can note that the result will be PB (Positive big). It means that the variation on duty cycle will be big in order to do a big step change on the Power-Voltage curve and achieve the MPP.
In the defuzzification stage we will do the inverse operation that is done during the first stage. It means that the variation of duty cycle matched by the couple E-ΔE will be converted from linguistic variable to a numeric variable still using the rules as shown in Figure 7.24. It's obvious that an analog signal is required to command the duty cycle of the switch.

Advantages:
-This technique can work with imprecise inputs, not needing an accurate mathematical model.
-Fast convergence to the MPP and minimal fluctuation around it.

Drawbacks:
-The effectiveness depends on the control that has to choose the right error.

7.11 Artificial Neural Networks (ANN)

This technique is based on a neural network which has three-layer that consists of an input layer, a hidden layer of neurons, and an output layer, shown in Figure 7.26.

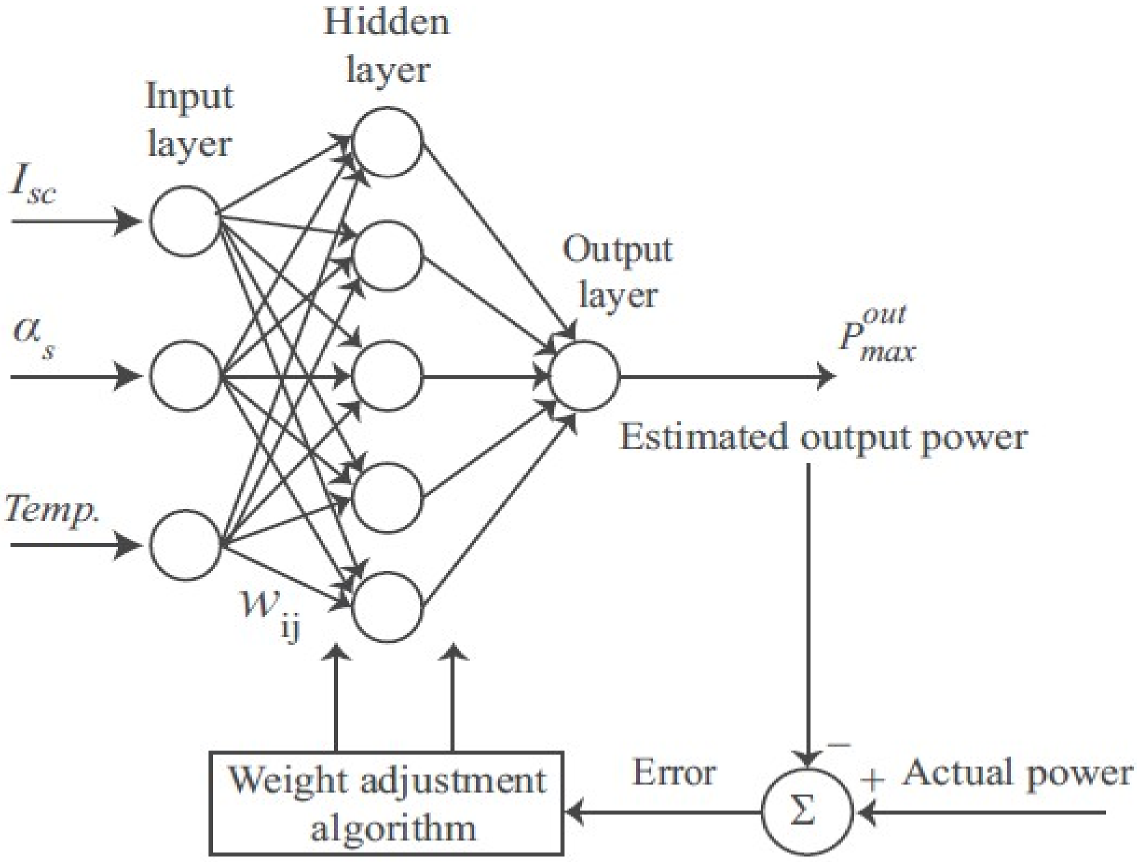


Figure 7.26

The algorithm takes into account the effect of some factors such as temperature Temp., short circuit current I_{SC} and the tilt angle between the sun and the panel α [15].
The neural network works processing the input and try to assess the position of the MPP. The system needs to be trained with a known set of input and output data in order to find the right value of the variables "w_{ij}", which describes the "weight" of different inputs to map the right output.
The algorithm makes the assumptions that the shading due to the movement of objects such as clouds has a uniform effect. It means that the only effect taking into account in partial shading is the sun's position. However, the consideration done before are not always true. An additional fuzzy logic controller is used to track voltage generated by the ANN and thus, the MPP.

Advantages:
-As it is shown in the experiment reported in [15], this solution can track the MPP with a good accuracy and speed.
-This solution can be implemented by an inexpensive microcontrollor, current and temperature sensors.

Drawbacks:
-This system need to be periodically tuned in order to calculate the right irradiance factor at any conditions .
-In order to preserve the accuracy, the system needs to be trained due to the change in time by the characteristic of the PV array.

7.12 Comparison of various techniques to detect MPP

The various aspects are taken into account in order to compare the solutions explained so far [16].

Implementation
This aspect depends on the end-users' knowledge. In the case of analog circuit it is better to choose implementations such as load current or voltage maximization. Otherwise, in digital circuitry it could be necessary to use softwares and algorithms such as P&O, IncCond, fuzzy logic control, artificial neural network (ANN) and dP/dV.

Sensors
The number of sensor affects the overall cost of the system MPPT. Thus, it is easier and more reliable to measure voltage than current. They are usually expensive and bulky. This consideration has to be taken into account in the case of several PV arrays with separate MPP tracker. It's preferable to choose a solution in which one sensor is required.

Costs
It is very hard to speak about costs of different solutions until the system is built. However, a good way to make a comparison could be if the technique is analog or digital, if it requires software and programming and the number of sensors. Usually analog circuit based solution is cheaper than digital, which normally require the presence of a microcontroller and they need to be programmed. Moreover solutions with no current sensors are preferred, which are much more expensive than voltage sensors.

Application
The techniques and the purposes are different in relation to the application in which the MPP tracker is applied:

-space satellites and orbital station: in this case the costs and complexity of the overall project is not really important. The main purpose is to have a MPPT with high performance, reliability and without the requirement of periodical tuning. The tracking time has to be very fast and the system has to work on the MPP in any condition. In such cases are adopted solution as P&O, IncCond.

-solar vehicle: in this case the main interest is to have a system in which the convergence to the MPP is very fast. In this case the techniques such as Fuzzy logic control and artificial neural network (ANN) are appropriate.

-residential areas: in this application constantly and quickly tracking the MPP is the most important factor in order to payback the cost of the system as soon as possible. A suitable method is IncCond.

8 A new technique for detecting MPP under Partial Shading Condition

8.1 Purpose of the project

In the project that I developed I used the same circuit with boost converter treated in the previous case to verify and compare different solution about the problem of partial shading.
The circuit of the boost converter used in the simulation is reported picture Figure 4.2.
In the following documentation two different techniques using the same electrical circuit are compared in order to find the best one, relative advantages and drawbacks.
Every solution was tested in different panel's configurations with different values of insolation.
Initially every circuit is under condition of uniform insolation and after a certain time a condition of partial shading
is applied in order to check the performances about the algorithm to achieve the maximum point of power.

8.2 First solution proposed

The first algorithmic uses the techniques explained in the paper [6].
The algorithm is based on the generic algorithm called *Perturbation & Observation* to identify the local maximum and then it uses the condition of partial shading explained in the paper mentioned before. This is the reason because the power and the voltage are not very smooth.
The condition of partial shading is verified when the following two equations are satisfied:

$$\Delta V_{pv} = V_{pv}[n] - V_{pv}[n-1] < \Delta V_{SET} \tag{8.1}$$

$$\frac{\Delta I_{pv}}{I_{pv}[n-1]} = \frac{I_{pv}[n] - I_{pv}[n-1]}{I_{pv}[n-1]} < -\Delta I_{SET} \tag{8.2}$$

The condition is satisfied when both a negative step of current and voltage is occurred. The negative step of voltage is usually very small and the step of current has to be very high.
When the equations above are satisfied the value of duty cycle provided to the PWM block has to change.
When the condition of partial shading occurs the MPPT algorithm acts by changing the value of duty cycle in its output in order to move the voltage towards V_{PV} and then it will start again to try to find the maximum point of power using the technique *Perturbation & Observation*, but this time it will be the global maximum.
The value of voltage V_{PV} is

$$V_{pv}^{x} = \left(\frac{N_{sM} \times V_{ocM}}{N_{pM} \times I_{scM}}\right) \times I_{pv}[n] \tag{8.3}$$

Once the value of the new voltage is calculated, the MPPT algorithm acts by changing the value of the duty cycle in its output in order to reach the value of the voltage required.
The code of the algorithm is reported in Appendix A.1.

In the following picture is reported the flowchart of the algorithm (Figure 8.1).

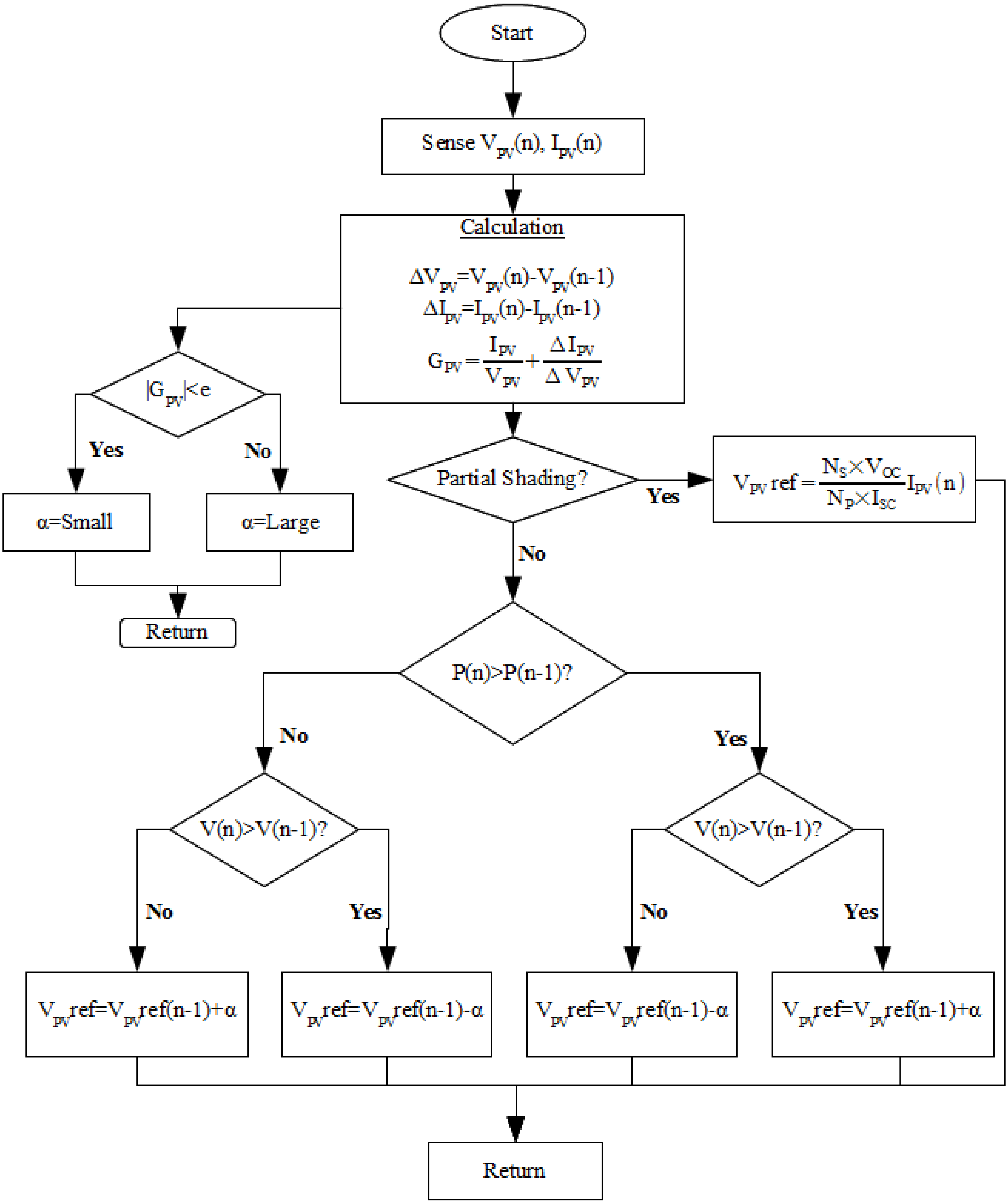


Figure 8.1

The characteristics of this method are as follows:
-The algorithmic needs to know the parameters of the PV Panel, thus it could be a problem once it's commercialized in the market. We need to instruct an operator to set the parameters for every different panel.
-The solution proposed to detect the conditions of partial shading is pretty smart, it doesn't need to

scan all the characteristic Power-Voltage but it determines the right voltage for the working point at which the system has to work to extract the maximum power. This means that the time required by the algorithm to move towards the new maximum point of power is very small, and thus the power loss during the transition is very low.
-For the algorithm proposed, the conditions of partial shading is detected by making the comparison between two different instant of time given by the block “clock”. It becomes obvious that if we are moving from a condition of “uniform insolation” to a condition of “partial shading” over a very long time, we can have some problem because the condition to detect the partial shading between two different instant of the clock will not be satisfied. To solve this problem we could add a condition in which the values of current and power are stored in order to verify the condition of partial shading after a certain time. For this purpose the transition between one look-up table to another one can be made in a very short time (approximate to zero).

8.3 Algorithm based on the scanning of the PV curve

The other algorithm detects the maximum point of power by using a very intuitive technique that is shown in the following picture.
Initially the MPPT algorithmic makes a wide range search to scan the characteristic Power-Voltage and stores the value of the maximum power.

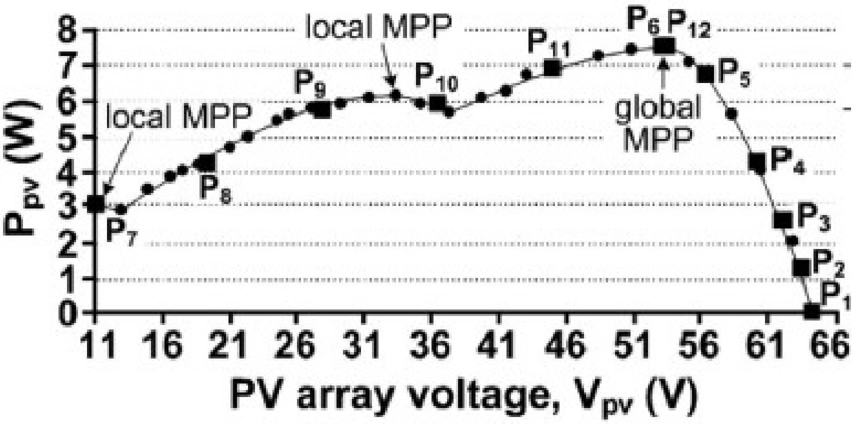


Figure 8.2

The scan is done by changing the value of duty cycle and checking the power along the whole characteristic.
After that the MPPT will go to work in the point of maximum power that was found during the previous scan. Once the maximum is achieved, the algorithmic will start to work with the technique of perturbation and observation (P&O). To detect the conditions of partial shading the value of the maximum power is stored and compared at every cycle of the clock with the operating power. If the difference between the two values of power are greater than a prefix value it means that the partial shading has occurred. In this case a new scan will be done in order to find the new global maximum of power.

Characteristic of this algorithm:
-This MPPT algorithm doesn't require to know the parameters about the connected PV panel. Thus, this algorithmic can have a very commercial application, it doesn't need to instruct operators to set parameters for different panels.

-High precision to detect the global maximum because at every condition of partial shading the whole characteristic of Power-Voltage is scanned.

-The algorithm lets to choose the sampling frequency at which the characteristic Power-Voltage is scanned. In the simulation with MATLAB, the time required by the algorithm can be around 0.1-0.2 sec.

The code of the algorithm is reported in Appendix A.2.

In the following picture is reported the flowchart of the algorithm (Figure 8.3).

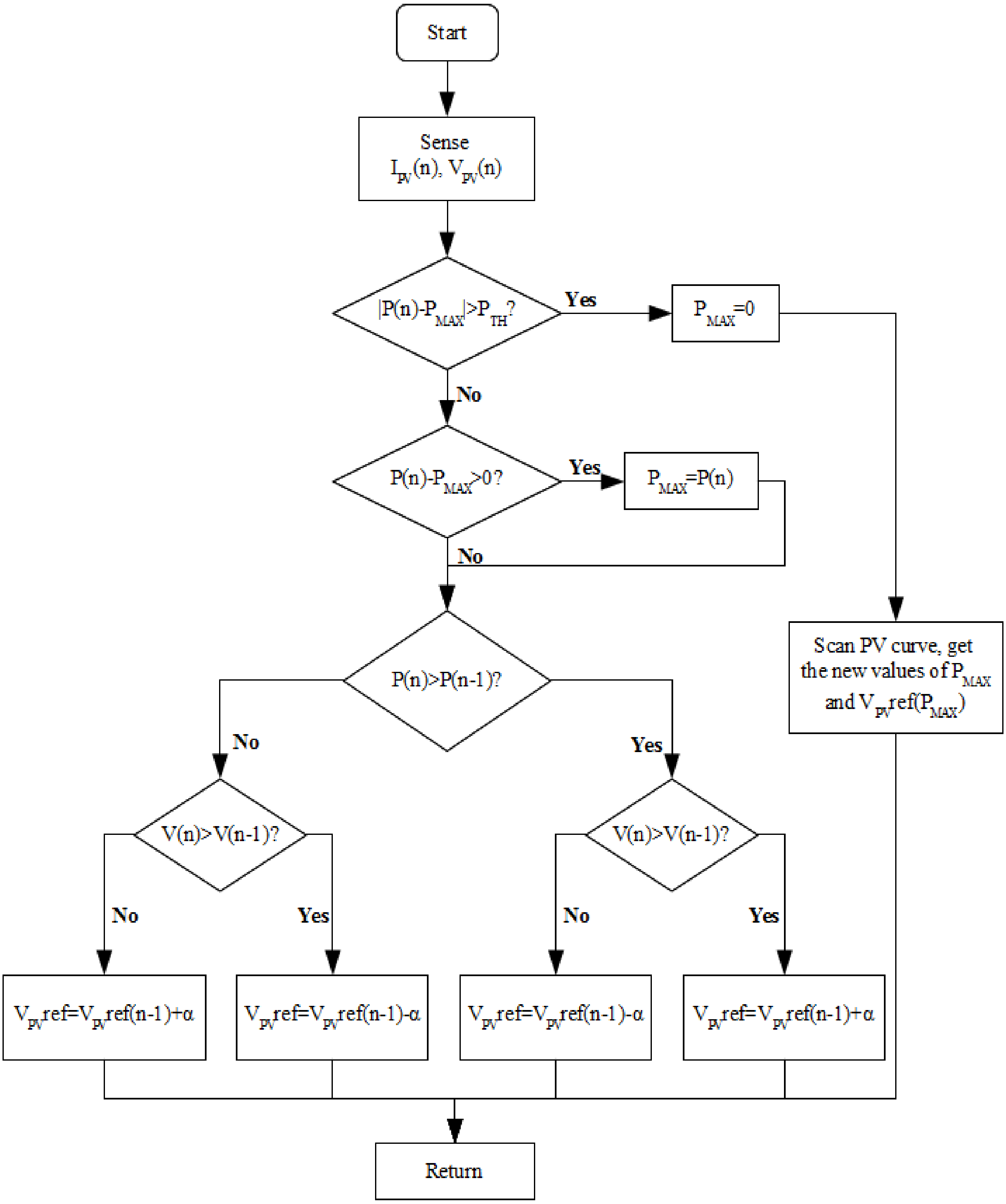


Figure 8.3

8.4 Simulations in MATLAB

In the following pictures (Figure 8.4) some screens of the simulation are reported in order to compare the performance about the two algorithms explained in the previous pages.
In condition of uniform insolation the details of the panel are as follows:

- Voltage open circuit (Voc) : 205.4 Voltage
- Current short circuit (Isc) : 11.22 Ampere
- Insolation values: PS Constant1=PSConstant2=...=PSConstant8=1000 $\frac{W}{m^2}$

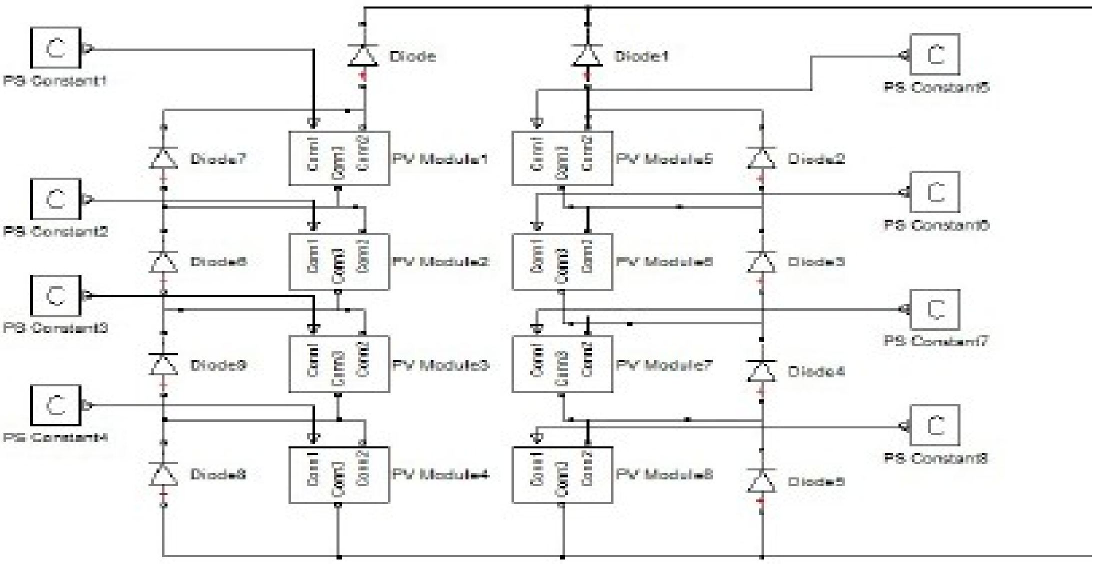


Figure 8.4

The following pictures show the characteristics of Power (Watt)- Voltage (Volt) and Current (Amper)- Voltage(Volt) under condition of uniform insolation.

Power (Watt)-Voltage (Volt)

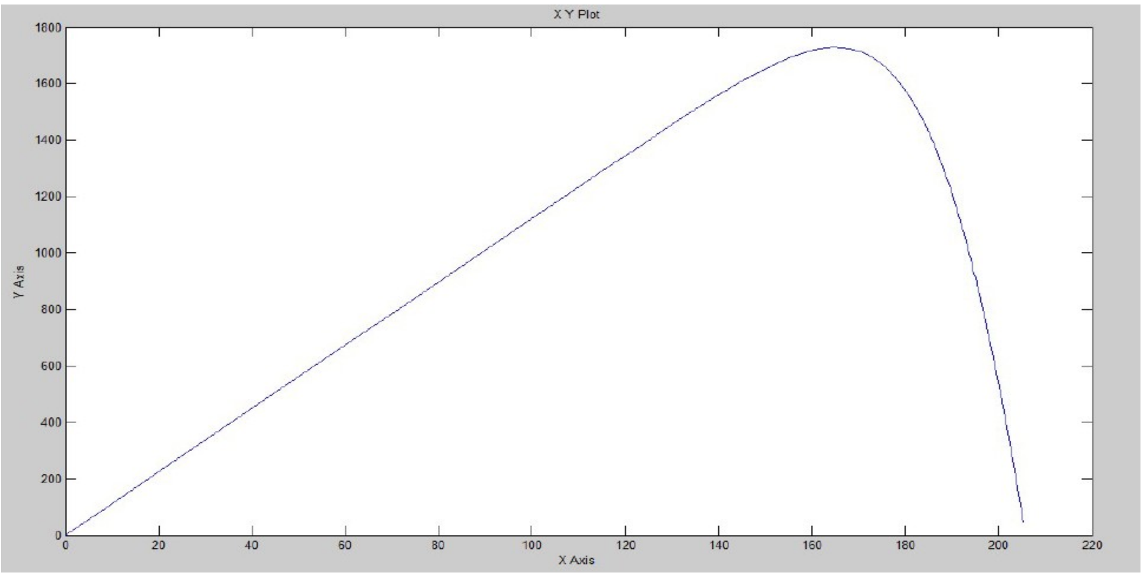


Figure 8.5

Current (ampere)-Voltage (Volt)

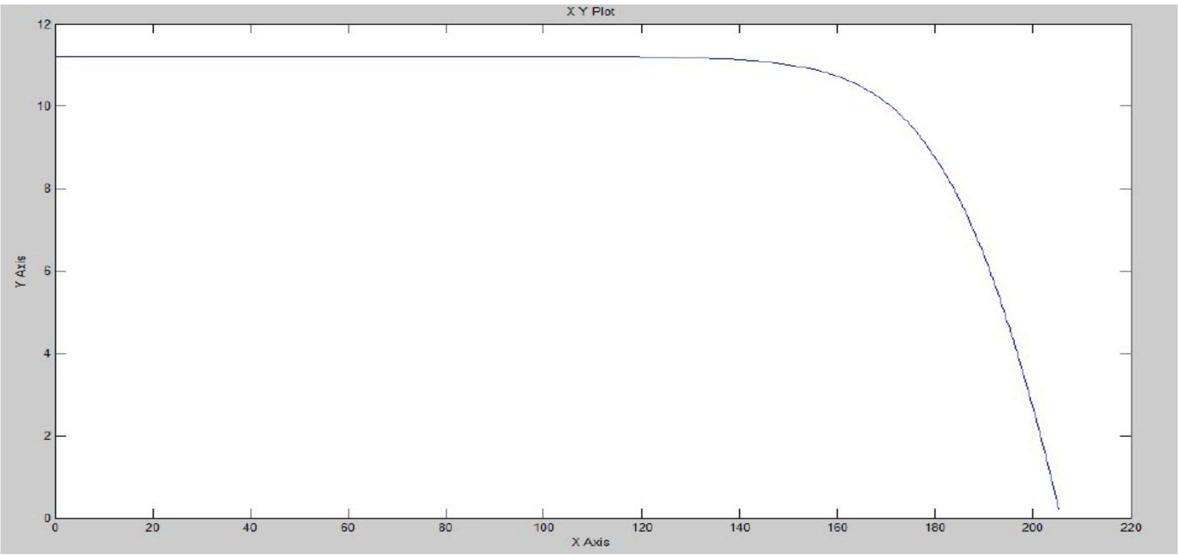


Figure 8.6

Characteristic:

- $V_{MaxPowerPoint}$ (V_{MPP})=165 Volt
- $P_{MaxPowerPoint}$ (P_{MPP})=1740 Watt

In order to test the circuit and the algorithm three conditions of partial shading are created with different combination of insolation.

First Peak Global Maximun Point of Power

Values of insolation: PsConstant1=PsConstant2=PsConstant6=PsConstant8=1000 $\frac{W}{m^2}$

PsConstant3=PsConstant4=100, PsConstant5=200, PsConstant7=700 $\frac{W}{m^2}$

Power (Watt)-Voltage (Volt) Current (ampere)-Voltage (Volt)

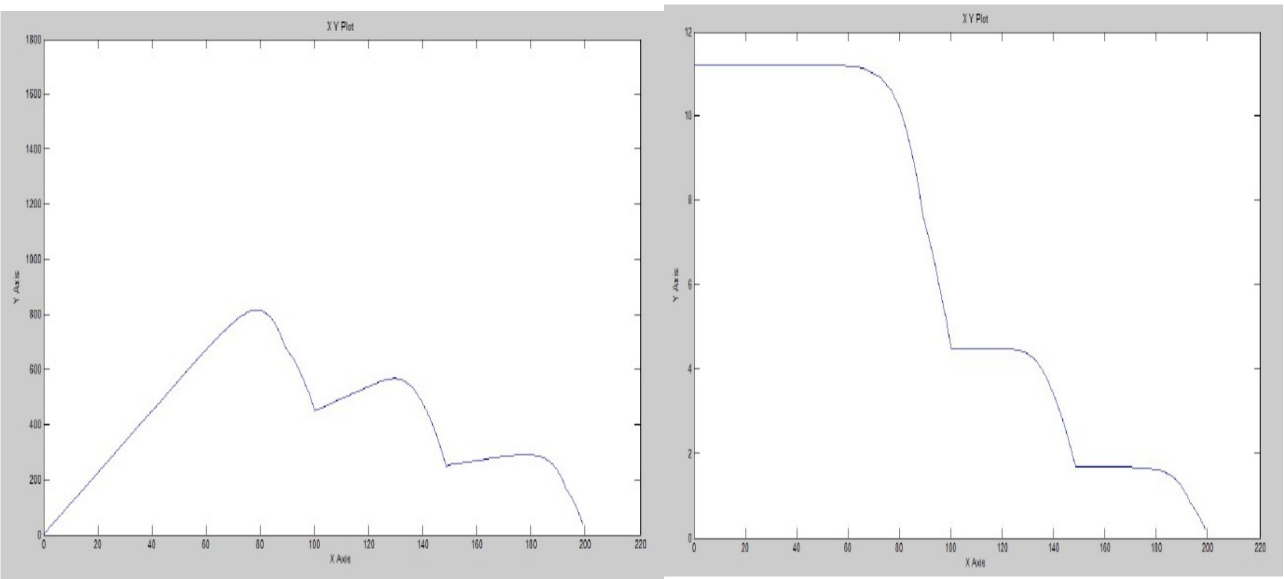


Figure 8.7

Characteristic:

- $V_{MaxPowerPoint}$ (V_{MPP})=78 Volt
- $P_{MaxPowerPoint}$ (P_{MPP})=810 Watt

<u>Second Peak Global Maximun Point of Power</u>

Values of insolation:

PsConstant1=PsConstant2=PsConstant5=PsConstant6=PsConstant7=PsConstant8=1000 $\frac{W}{m^2}$

PsConstant3=700, PsConstant4=50 $\frac{W}{m^2}$

Power (Watt)-Voltage (Volt) Current (ampere)-Voltage (Volt)

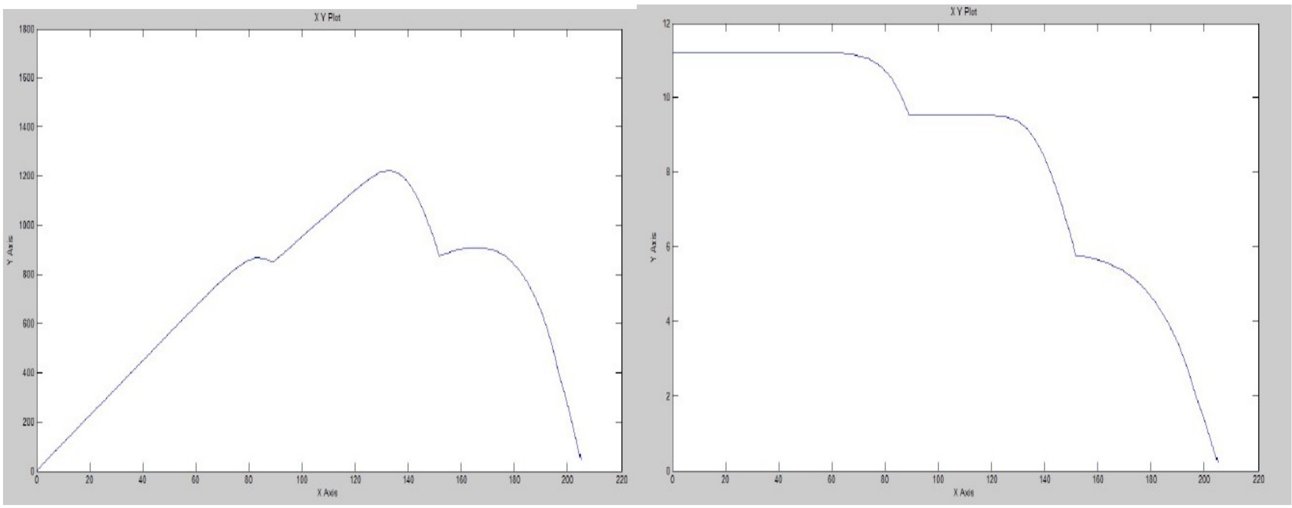


Figure 8.8

Characteristic:

- $V_{MaxPowerPoint}$ (V_{MPP})=135 Volt
- $P_{MaxPowerPoint}$ (P_{MPP})=1220 Watt

Third Peak Global Maximun Point of Power

Values of insolation:

PsConstant1=PsConstant2=PsConstant3=PsConstant4=PsConstant8=1000 $\frac{W}{m^2}$

PsConstant5=PsConstant6=100, PsConstant7=500 $\frac{W}{m^2}$

Power (Watt)-Voltage (Volt) Current (ampere)-Voltage (Volt)

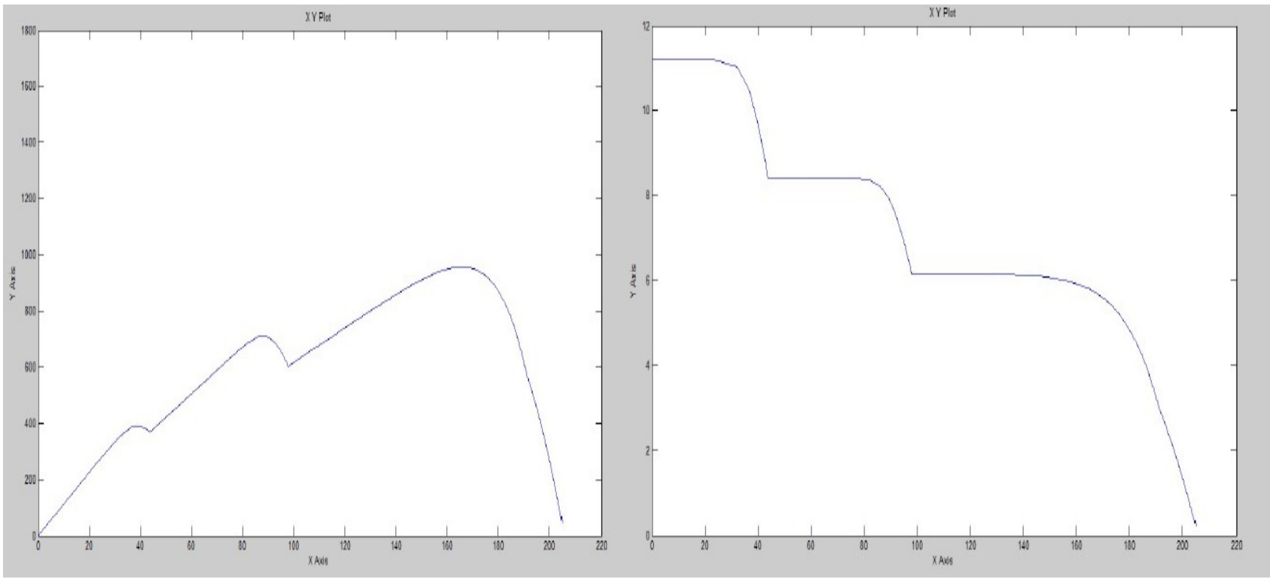


Figure 8.9

Characteristic:

- $V_{MaxPowerPoint}$ (V_{MPP})=167 Volt
- $P_{MaxPowerPoint}$ (P_{MPP})=975 Watt

In order to simulate the circuit in the SimPowerSystem environment for every characteristic the corresponding look-up table was created.

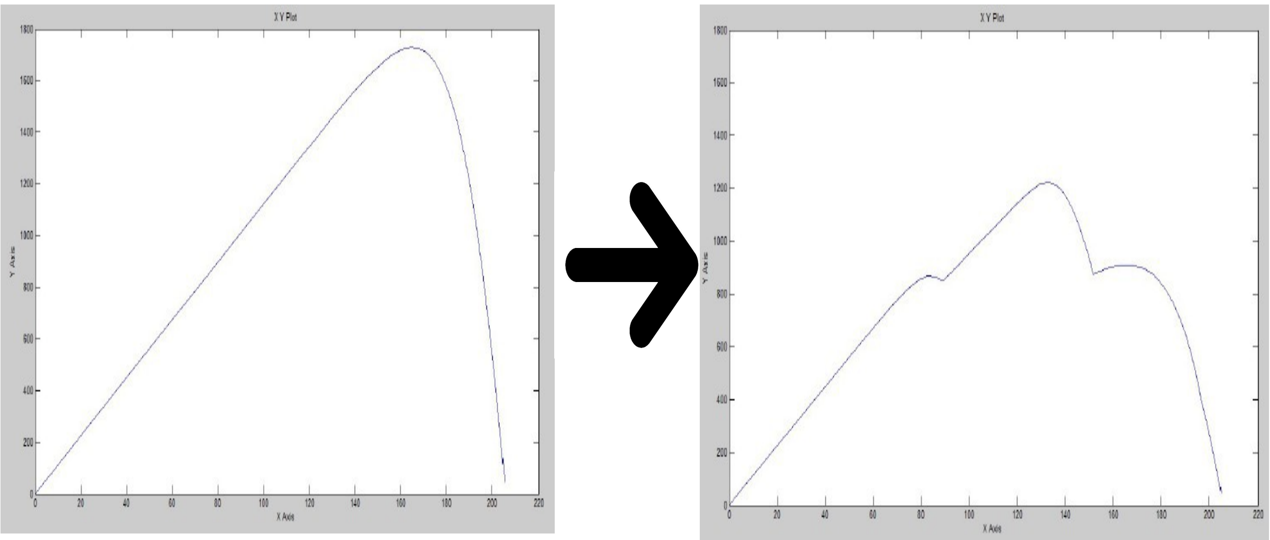
The proposed MPPT were tested under specific conditions of insolation:

-Initially we are under uniform insolation 1000 $\frac{W}{m^2}$

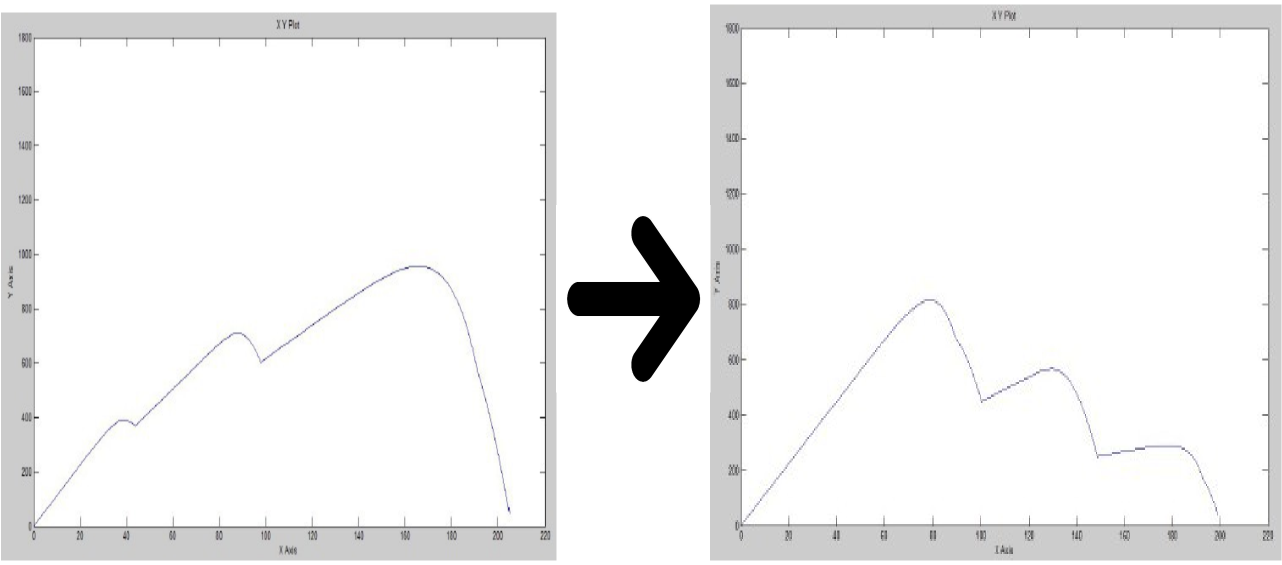
-After 1 sec we shift towards the characteristic "*Second Peak Global Maximun Point of Power*"

-After 2 sec start the we move under condition "*Second Peak Global Maximun Point of Power*"

-After 3 sec start the last condition "*First Peak Global Maximun Point of Power*", this last condition will last for 2 sec.


First conditon (Power-Voltage)

Second condition (Power-Voltage)


Third condition (Power-Voltage)

Fourth condition (Power-Voltage)

Figure 8.10

From the following equations and calculations we can determine how much will be the duty cycle and output voltage for every condition of insolation.

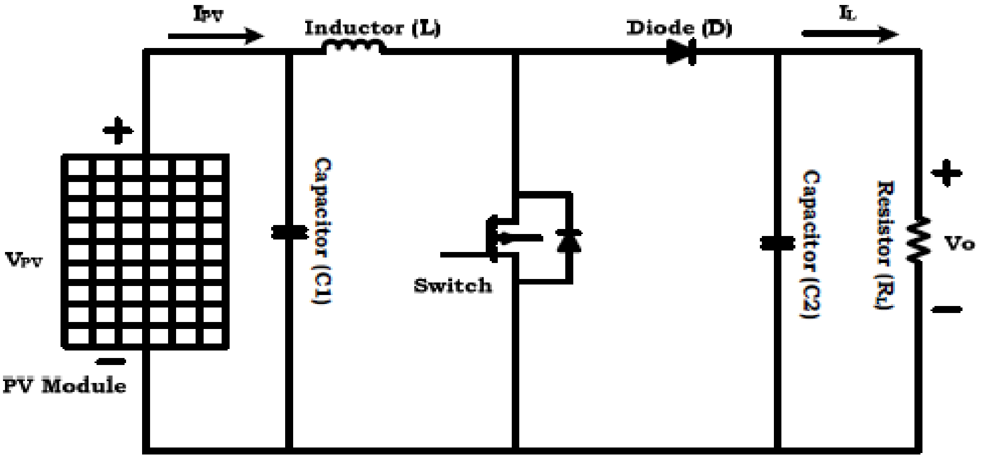


Figure 8.11

The current that goes to the load is given by the follow equations:

$$I_L = \frac{P_0}{V_0} \qquad R_L = \frac{V_0}{I_L} \tag{8.4}$$

and the boost converter output can be expressed as

$$V_0 = \frac{V_i}{1-D} \tag{8.5}$$

If we substitute the last equations we can obtain

$$I_L = \frac{P_0(1-D)}{V_i} \qquad I_L = \frac{V_i}{R_L(1-D)} \tag{8.6}$$

Following can be written

$$V_i^2 = P_0 \times R_L \times (1-D)^2 \tag{8.7}$$

where,

- Vi(VPV) :boost converter input voltage, PV input voltage
- V0 :boost converter output voltage
- IL :boost converter load current.
- P0 :boost converter output power
- RL :load resistence
- D :duty cycle of boost converter

Thus it means that once we know exactly the value of V_{MPP} and P_{MPP} for every condition of insolation we can determine the value of the duty cycle from the follow equation:

$$D = 1 - \frac{V_{MPP}}{\sqrt{P_{MPP} \times R_L}} \tag{8.8}$$

and the voltage output will be:

$$V_{out} = \frac{V_{mpp}}{1 - D} \tag{8.9}$$

Substituting the value of the condition of insolation for a Resistence load of 60 Ohm we will have:

Uniform Insolation:

$$D = 1 - \frac{V_{mpp}}{\sqrt{P_{mpp} \cdot R_l}} = 1 - \frac{165}{\sqrt{1740 \cdot 60}} = 0.4893378 \approx 0.49$$

$$V_{out} = \frac{V_{mpp}}{1 - D} = \frac{165}{1 - 0.49} = 323.529 \approx 325$$

First Peak Global Maximun Point of Power:

$$D = 1 - \frac{V_{mpp}}{\sqrt{P_{mpp} \cdot R_l}} = 1 - \frac{78}{\sqrt{810 \cdot 60}} = 0.6461848 \approx 0.64$$

$$V_{out} = \frac{V_{mpp}}{1 - D} = \frac{78}{1 - 0.64} = 216.66 \approx 215$$

Second Peak Global Maximun Point of Power:

$$D = 1 - \frac{V_{mpp}}{\sqrt{P_{mpp} \cdot R_l}} = 1 - \frac{135}{\sqrt{1220 \cdot 60}} = 0.5010256 \approx 0.50$$

$$V_{out} = \frac{V_{mpp}}{1 - D} = \frac{135}{1 - 0.50} = 270$$

Third Peak Global Maximun Point of Power:

$$D = 1 - \frac{V_{mpp}}{\sqrt{P_{mpp} \cdot R_l}} = 1 - \frac{167}{\sqrt{975 \cdot 60}} = 0.30953998 \approx 0.31$$

$$V_{out} = \frac{V_{mpp}}{1 - D} = \frac{167}{1 - 0.31} = 242.02896 \approx 240$$

Here are reported the screens of the simulations in MATLAB environment

Duty Cycle First Algorithmic (%)-Time (s)

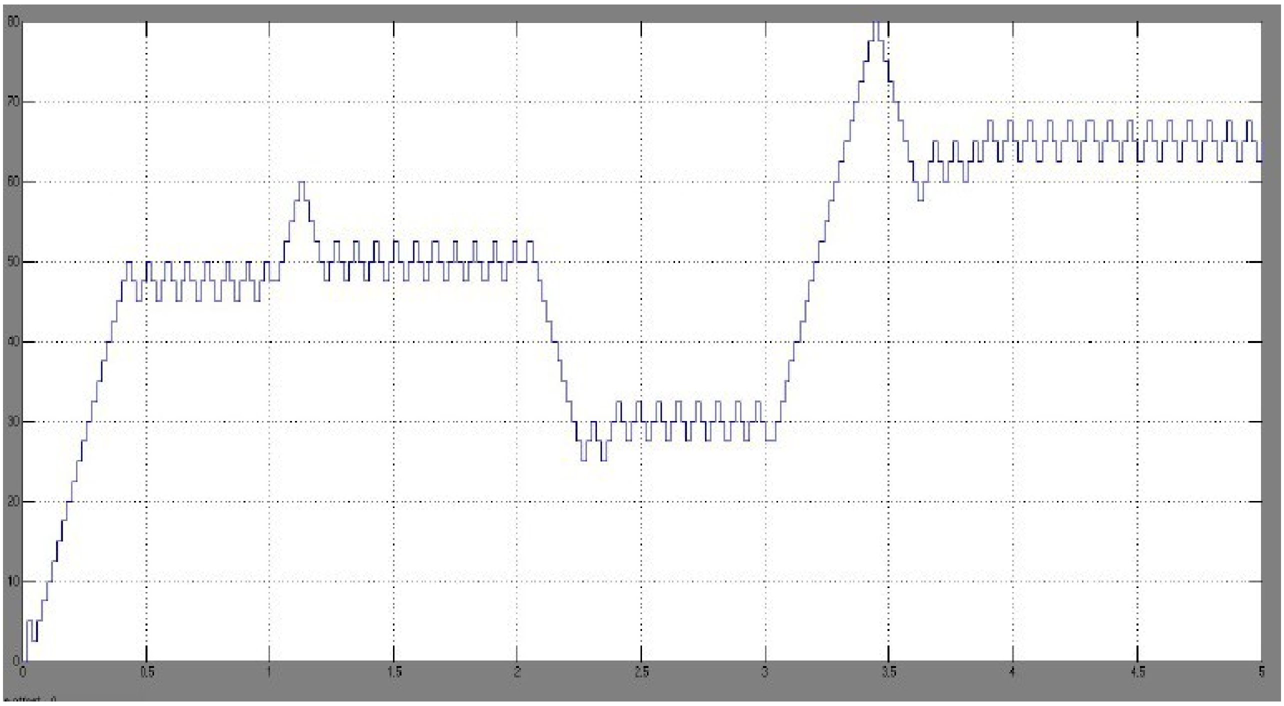


Figure 8.12

Duty Cycle Second Algorithmic (%)-Time (s)

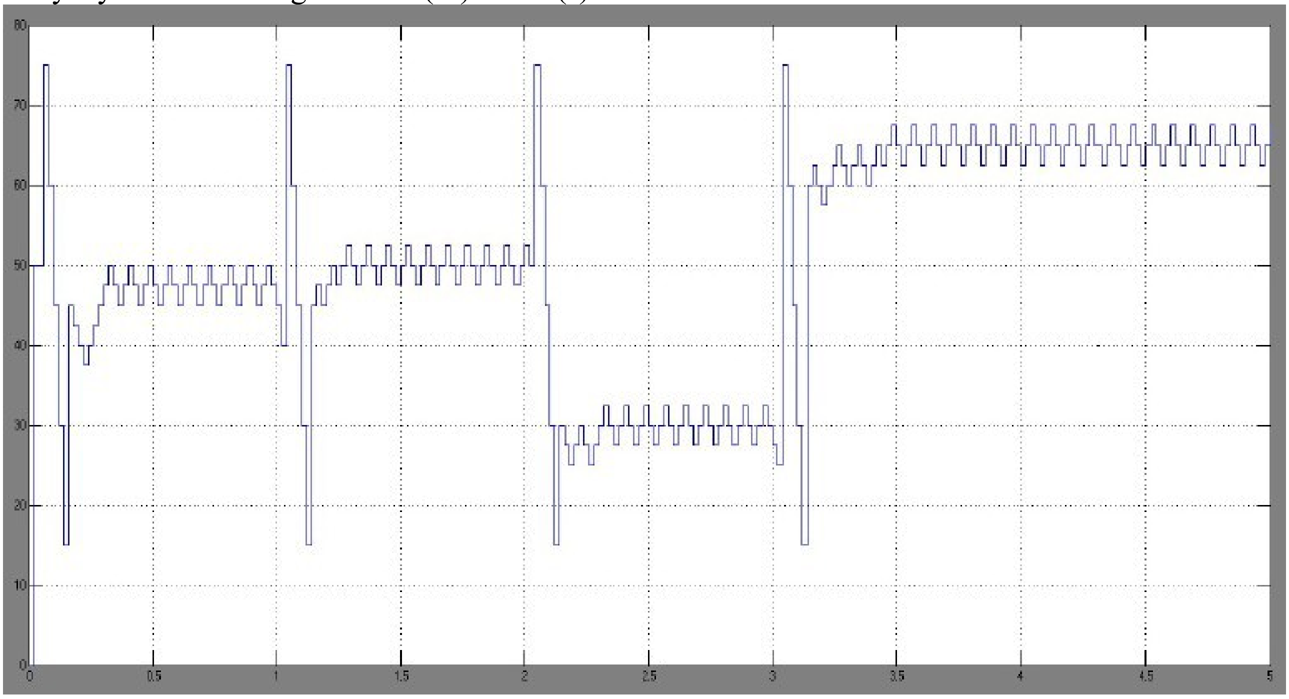


Figure 8.13

Power Input and Output Boost First Algorithmic (Watt)- Time (s)

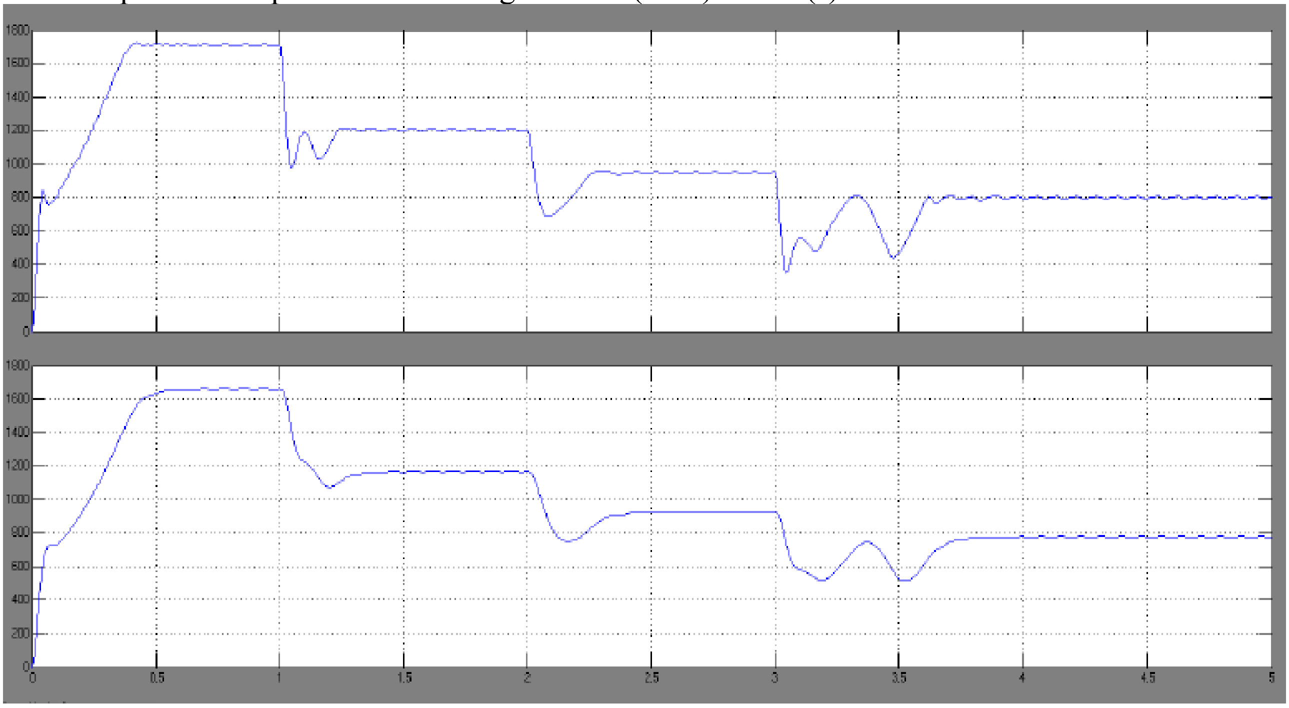


Figure 8.14

Power Input and Output Boost Second Algorithmic (Watt)- Time (s)

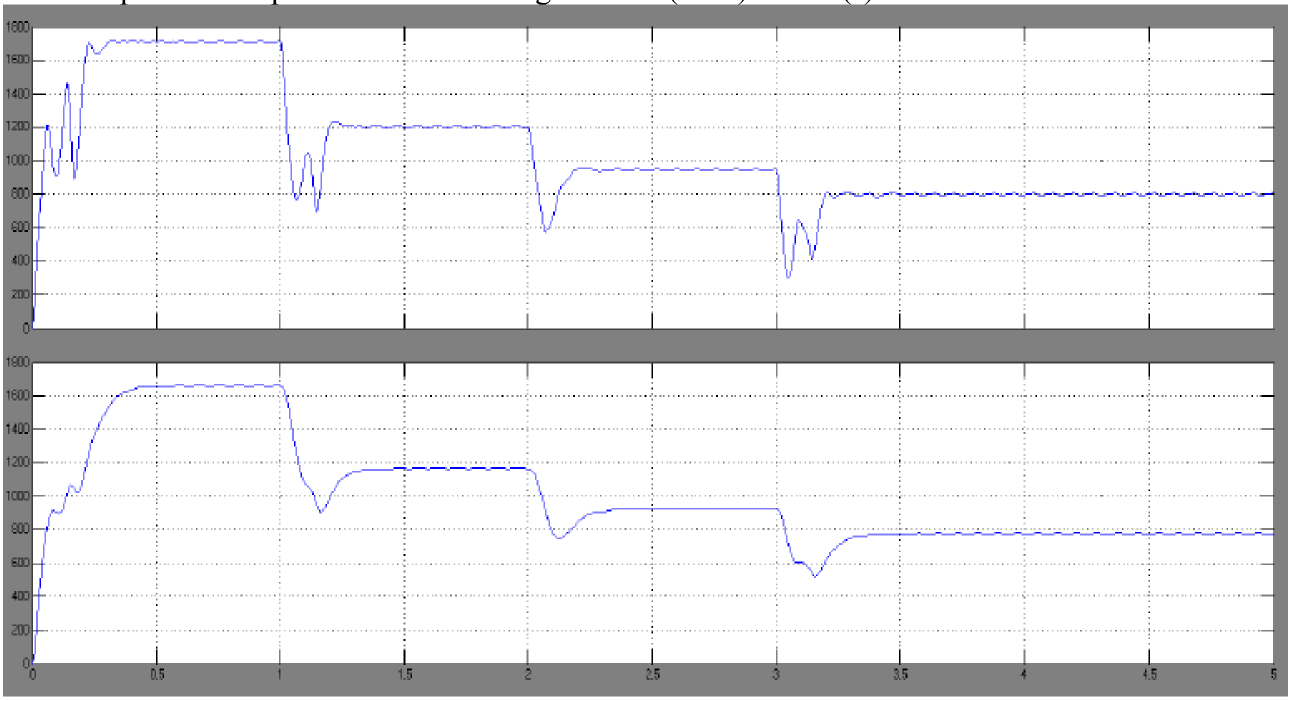


Figure 8.15

Voltage Output First Algorthmic (Volt)- Time (s)

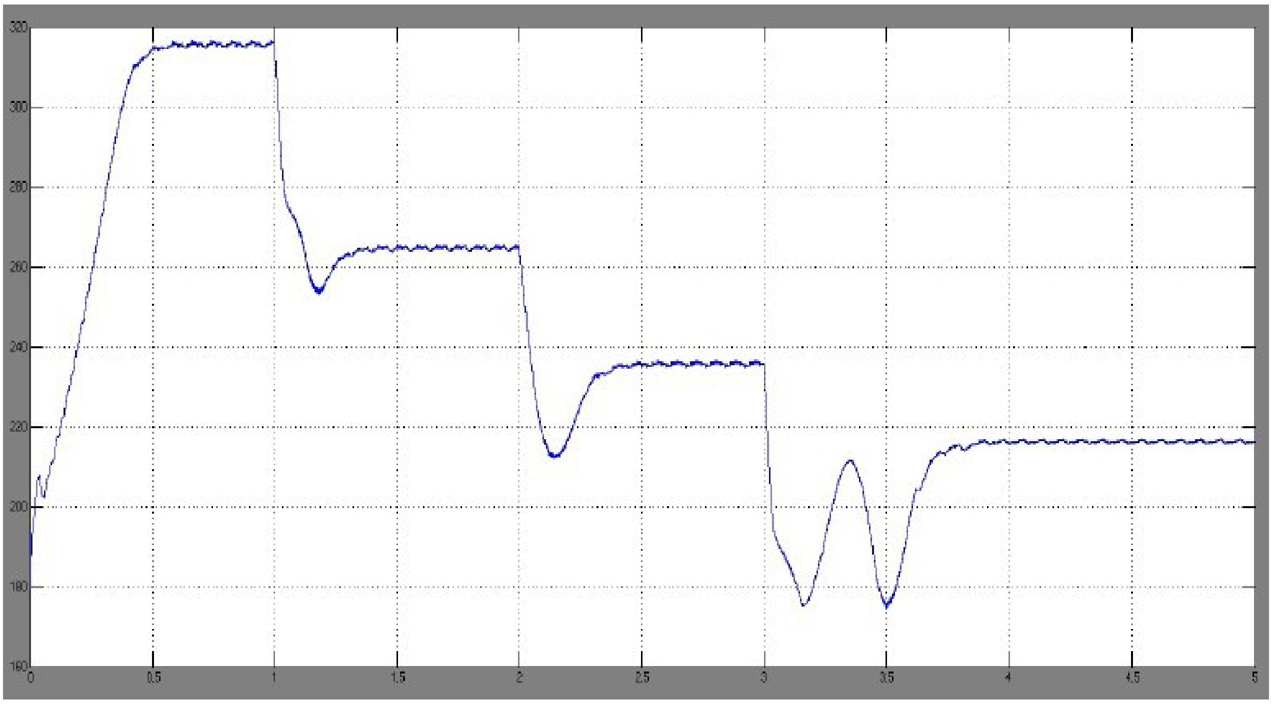


Figure 8.16

Voltage Output Second Algorthmic (Volt)- Time (s)

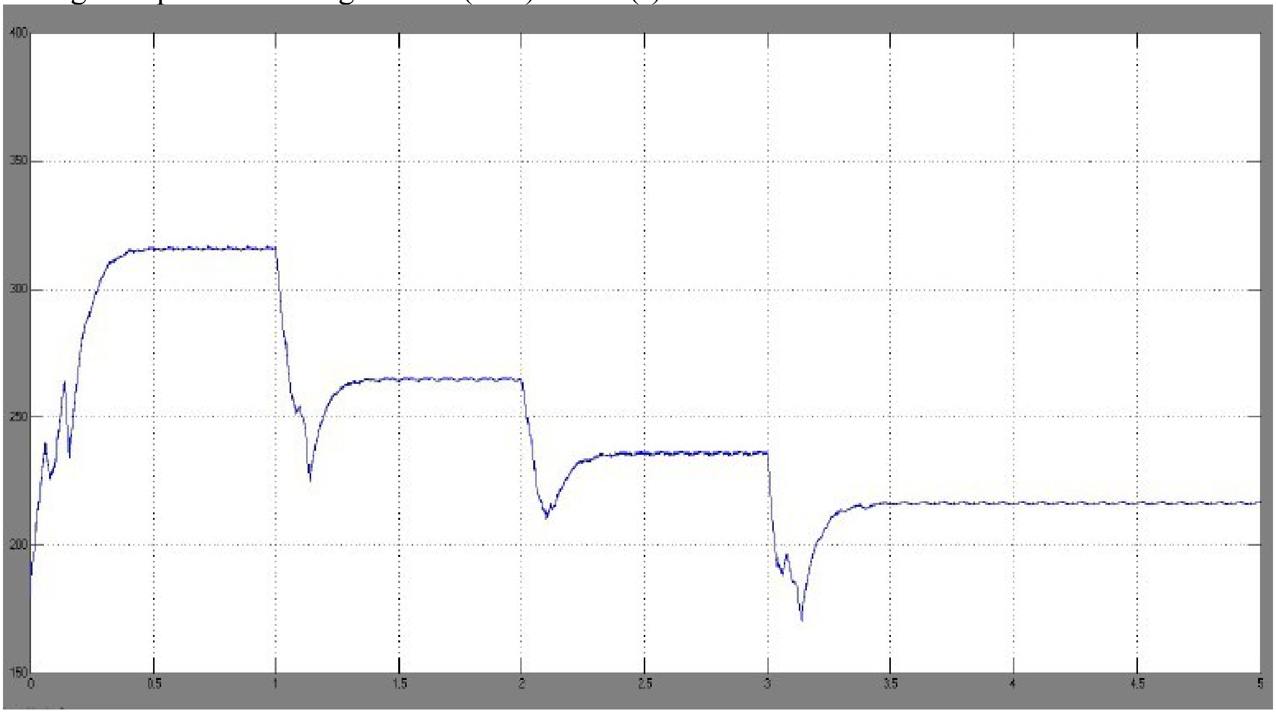


Figure 8.17

As we can see from a comparison between the two solutions:

- the second algorithm, whenever a partial shading occurs a new scan of the whole characteristic is done, it takes less time than the first algorithm to achieve the global maximum of power, but depending upon the scanning frequency the power disturbance could be sharper. In the program is possible to choose the value of the duty cycle step for the application required.
- the second algorithm is easier to deliver in the market because it doesn't require to know the parameters of the PV panels connected.
- the second algorithm is very precise and more reliable to track the maximum power point because the new maximum is tracked with a scan every time a partial shading occurs. Supposing the panel will be placed in a environment where partial shading doesn't occur very often, the loss of power during the scan can be neglected.

8.5 Simulations in real time Opal-RT

RT-LAB from Opal-RT Technologies Inc. is a distributed, real-time, PC-based platform that facilitates the design process for engineering systems. It allows designers to easily implement their Simulink dynamic models in real-time. Its scalability allows developers to add computing power where and when needed.
The algorithms proposed are verified in Opal-RT. For the first solution the simulation is reported in the Figure 8.18.

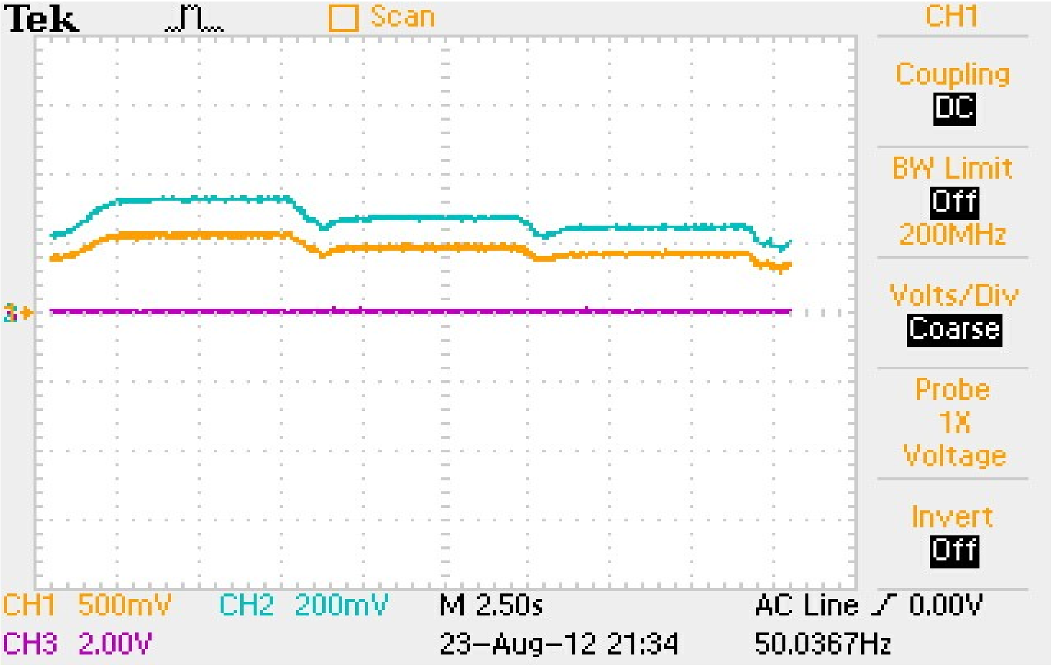


Figure 8.18

where the signals are organised as follow:

- The blu signal is output power of the boost. *(200mV/div→1000W/div)*
- The orange signal is the input power of the boost. *(500mV/div→1500W/div)*

It is also possible to note the transition between different pattern of shading.
The simulation of the second algorithm based on scan P-V curve is reported in Figure 8.19.

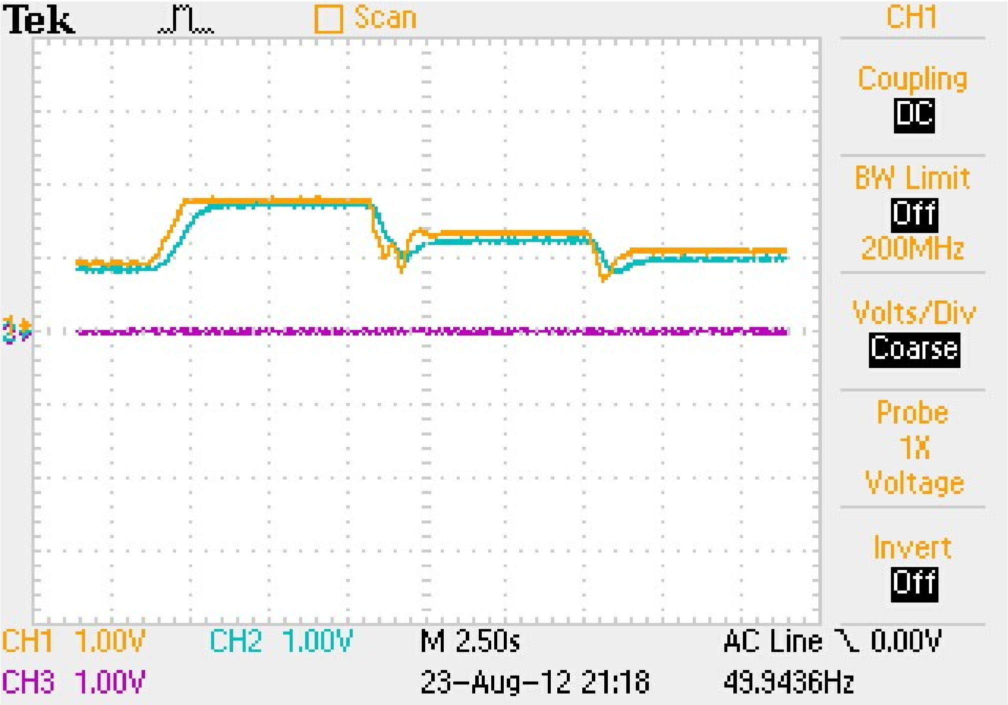


Figure 8.19

where the signals are organised as follow:

- The blu signal is input power of the boost. *(1 V/div→1000W/div)*
- The orange signal is the output power of the boost. *(1V/div→1000W/div)*

The transition is highlighted in Figure 8.20. In this picture we can see the action of the switching which scan the whole P-V characteristic before choosing the final value of duty cycle that gives the maximum power available.

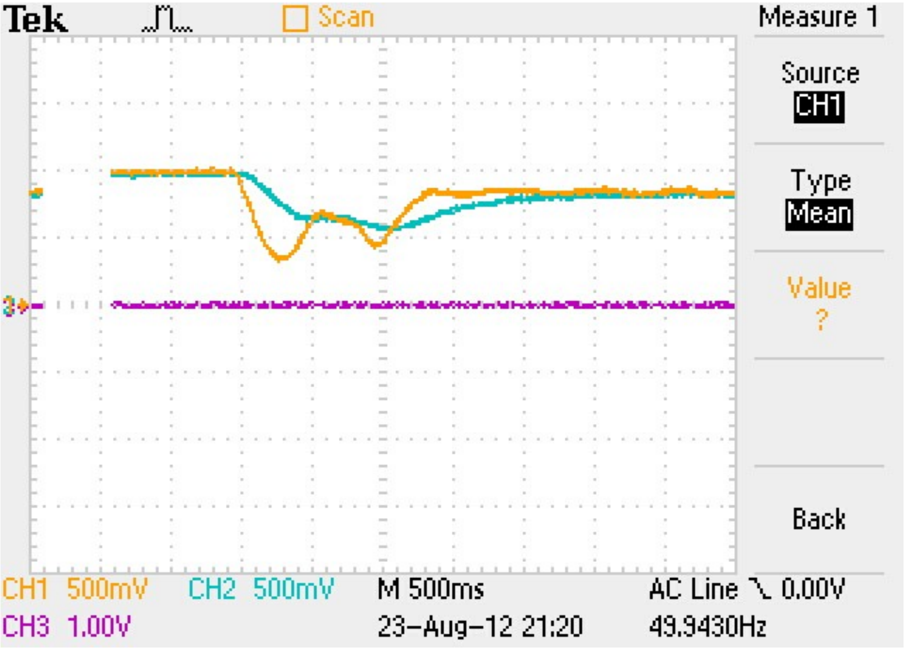


Figure 8.20

The signals are organized as follow:

- The blu signal is the input power of the boost. *(500mV/div→500W/div)*
- The orange signal is the output power of the boost. *(500mV/div→500W/div)*

9 Inverter

9.1 Topologies of Inverter

The inverter is a device that converts the voltage from DC to AC. One of its main use is in photovoltaic field, especially when we want to integrate a PV system to the utility grid .
The main topology developed for the transformerless PV inverters are:

- H-Bridge
- Neutral point clamped (NPC)

The H-Bridge topology has three main modulation strategies:
- Bipolar (BP) modulation
- Unipolar (UP) modulation
- Hybrid modulation

As we can see in Figure 9.1, the BP modulation works with the switches switched in diagonal S1 synchronous with S4 and S3 with S2.

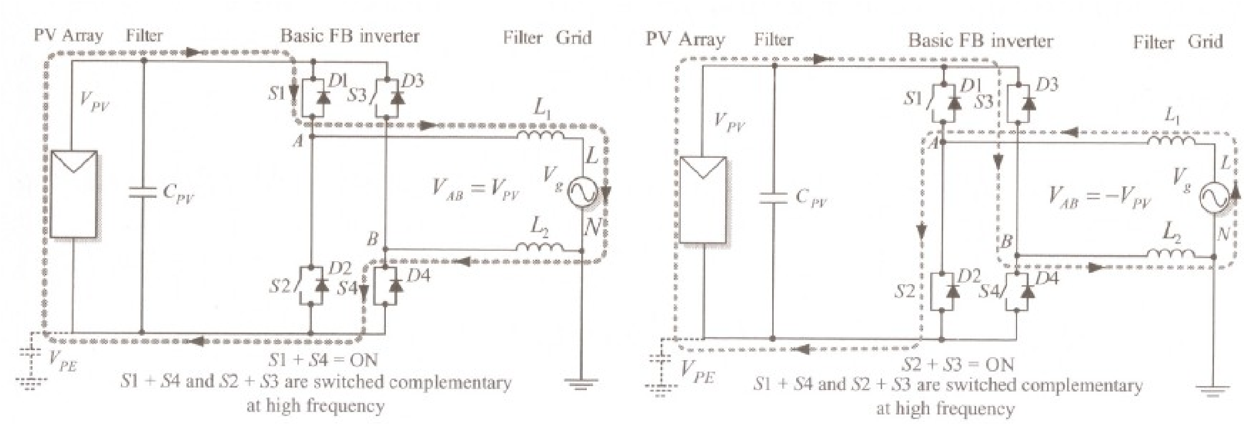


Figure 9.1

The voltage variations is bipolar, it means that it follows the sequence (+Vp, -Vp, +Vp, -Vp) and it has high losses.
All these reasons explain that this topology is not suitable for the transformerless PV application due to its low efficiency compared with the other inverters (just up to 96.5%). .
The unipolar modulation works with high frequency that generate this voltage
(0 Volt, +Vp, 0 Volt, -Vp, 0 Volt), but in this kind of modulation the voltage V_{PE} has high frequency content, yielding high leakage current and EMI.
In the next page is reported Figure 9.2 explains how this new topology works, where the “column a” represents the positive current and the “column b” the negative current.

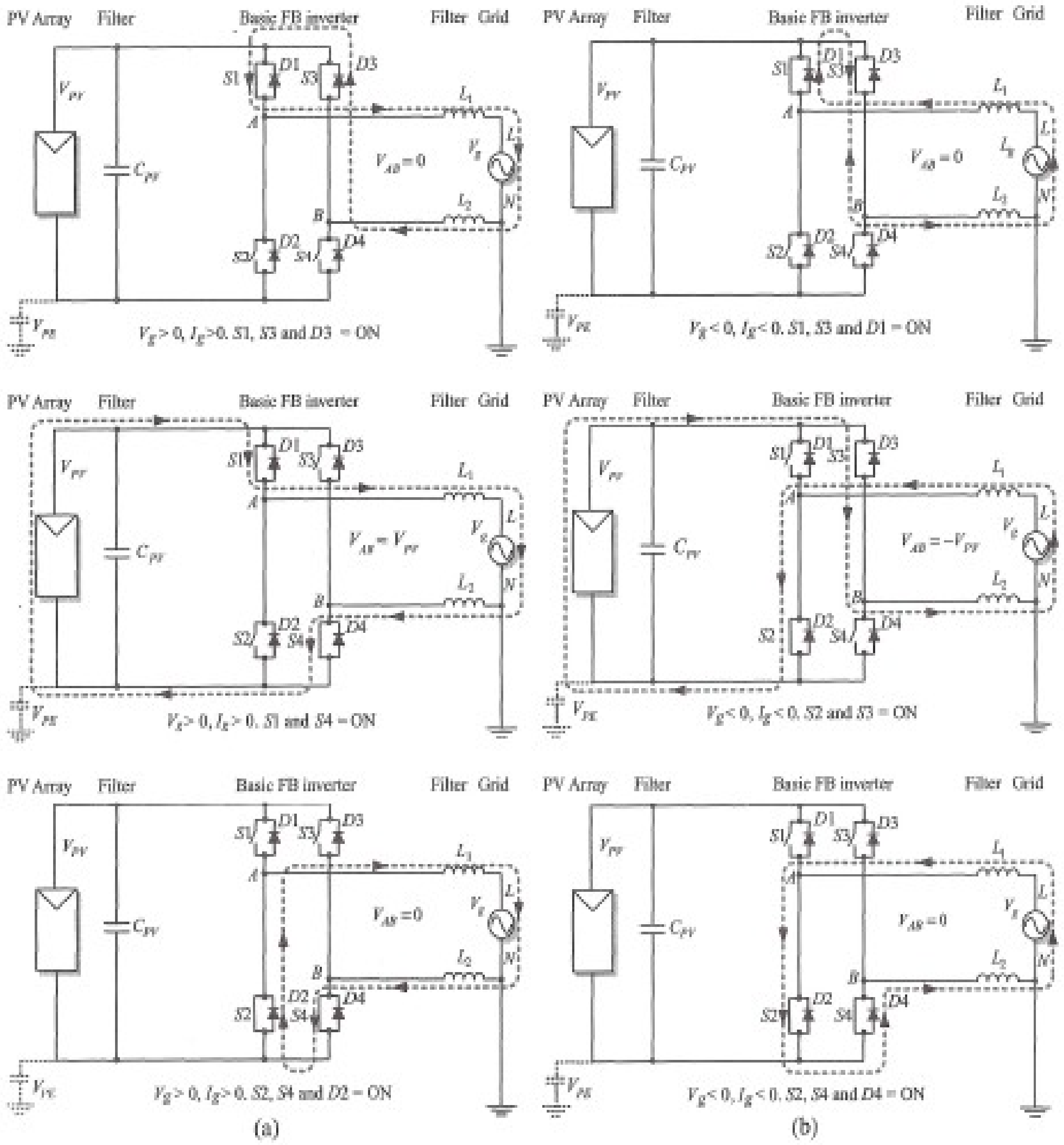


Figure 9.2

The last technique of modulation for the H-bridge is the hybrid modulation: one leg is switched at grid frequency and the other one at high frequency. The voltage generated is unipolar (0 Volt, +Vp, 0 Volt, -Vp, 0 Volt), and it lets to reach high value of efficiency up to 98%. This configuration has some drawbacks, such as ripple current at switching frequency, needing a filter and the V_{PE} has a square variation at grid frequency.

Probably the best topology to use with Photovoltaic panel is the H5 Inverter(SMA) (Figure 9.3). This configuration is similar to the other one that was taken into account before. The only difference lies on the fact that in this configuration there is one more switch S5 that isolates the PV panel from the grid when the voltage state is zero, so we don't need to use filtering for the V_{PE}

issue as in the case considered before. It uses Hybrid modulation that generates a unipolar modulation with lower losses and the efficiency can raise up to 98%.

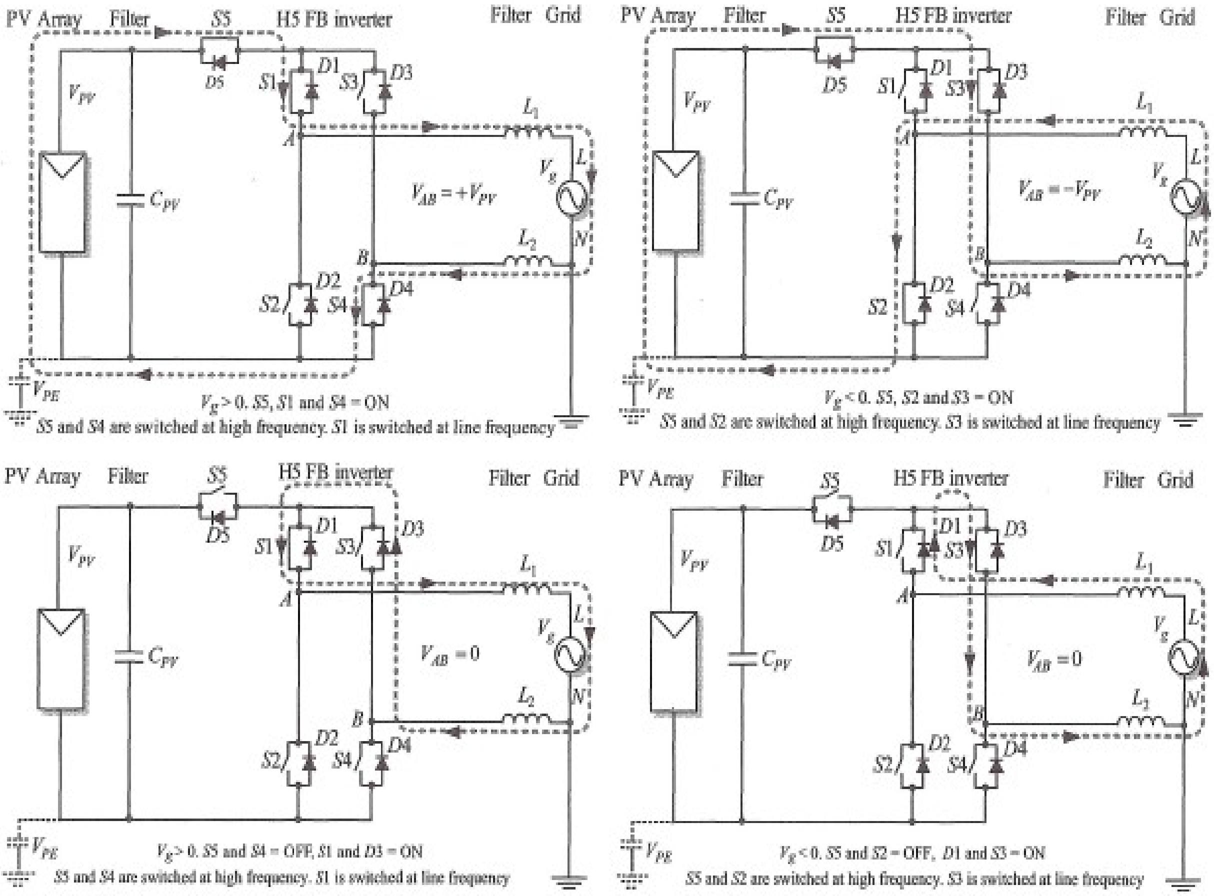


Figure 9.3

There are several other kind of inverters like HERIC Inverter, REFU Inverter, Full-Bridge Inverter with DC Bypass and Full-Bridge Zero Voltage Rectifier. These type of devices achieve the same result as the H5 but with a little bit lower efficiency or at the price of using more switching.
The other main topology is NPC that present a lower dV/dt and switch stress in comparison with the FB inverter. The zero state of the voltage is achieved by clamping the output to the ground. These topology achieve the same result in term of efficiency and complexity hardware as in the case of Full-Bridge but they present the drawbacks of more hardware complexity (more diodes), or they need a double voltage input.

9.2 PLL-Inverter

In order to guarantee the safety condition and the stability of the grid many international grid codes were delivered to regulate the behaviour of photovoltaic energy. Actually, the grid codes define the boundaries of the voltage and current that let the Photovoltaic Panel to stay connected to the grid. The power converter has to screen the state of the grid, voltage and frequency, and decide to disconnect the panel from the grid when the parameters of the grid are over the limits imposed by the rules. In this context the grid synchronization is a very important process that uses an algorithm to send some information regarding the state of the grid. It's fundamental because it provides the magnitude and phase-angle of the grid voltage, so it lets power converter to work in unison with the grid.

In this context one of the most important devices is the PLL, a closed loop system that uses a feedback loop to control an internal oscillator to be tracked with some external periodical signal. This allows to phase-lock the internal oscillator to some parameters of the grid in order to generate a signal whose amplitude and phase will be used by the next control block.

As we can see from the picture below (Figure 9.4), the basic structure of the PLL is made up of three main blocks [17]:

- Phase detector is the block that every time the signal in input is compared with the internal oscillator. As output signal, it provides the difference between those two signals.
- Loop filter (LF) is usually developed as low pass filter or a PI controller. Its purpose is to reduce the high frequency component from the phase detector block.
- Voltage-controlled oscillator is a block that requires as input signal a voltage whose value is used to generate an AC voltage with a well defined frequency.

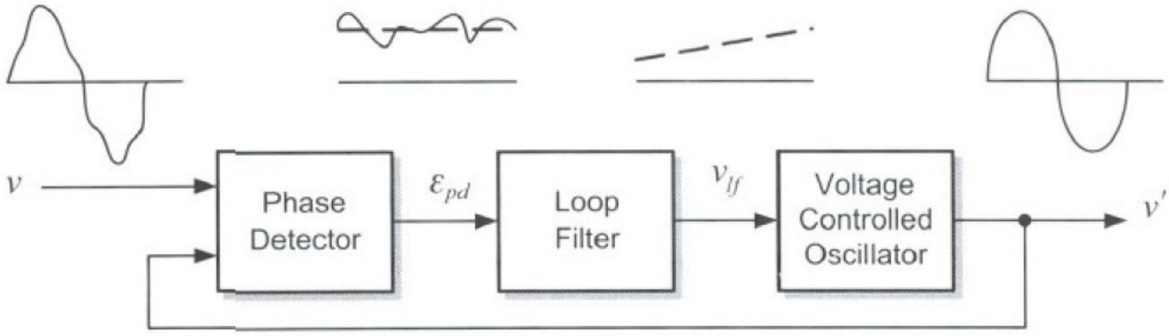


Figure 9.4

There are several different techniques that can be used to develop every block of the PLL [17]. The simplest solution that leads to a PLL is shown in the picture reported below (Figure 9.5).

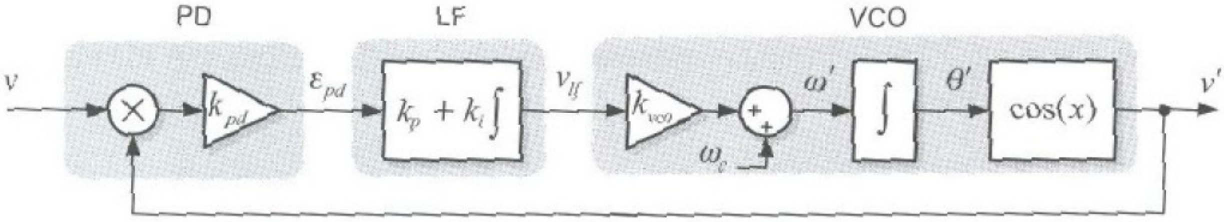


Figure 9.5

The first block is implemented by a simple multiplier. If we suppose that the input signal is

$$V = V\sin(\Theta) = V\sin(wt+\Phi) \tag{9.1}$$

and the signal generated by the the VCO is

$$V' = \cos(\Theta') = \cos(w' t+\Phi') \tag{9.2}$$

the signal in output of the Phase detector (PD) will be the multiplication of these two signals. The result will be a signal with two component, one at low frequency and the other one at high frequency. It means that in output of the Low Pass filter there will be only the low component of frequency.

$$\bar{\epsilon}_{pd} = \frac{V\,K_{pd}}{2}\sin((w-w')t+(\Phi-\Phi')) \tag{9.3}$$

If we suppose that the PLL is well tuned, it means that the internal oscillator's frequency is very closed to the input signal's frequency, we can neglect the difference between the two *w*. Moreover if the difference between the phases is very small, the output can be linearized and the new value of output of the PD block can be simplified.

$$\bar{\epsilon}_{pd} = \frac{V\,K_{pd}}{2}\sin(\Phi-\Phi') = \frac{V\,K_{pd}}{2}(\Phi-\Phi') \tag{9.4}$$

The VCO block is normally tuned with a central frequency *Wc* and the output of the LF filter is processed in order to determine the variation from the central frequency.
If we call the output of the LP filter as $\tilde{V}_{lf}$, the output of the VCO will be:

$$\tilde{\Theta}'(t) = \int \tilde{w}'\,dt = \int K_{vco}\,\tilde{v}_{lf}\,dt \tag{9.5}$$

In order to understand the performance of the PLL is useful to have a look on the equation under Laplace transform domain [17].

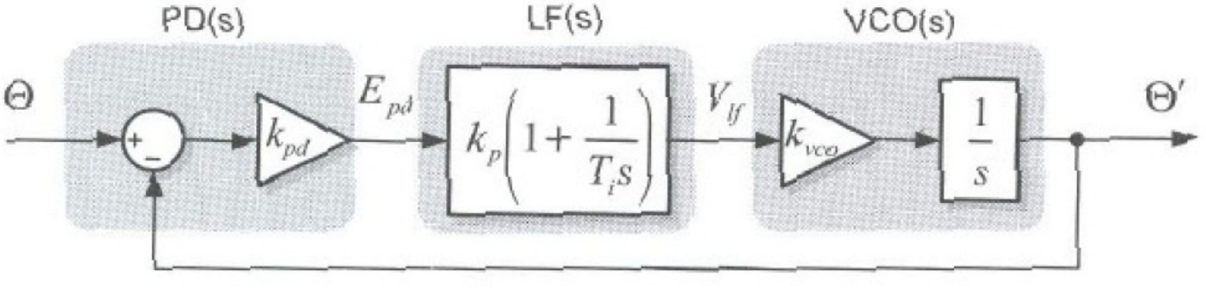


Figure 9.6

If it's considered that $K_{PD}=K_{VCO}=1$, the main result of interest can be expressed as follows:

-Open-loop phase function:

$$F_{OL}(s)=PD(s)\cdot LF(s)\cdot VCO(s)=K_i\frac{K_p\left(1+\frac{1}{T_i s}\right)}{s}=\frac{K_p s+\frac{K_p}{T_i}}{s^2} \tag{9.6}$$

-Closed-loop phase transfer function:

$$H_{\Theta}(s)=\frac{\Theta'}{\Theta}=\frac{LF(s)}{s+LF(s)}=\frac{K_p s+\frac{K_p}{T_i}}{s^2+K_p s+\frac{K_p}{T_i}} \tag{9.7}$$

-Closed-loop error transfer function:

$$E_{\Theta}(s)=\frac{E_{pd}(s)}{\Theta(s)}=1-H_{\Theta}(s)=\frac{s}{s+LP(s)}=\frac{s^2}{s^2+K_p s+\frac{k_p}{T_i}} \tag{9.8}$$

As we can see the closed-loop phase transfer function has the same structure as a low pass filter. It's very useful because it allows attenuating the error due to noise or high order harmonics. If we have a look at the structure of the function close-loop phase transfer or closed-loop error transfer it is possible to understand some important characteristic about the dynamic response.

$$w_n=\sqrt{\frac{K_p}{T_i}} \qquad \xi=\frac{\sqrt{K_p T_i}}{2} \tag{9.9}$$

This implies that the settling time is considered like the interval time from the start time to the time that the system is within 1% of the steady state and is given as follows:

$$t_s=4.6\tau=\frac{4.6}{\xi w_n} \tag{9.10}$$

The difference between the phase of the input signal and the internal oscillator is affected by a small ripple due to the high component of frequency in output of the PD block. If we want to have smaller error phase we can reduce the bandwidth of the LF filter but we will pay more in terms of dynamic settling time the PLL.

Drawbacks: this kind of topology is affected by some problems which is observed during the simulation. This drawback lies on the fact that initially in the PD block the multiplication between the internal oscillator signal and the input signal is made, so we will have two different component of frequency, the first one will be at low frequency and the other one will be at double frequency of the grid. It means that the low pass filter will not filter everything, so we will have some oscillation at double frequency of the grid in the output of the PLL. This explains why sometimes it's better to use a PD based on in-quadrature signals, whose signal in output of PD doesn't have any steady-state oscillatory term when the PLL is well synchronized.

9.3 MATLAB-Simulation

The importance of the PLL with PI controllers is due the fact that its function is to control the inverter in order to provide the right value of voltage to the grid (220 V_{RMS} 50 Hz).
The PLL-inverter uses in its input a voltage higher than the peak of voltage in its output, so we need to provide as input a higher value than 220 V_{RMS} in order to generate a voltage of 311 V_{PEAK} at 50Hz.
The main structure of the controller-inverter is shown in the follow picture (Figure 9.7-9.8):

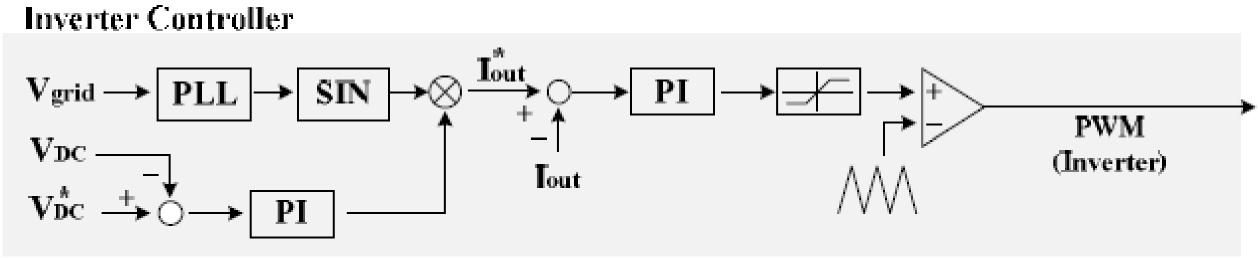


Figure 9.7

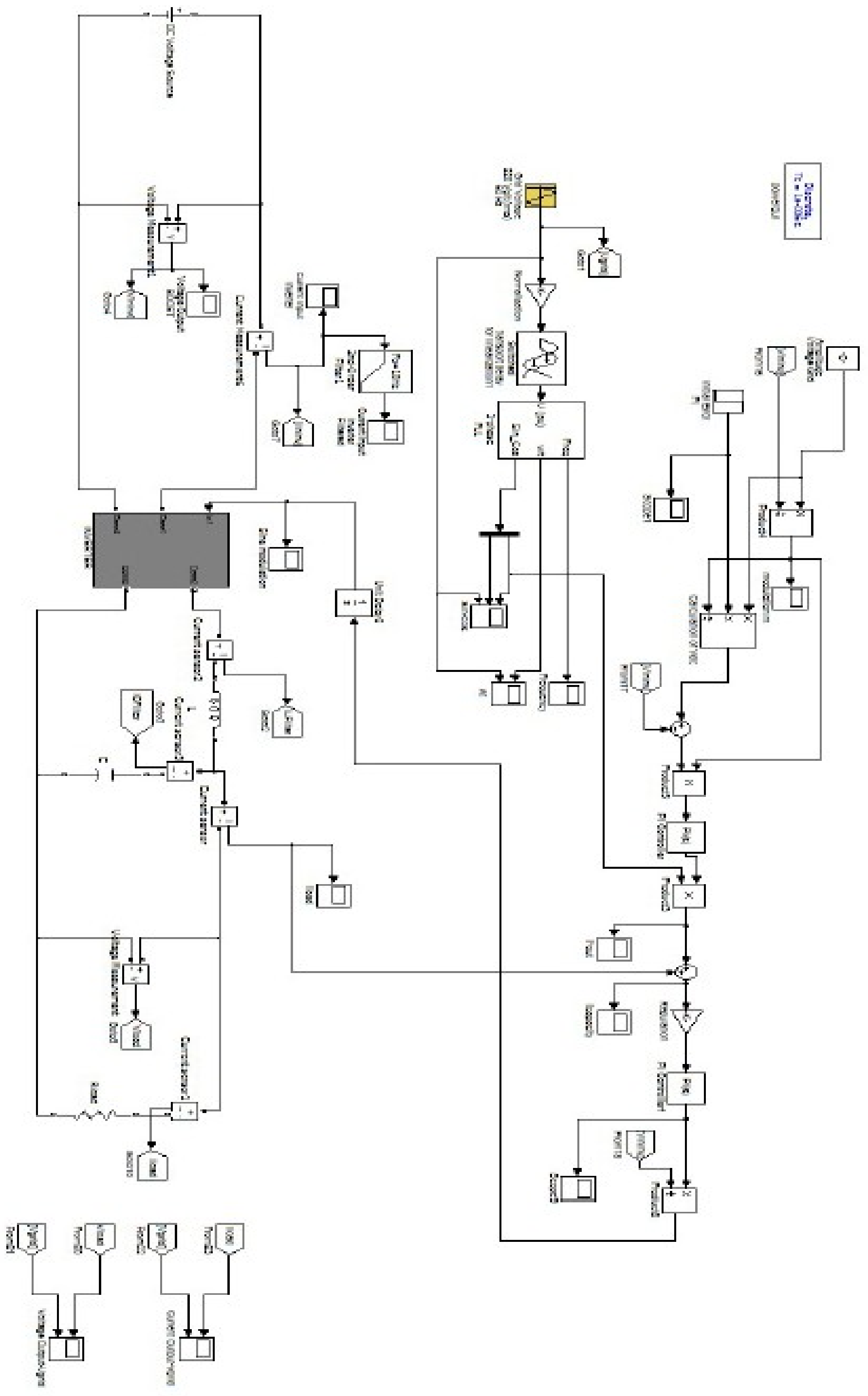


Figure 9.8

The inverter developed in the project is a full-Bridge as shown in Figure 9.9.

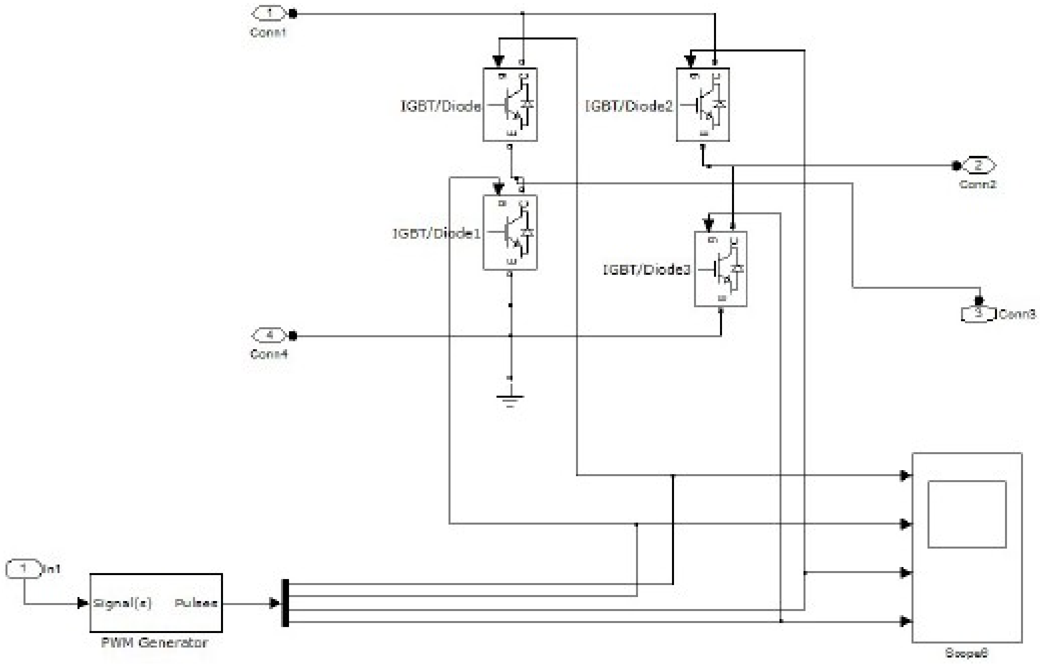


Figure 9.9

The value of the PI controller was found by trial and error method. At every attempt the value of the output was checked and the value of the PI parameters was adjusted in order to find the desired shape of the signals.
In output of the inverter there is a second order filter LC, whose transfer function is given by the following equation:

$$H(s)=\frac{1}{CLs^2+\frac{L}{R_0}s+1} \tag{9.11}$$

where R_0 is the resistance of the load. It's easy to note that in the second order filter the resonant frequency is:

$$W_T=\frac{1}{\sqrt{LC}} \tag{9.12}$$

and thus, it's doesn't depend on the value of resistance which is connected. For the filter developed the parameters are

C=3 μF
L=40 mH

The transfer function has been simulated in MATLAB (Figure 9.10) assuming an R_{LOAD}=100ohm.

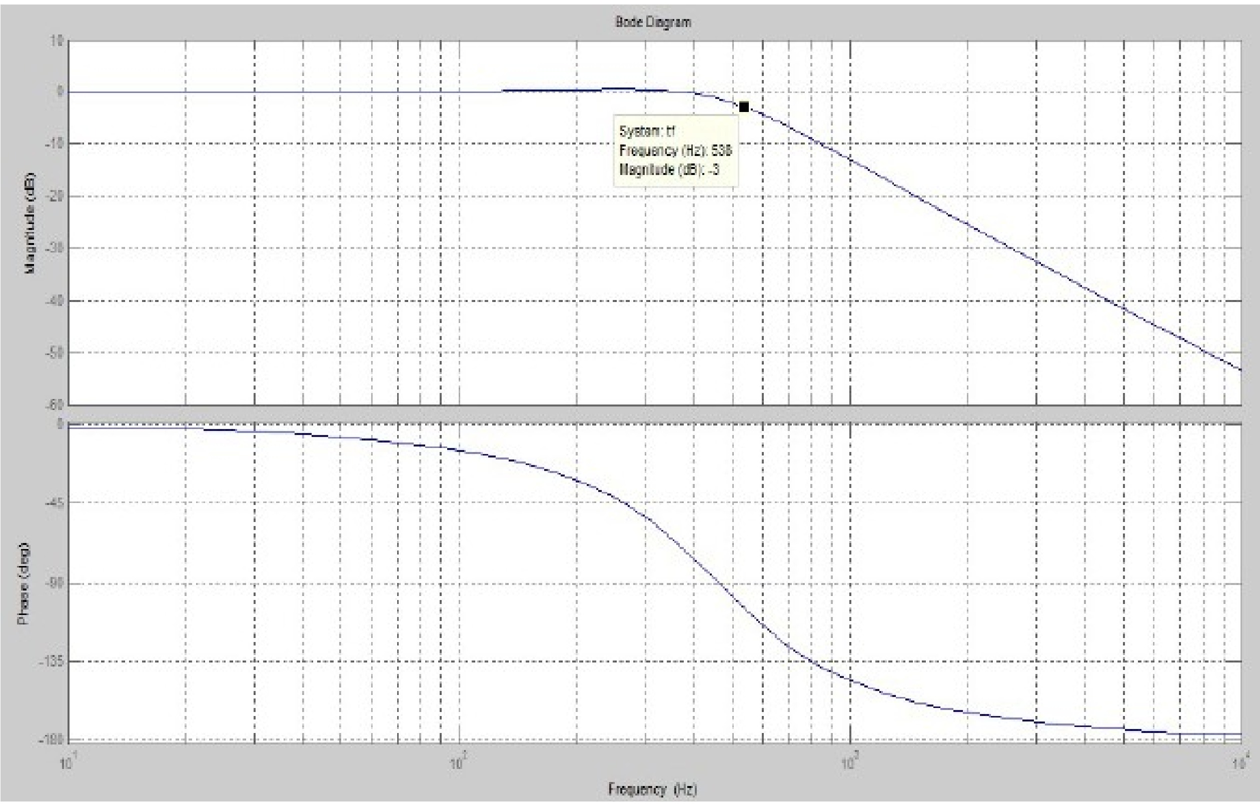


Figure 9.10

In this case we see that the bandwidth is B=538 Hz, thus it is important that the switching frequency of the inverter is much higher than this value in order to filter component of voltage at switching frequency. In the simulation the switching frequency of the inverter is chosen to be 5 KHz. Making the assumption of an input voltage of 400 Volt, the output screens are reported in Figure 9.11 where the first picture on the top is the grid voltage and the other one in the bottom is voltage output generated by the PLL-Inverter.

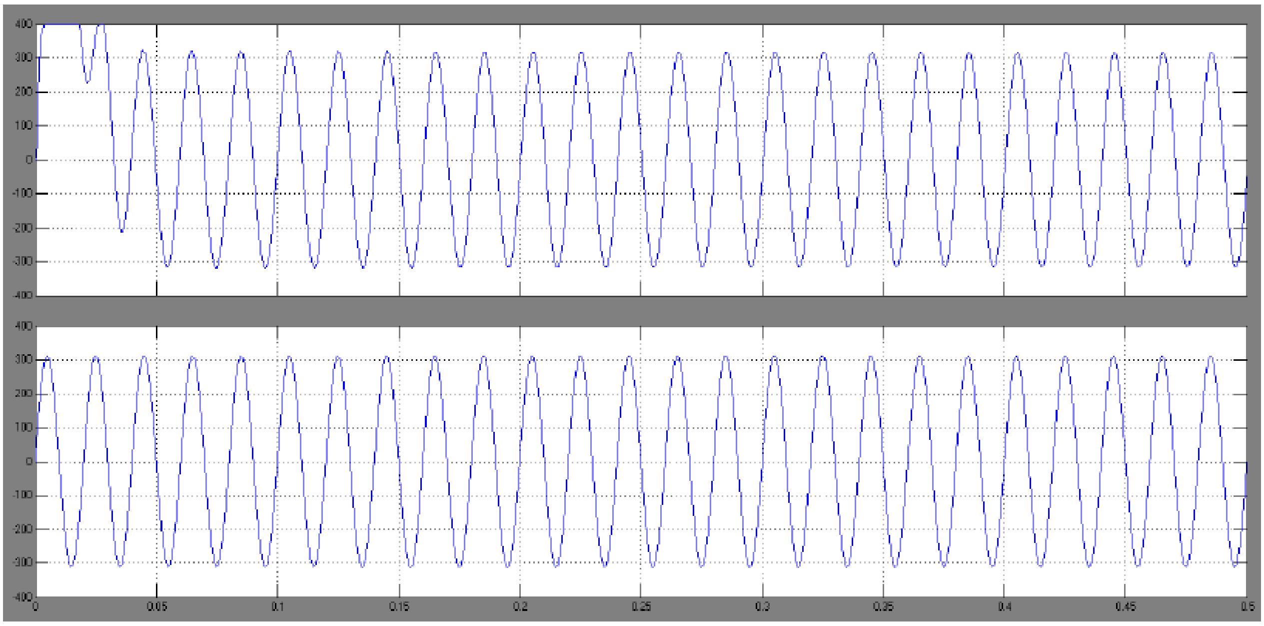
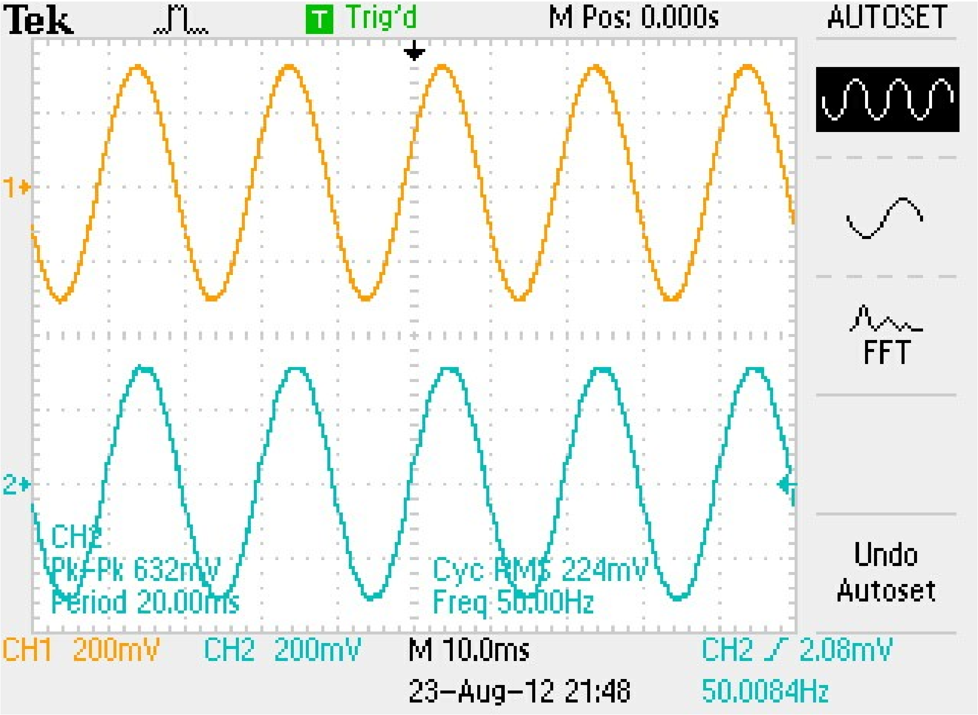


Figure 9.11

As we can see, the voltage results to be in phase with the voltage grid and with the same value of amplitude. The frequency is 50 Hz as the frequency supplied by the grid.

9.4 Simulation in real time Opal-RT

The project is verified in Opal-RT as shown in the Figure 9.12.



M Pos: 0.000s

CH2
Pk-Pk 632mV
Period 20.00ms

Cyc RMS 224mV
Freq 50.00Hz

CH1 200mV CH2 200mV M 10.0ms CH2 ⁄ 2.08mV

23-Aug-12 21:48 50.0084Hz

Figure 9.12

where the signals are organised as follow:

- The blu signal is the output voltage at 50Hz generated by the inverter *(200mV/div→200Volt/div)*
- The orange signal is the voltage grid reference at 50 Hz. *(200mV/div→200V/div)*

10 PV system in stand-alone configuration

10.1 Introduction to stand-alone system

A stand-alone system is also composed of a PV array-boost with the PLL-Inverter. In this case, one important aspect to keep in consideration is the matching power between the boost and the PLL-Inverter output. As it is well-known, the MPPT tries to catch the MPP at any operative conditions of work. It means that, if we are under conditions of uniform isolation in which the PV array delivers 1700 W, the load connected in the output of the inverter should be able to absorb this power at a voltage of 311 V_{PEAK}.
The interface between the two system is realized by connecting a resistance $R_{BALANCE}$ and the load has the follow characteristics:

- Nominal voltage Vn (Vrms): 220
- Nominal frequency fn (Hz): 50
- Active power P (W):1500

In the next page the picture of the stand-alone system realized in MATLAB-SimPowerSystem (Figure 10.1) in condition of uniform insolation is reported.

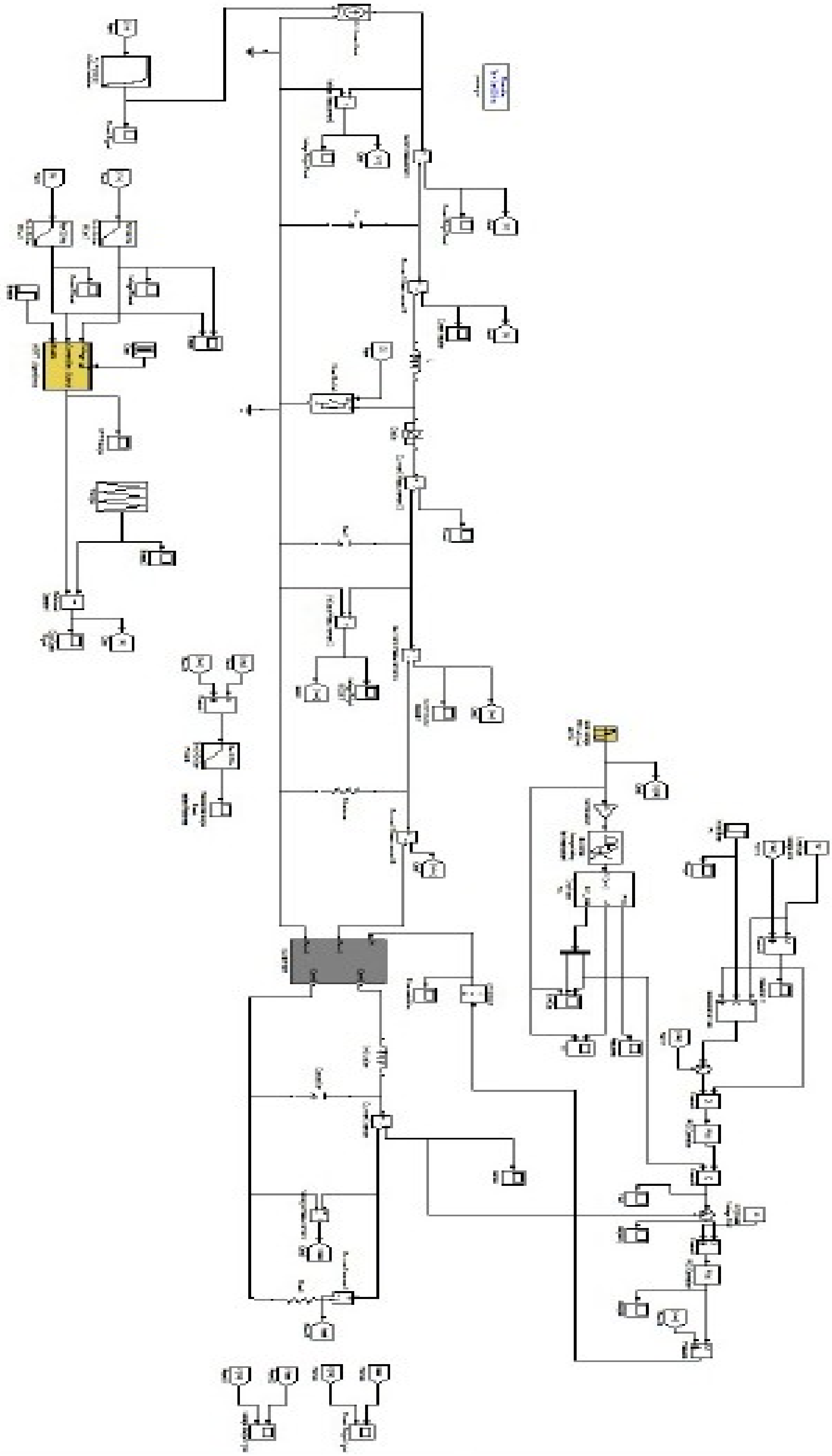


Figure 10.1

In the follow picture (Figure 10.2-10.3) are reported the screens of the voltage and current in output.

Voltage load (Volt)-Voltage grid (Volt)

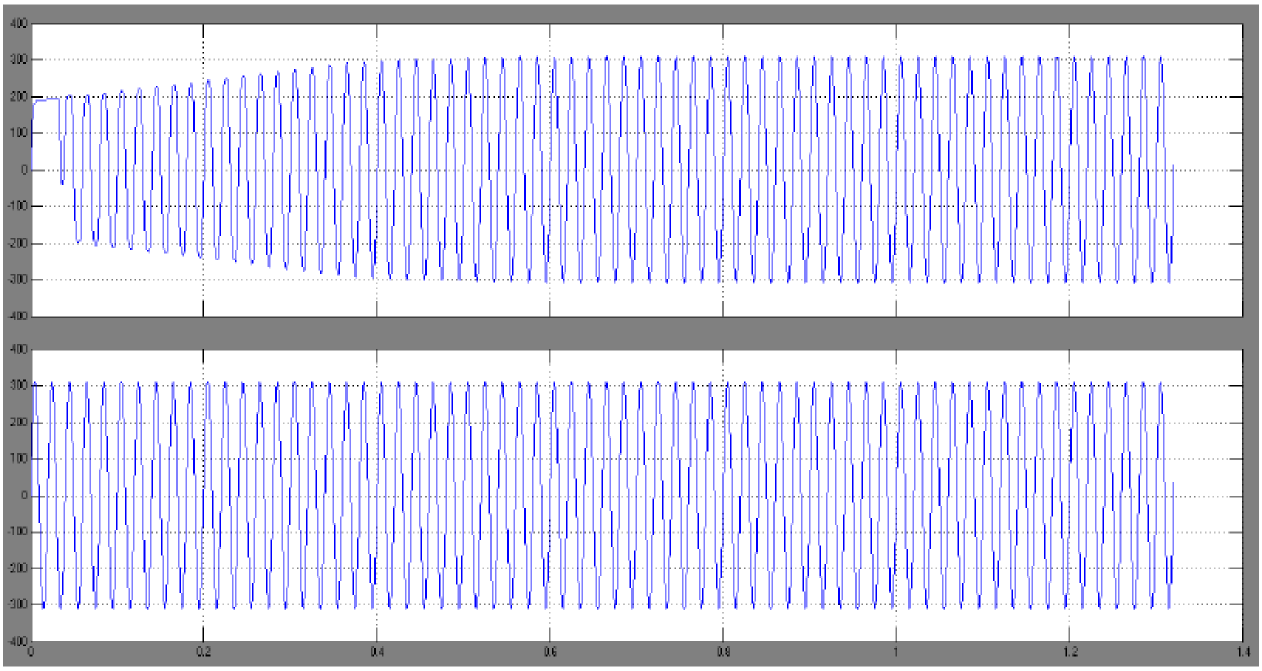


Figure 10.2

Current load (A)-Voltage grid (Volt)

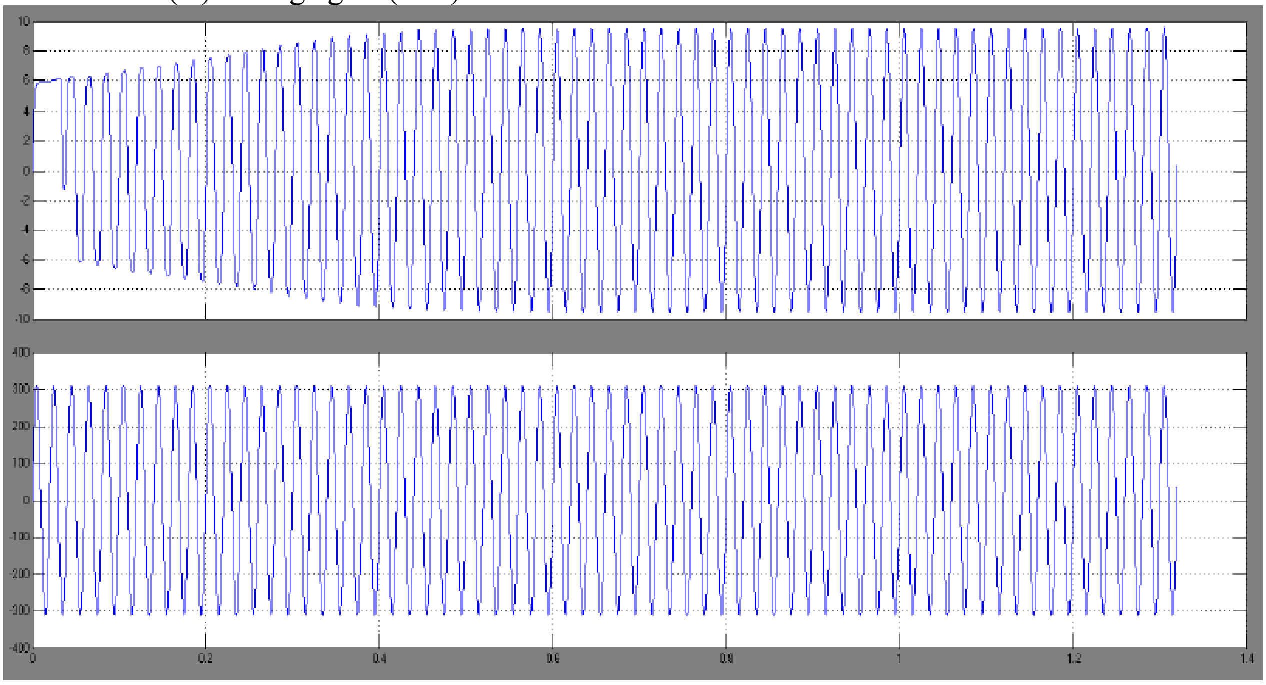


Figure 10.3

Moreover, the power delivered by the boost is reported in Figure 10.4.

Power (Watt)-Time (sec)

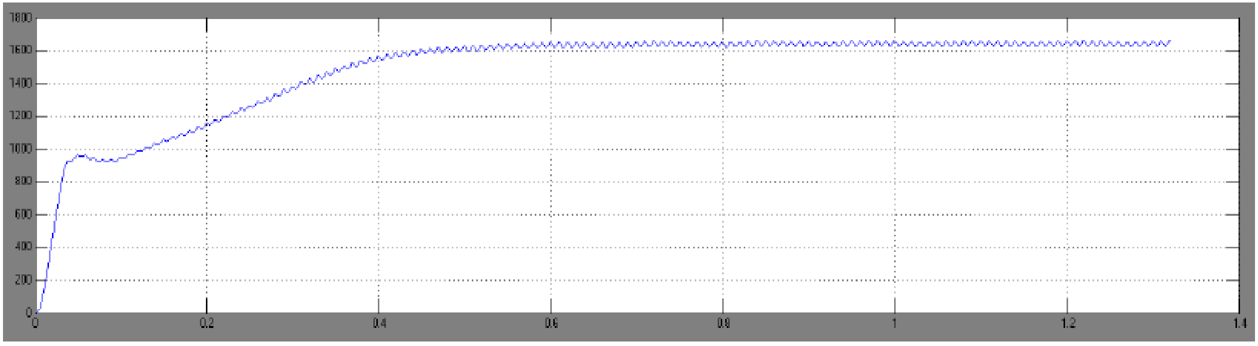


Figure 10.4

It's also shown the instantaneous output power across the load (Figure 10.5)

Power (Watt)-Time (sec)

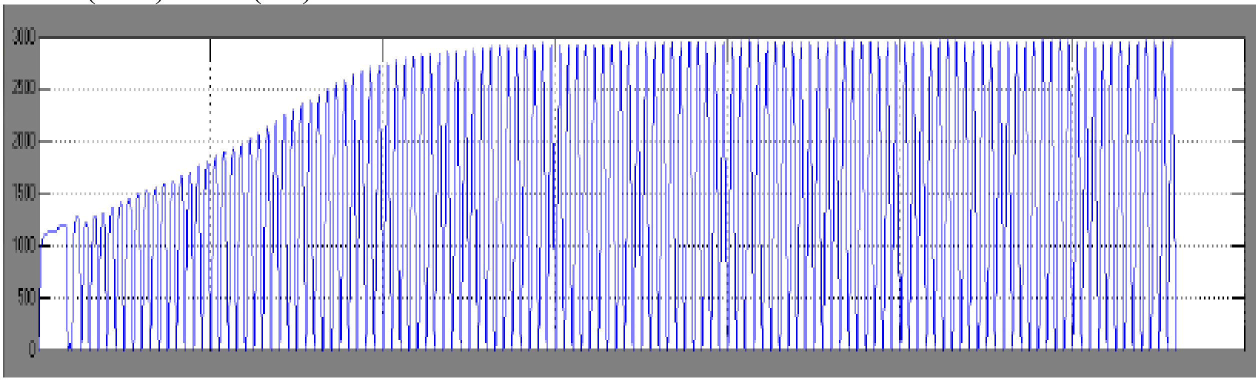


Figure 10.5

10.2 Simulation in real time Opal-RT

To confirm the validation of the results is reported the screens of the simulation in Opal-RT. In Figure 10.5 is shown the follow signals:

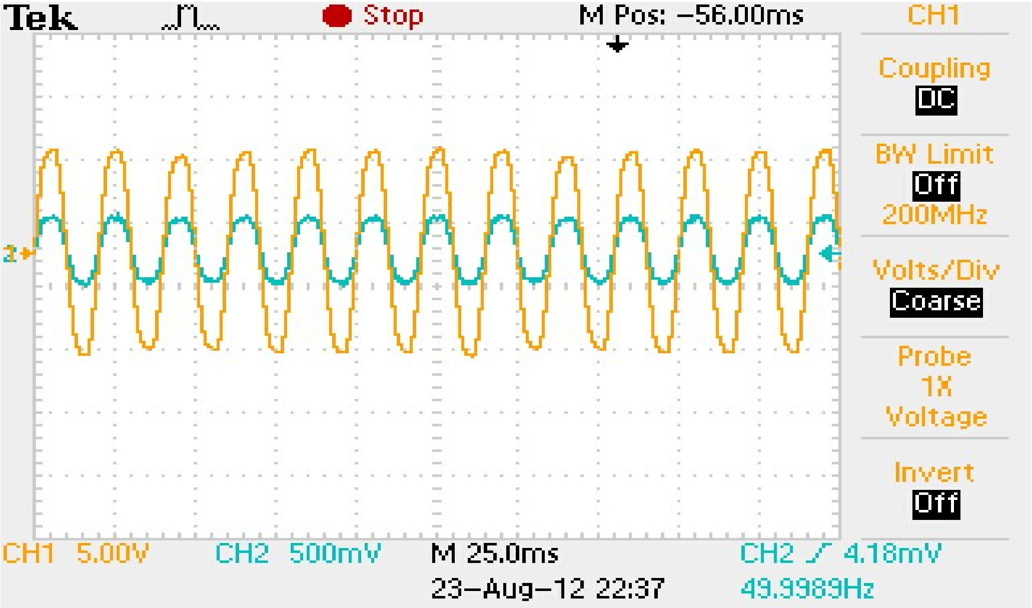
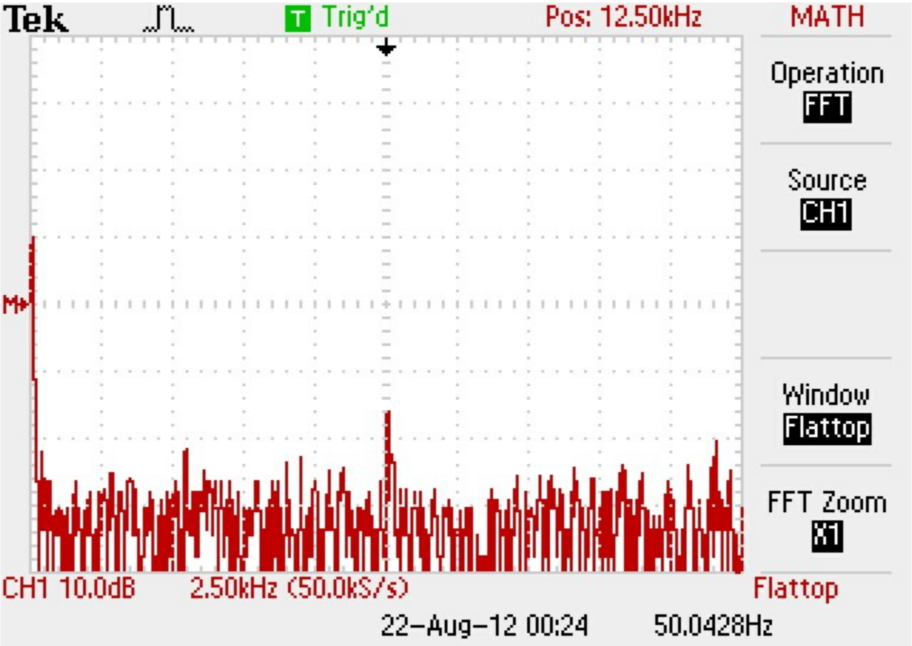


Figure 10.5

- The blu signal is the voltage grid reference at 50Hz. *(5V/div→600Volt/div)*
- The orange signal is the output voltage at 50 Hz generated by the inverter. *(500mV/div→200V/div)*

In Figure 10.6 is also reported the FFT screen of the output voltage in which is possible to note the frequency of 50 Hz.



Operation FFT
Source CH1
Window Flattop
FFT Zoom X1

Figure 10.6

11 Grid Requirements for PV

11.1 Introduction to the grid requirements

The PV systems need to satisfy some series of requirements to ensure the safety and the seamless transfer of the electrical energy to the grid.
There are several institutions that are developing standards for grid connected system:
IEEE (Institute of Electrical and Electronic Engineers) in US, IEC (International Electrotechnical Commission) in Switzerland and DKE (German Commission for Electrical, Electronic and Information Technologies of DIN and VDE).
The most relevant requirements regard power quality and anti-islanding issue [17].

IEEE 1547 Interconnection of Distributed Generation
This requirement is present in US where the most popular and important standard is the IEEE 929-2000, *Recommended Practice for Utility Interface of Photovoltaic (PV) System.*
Derived from IEEE 929 is called UL1741, *Standard for Inverters, Converters, and Controllers for Use in Independent Power System,* whose purpose is to give information about construction, electrical safety and principle derived from National Electric Code (NEC) especially in small grid-tied inverters. UL1741 is one of the few standard that provide address performance, so where it was used it has simplify the things.
Another standard which is very important is called IEEE 1547-2003 *Standard for Interconnecting Distributed Resources with Electric Power System* that it tries to impose a single standard interconnection for all technologies up to 10 MW. It speaks about response to abnormal conditions, power quality, islanding, test specification, requirements for design, production, installation evaluating, commissioning and periodic test.

IEC 61727
In this field the most famous requirements is the standards IEC 61727 *Photovoltaic (PV) System-Characteristic of the Utility Interface* that is applied to utility-interconnected PV power systems operating in parallel with the utility and using a non island inverters.

VDE 0126-1-1 Safety
In this context, the main requirement developed by Germany is the ENS, *Automatic Disconnection Device between a Generator and the Public Low-Voltage Grid.* This device should detect a variation of 0.5 Ohm in the impedance of the grid in a power-balanced situation.
After some years of experience was released a new standard called VDE 0126-1-1-2006 that relaxed this thresholds, from 0.5 ohm to 1 ohm as well as it includes voltage limits, frequency detection and describes the procedures when the inverter has to be disconnected automatically from the grid. Was released the limit for leakage current of 300 mA, monitoring that the fault current has to be down to 30 mA and isolation monitoring (>1 Kohm/Volt).

IEC 61000 Electromagnetic Compatibility (EMC low frequency)
This law specified the limits of the harmonic components of current that can be generated by the photovoltaic panel. This test is obtained with the equipment tested under specified conditions.
Moreover, the law IEC 61000-3-3 is regarding the limits about the voltage fluctuation for an equipment which is connected to low-voltage public system. It specified also how to set the equipment in order to obtain the test.

EN 50160 Public Distribution Voltage Quality

The EN 50160 defines the characteristic about the quality of voltage in public distribution at the customer's point in public low-voltage and medium-voltage. The parameters are intended within the range of 95% of the period test, while the remaining 5% could be greater. For the PV photovoltaic is important to show that it can work with whole range of this parameters.
The parameters are the follow:

- Voltage harmonic levels. Maximum voltage THD is 8% (Shown on the picture at the below).
- Voltage unbalance for three-phase inverters. Maximum unbalance is 3%.
- Voltage amplitude variations: maximum ±10%.
- Frequency variations:maximum ±1%.
- Voltage dips:duration < 1 sec. Deep <60%.

Odd harmonics				Even harmonics	
Not multiple of 3		Multiple of 3			
Order h	Relative voltage (%)	Order h	Relative voltage (%)	Order h	Relative voltage (%)
5	6	3	5	2	2
7	5	9	1,5	4	1
11	3,5	15	0,5	6 to 24	0,5
13	3	21	0,5		
17	2				
19	1,5				
23	1,5				
25	1,5				

Figure 11.1

Response to abnormal grid conditions

In cases of the abnormal conditions of voltage or frequency the PV panel has to be disconnected from the grid in order to ensure the condition of safety.

In table (Figure 11.2) reported below the nominal voltage at the point of utility connection expressed in RMS (root means square) and the time within the panel has to be disconnected from the grid is shown . The inverter has to be connected to the grid in order to control the electrical conditions for the future reconnection.

IEEE 1547		IEC 61727		VDE 0126-1-1	
Voltage range (%)	Disconnection time (sec.)	Voltage range (%)	Disconnection time (sec.)	Voltage range (%)	Disconnection time (sec.)
$V<50$	0,16	$V<50$	0,10	$110\leq V<85$	0,2
$50\leq V<88$	2,00	$50\leq V<85$	2,00		
$110<V<120$	1,00	$110<V<135$	2,00		
$V\geq 120$	0,16	$V\geq 135$	0,05		

IEEE 1547		IEC 61727		VDE 0126-1-1	
Frequency range (Hz)	Disconnection time (sec.)	Frequency range (Hz)	Disconnection time (sec.)	Frequency range (Hz)	Disconnection time (sec.)
$59,3<f<60,5$[a]	0,16	$f_n-1<f<f_n+1$	0,2	$47,5<f<50,2$	0,2

[a]:For systems with power < 30 kW the lower limit can be adjusted in order to allow participation in the frequency control.

Figure 11.2

In the picture reported below is shown the time and conditions for reconnection after trip.

IEEE 1547	IEC 61727	VDE 0126-1-1
$88<V<110$(%)	$85<V<110$ (%)	
	AND	
AND	$f_n-1<f<f_n+1$ (Hz)	
	AND	
$59,3<f<60,5$ (Hz)	Minimum delay of 3 min.	

Figure 11.3

Power quality

The Photovoltaic Panel has to deliver the energy whose parameters has to be within the limits in terms of voltage, flicker, frequency, harmonics and power factor otherwise the panel should be disconnected.

DC current injection limitation		
IEEE 1574	IEC 61727	VDE 0126-1-1
$I_{DC} < 0,5$ (%) of the rated RMS current	$I_{DC} < 1$ (%) of the rated RMS current	$I_{DC} < 1$ A Maximum trip time 0,2 sec.

Maximum current harmonics						
IEEE 1547 and IEC 61727						
Individual harmonic order (odd)[a]	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	Total harmonic distortion (%)
(%)	4,0	2,0	1,5	0,6	0,3	5,0

[a]:Even harmonics are limited to 25% of the odd harmonic limits above.

Current harmonic limits set by IEC 61000-3-2 (class A)			
Odd harmonics		Even harmonics	
Order h	Current (A)	Order h	Current (A)
3	2,30	2	1,08
5	1,14	4	0,43
7	0,77	6	0,30
9	0,40	$8 \leq h \leq 40$	0,23 x 8/h
11	0,33		
13	0,21		
$13 \leq h \leq 39$	0,15 x 15/h		

Figure 11.4

<u>Observation</u>: The IEEE 1574 and IEC 61727 require that the test has to be made for different values of loading conditions (1/3 2/3 and 3/3 for the nominal load) and there is no maximum trip time condition. The voltage test has to be made with an ideal electronic power source with THD < 2.5% and voltage harmonics lower than 50% of the current harmonic limits.

For the requirement regarding the power factor, only in IEC 61727 is written that the PV inverter needs to have an average power factor greater than 0.9 when the output is greater than 50% of the nominal voltage.

Anti-islanding Requirements

The Anti-islanding occurs when there's a grid disconnection due to a failure that can be detect by the ground fault protection or for intentional disconnection while the PV inverter continues to operate and injects power.

This can cause some problems:

- Retripping the line can cause damage due to an out of phase closure.
- Risk for people who are working in the lines.

Some rules define the behaviour of the Photovoltaic panel when the Anti-islanding occurs.

IEEE 1547/UL 1741

The requirement is that after an islanding the panel has to cease to deliver energy within 2 sec. Moreover in the IEEE 1547.1 is described the test setup, where the EUT is the inverter and a load RLC is connected in parallel to the EUT. The LC resonate at grid frequency with a quality factor of 1.

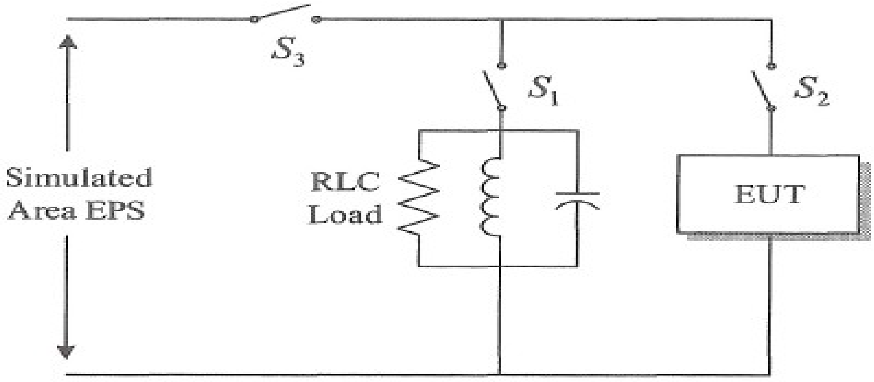


Figure 11.5

IEC 62116

The test circuit is the same as the test circuit in IEEE 1547.1 but in contains more test cases:

-case A: is tested under maximum allowable inverter input power (100-105 %)

-case B: is tested under input power 50-66 %.

-case C: is tested under minimum allowable inverter output power (25-33 %)

The maximum trip time is the same as in IEEE 1547.1 standards 2 sec.

12 Conclusion and scope of future work

The main objectives of the thesis have been achieved as follow:

- A PV model with cells including along with series parallel combination has been done.
- It has been devoloped the I-V & P-V characteristics and identified the maximum power point (MPP)
- The investigation of the effect of PS and a Multi String PV array has been done.
- The comparison of different algorithms for MPPT under Partial Shading (PS) has been treated.
- It has been designed and developed a full PV System with boost converter and an inverter for power transfer from DC to AC.

From the simulations and the correspondent results we can derive the following conclusion:

- The P&O algorithm is not suitable under condition of partial shading, the loss of power affects the efficiency of the system.
- The algorithms developed can track the MPP under condition of partial shading, thus the efficiency of the overall system raises.
- From the simulations, the second solution results appear to be faster to track the MPP and thus less power is lost.
- The second solution doesn't require to know the PV array's parameters.
- The validation of the solution proposed have been tested in real-time simulator

For the future work the following points could be done in order to accomplish the project:

- Complete the system adding PLL-Inverter to make it work in stand-alone system and grid connected
- Increase the performance of tracking time and accuracy of the proposed solutions
- Implement the solution and test it in a real environment

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Appendices

Appendix A1

```
function [Output,Shading] = fcn(Voltage, Current, Enable)

% MPPT controller.
% V input = PV array voltage (V)
% I input = PV array current (A)


% Definitions of the variables used in the program.
DeltaVset=5; % This variable is used to define the condition of patial shading.
% It represents the variation of voltage across the PV panel when partial
% shading occurs.
Coefficient=205.4/11.22; % This coefficient is used to calculate the
% reference voltage, it stands for "(Voc * Ns)/(Isc * Np)".
Vth=5; % This variable is used to decide how much close has to be
% the operative voltage across the PV panel with the reference voltage
% calculates after partial shading

persistent Vold Iold DutyCycle Pold Vshading;

dataType = 'double';
if isempty(Vold)
    Vold=0;
    Iold=0;
    DutyCycle=0;
    Pold=0;
    Vshading=0;
end

I=Current;% Sense of current
V=Voltage;% Sense of voltage
P=I*V; % Power in input of the boost
dV=V-Vold;
dP=P-Pold;
dI=I-Iold;
Gpv=(I/V)+(dI/dV);
Iold=I; % Value used to calculate "dI" in the next cycle
Vold=V; % Value used to calculate "dV" in the next cycle
Pold=P; % Value used to calculate "dP" in the next cycle

Gpvabs = abs(Gpv); % Absolute value of Gpv

if (Gpvabs < 1) % I set a generic value, in the paper is written "e"
% Variable "a" is used to calculate the path of increment for the Duty Cycle
    a=2.5; % In this case "a" has to be small, I set a generic value
else
    a=5; % In this case "a" has to be high, I set a generic value
end
```

```
if (Vshading ~= 0 && Vth < abs(Voltage-Vshading))

        if Voltage > Vshading
           DutyCycle=DutyCycle+a;
        else
           DutyCycle=DutyCycle-a;
        end
else
        if Vth > abs(Voltage-Vshading)
           Vshading=0;
        end
end

if Vshading == 0
    if (dV < deltaVset && dI < -(I/2))
    % Condition of partial shading is satisfied.
    % The variable in output is called Shading
    Vshading=coefficient*I;


    else
        if (dP ~= 0 && Enable ~=0)
           if dP < 0
              if dV < 0
                 DutyCycle=DutyCycle-a;

              else
                 DutyCycle=DutyCycle+a;

              end
           else
              if dV < 0
                 DutyCycle=DutyCycle+a;

              else
                 DutyCycle=DutyCycle-a;

              end
           end
        end
  end
end
% Limitation of the value of the Duty Cycle in the range from 0% to 100%
if DutyCycle>90
   DutyCycle=85;
end
if DutyCycle<0
   DutyCycle=5;
end
Output=DutyCycle;
Shading=Vshading;

end
```

Appendix A2

```
function [Output,Shading] = fcn(Voltage, Current, Enable)

% MPPT controller.
% V input = PV array voltage (V)
% I input = PV array current (A)


% Definitions of variables used for the cycle

Pth=300; % This value stands for the threshold which rules the algorithm, if
% the difference between the current power and Pmax is more than Pth a
% new scan of the curve Power-Voltage is done in order to find the new
% global maximum.
DutyStep=15; % This value is the step of duty cycle used to scan the curve
% Power-Voltage in order to find the new global maximum.
Nth=2; % This value represents how long a step of duty cycle lasts during the
% the scanning of the curve Power-Voltage. The time is given from
% the following equation: Time=Nth*clock, in this case clock is 0.02s
NumPmaxTh=5; % This value represent the delay after the condition of partial
% shading that decides when the comparison with Pmax is done. It is useful to
% postpone the comparison in order to give time to the circuit to be stable.
RangeMaxScan=75; % Define at which value of the duty cycle the program starts
% to scan the curve Power-voltage.
RangeMinScan=15; %Define at which value of the duty cycle the program
% finishes to scan the curve Power-voltage.
DutyCycleInitial=50; % This parameter defines the initial value of Duty
% Cycle when the external signal Enable is "0". It is important because it lets
% the circuit to be ready for the scanning.

persistent Vold Iold DutyCycle NumPmax Pold Vshading Scanner Pmax DutyScan
DutyMax NumCycle;

dataType = 'double';
if isempty(Vold)
    Vold=0;
    Iold=0;
    DutyCycle=0;
    Pold=0;
    Vshading=0;
    Scanner=1;
    Pmax=0;
    DutyScan=RangeMaxScan+DutyStep;
    DutyMax=0;
    NumCycle=0;
    NumPmax=0;

end

if (Enable ==0)
    DutyCycle=DutyCycleInitial;
else
if (Scanner==1 && DutyScan > RangeMinScan && NumCycle==(Nth-1))
    P=Current*Voltage;

    if (P>Pmax && DutyScan < RangeMaxScan)
        Pmax=P;
        DutyMax=DutyScan;
    end
```

```
    DutyScan=DutyScan-DutyStep;
    DutyCycle=DutyScan;


    NumCycle=0;

else
    if (NumCycle ~= (Nth-1))
        NumCycle=NumCycle+1;

    else
    if (Scanner==1)
        Scanner=0;

        Vshading=Pmax;
        DutyCycle=DutyMax;

    else

        I=Current;% Sense of current
        V=Voltage;% Sense of voltage
        P=I*V; % Power in input of the booster
        if (P > Pmax)
           Pmax=P;
        end

        dV=V-Vold;
        dP=P-Pold;
        dI=I-Iold;
        Iold=I; % Value used to calculate "dI" in the next cycle
        Vold=V; % Value used to calculate "dV" in the next cycle
        Pold=P; % Value used to calculate "dP" in the next cycle
        Gpv=(I/V)+(dI/dV);
        Gpvabs = abs(Gpv); % Absolute value of Gpv

        if (Gpvabs < 1) % I set a generic value, in the paper is written "e"
            % Variable "a" is used to calculate the step of increment for the
            % DutyCycle
            a=2.5; % In this case "a" has to be small, I set a generic value
        else
            a=5; % In this case "a" has to be high, I set a generic value
        end

        if dP ~= 0 % Start Algorithmic Perturbation&Observation
           if dP < 0
              if dV < 0
                 DutyCycle=DutyCycle-a;

              else
                 DutyCycle=DutyCycle+a;

              end
           else
              if dV < 0
                 DutyCycle=DutyCycle+a;

              else
                 DutyCycle=DutyCycle-a;

              end
           end
```

```
        end
       if(NumPmax < NumPmaxTh)
          NumPmax=NumPmax+1;
       end
       if  (Pmax-P > Pth && NumPmax==NumPmaxTh)
           Scanner=1;
           Pmax=0;
           Vshading=0;
           DutyScan=RangeMaxScan+DutyStep;
           NumCycle=0;
           NumPmax=0;
       end
    end
end
end
% Limitation of the value of Duty Cycle between the range from 0% to 100%
if DutyCycle>90
   DutyCycle=85;
end
if DutyCycle<0
   DutyCycle=5;
end
end
Output=DutyCycle;
Shading=Vshading;
end
```