Efficiency Maximization of Solar Photovoltaic Systems

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ABSTRACT
Photovoltaic (PV) power generation has an important role to play due to the fact that it is a green source. The only emissions associated with PV power generation are those from the production of its components. Increasing the efficiency in PV plants so the power generated increases is a key aspect, as it will increase the incomes, reducing consequently the cost of the power generated so it will approach the cost of the power produced from other sources. The efficiency of a PV plant is affected mainly by three factors. The paper discusses the factors affecting the overall efficiency of a solar PV system.

General Terms
Solar photovoltaic systems, efficiency et.al.

Keywords
Photovoltaic, solar cell model, partial shaded conditions, MPPT.

1. INTRODUCTION
Developed countries are trying to reduce their greenhouse gas emissions. For example, the EU has committed to reduce the emissions of greenhouse gas to at least 20% below 1990 levels and to produce no less than 20% of its energy consumption from renewable sources by 2020 [1]. In this context, *photovoltaic* (PV) power generation has an important role to play due to the fact that it is a green source.The only emissions associated with PV power generation are those from the production of its components. After their installation they generate electricity from the solar irradiation without emitting greenhouse gases. In their lifetime, which is around 25 years, PV panels produce more energy than that for their manufacturing [2]. Also they can be installed in places with no other use, such as roofs and deserts, or they can produce electricity for remote locations, where there is no electricity network. The latter type of installations is known as off-grid facilities and sometimes they are the most economical alternative to provide electricity in isolated areas. However, most of the PV power generation comes from grid-connected installations, where the power is fed in the electricity network. On the other hand, due to the equipment required, PV power generation is more expensive than other resources. Governments are promoting it with subsidies or feed-in tariffs, expecting the development of the technology so that in the near future it will become competitive [3]-[4]. Increasing the efficiency in PV plants so the power generated increases is a key aspect, as it will increase the incomes, reducing consequently the cost of the power generated so it will approach the cost of the power produced from other sourcesThe efficiency of a PV plant is affected mainly by three factors: the efficiency of the PV panel (in commercial PV panels it is between 8-15% [3]), the efficiency of the inverter (95-98 %) and the efficiency of the *maximum power point tracking* (MPPT) algorithm. Improving the efficiency of the PV panel and the inverter is not easy as it depends on the technology available, it may require better components, which can increase drastically the cost of the installation. Instead, improving the tracking of the *maximum power point* (MPP) with new control algorithms is easier, not expensive and can be done even in plants which are already in use by updating their control algorithms, which would lead to an immediate increase in PV power generation and consequently a reduction in its price.

2. BACKGROUND:PHOTOVOLTAICS
A photovoltaic (PV) cell, also known as solar cell, is a semiconductordevice that generates electricity when exposed to light.When light strikes a PV cell, the photons dislodge the electrons from the atoms of the cell. The free electrons then move through the cell, creating and filling in holes in the cell. This movementof electrons and holes generates electricity. The physical processby which a PV cell converts light into electricity is known as the photovoltaic effect.

The major types of materials for building PV cells include crystallineand thin films, which differ in terms of light absorption efficiency, energy conversion efficiency, manufacturing technology,and cost of production [4]. Table.1 lists a comparison of PV materials.Existing electronic models for solar cells characterize properties such as the open circuit voltage (*Voc*), the maximum power voltage (*Vmp*), and the maximum power current (*Imp*) in terms of the short circuit current (*Isc*), which is in turn modelled as a function of the beam and diffuse irradiance, air mass (*AMa*), incident angle (*AOI*), and panel temperature (*Tc*).

Table 1. A comparison of PV materials

	Crystalline			Thin films		
Materials	Single-Si	Poly-Si	GaAs	a-Si	CdTe	CuIn S2
Absorption efficiency	low	low	medi um	high	high	high
Conversion efficiency	15-20%	10-14%	25-30%	5-9%	7%	18%
Cost	low	low	high	medi um	medi um	high

3. EQUIVALENT CIRCUIT OF A SOLAR CELL
The solar cell can be represented by the electrical model shown in Figure:1. Its current voltage characteristic is expressed by the following equation (1):

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

where I and V are the solar cell output current and voltage respectively, $I_0$is the dark saturation current, q is the charge of an electron, A is the diode quality (ideality) factor, k is the Boltzmann constant, T is the absolute temperature and $R_S$and $R_{SH}$are the series and shunt resistances of the solar cell. $R_S$is the resistance offered by the contacts and the bulk semiconductor material of the solar cell. The origin of the shunt resistance R_{SH} is more difficult to explain. It is related to the non ideal nature of the p–n junction and the presence of impurities near the edges of the cell that provide a short-circuit path around the junction [4]. In an ideal case $R_S$would be zero and R_{SH}infinite. However, this ideal scenario is not possible and manufacturers try to minimize the effect of both resistances to improve their products. Sometimes, to simplify the model, the effect of the shunt resistance is not considered, i.e. $R_{SH}$is infinite, so the last term in (1) is neglected.

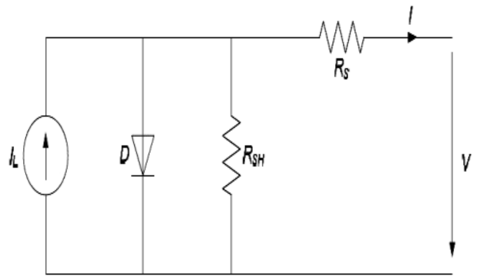


Figure 1. Equivalent circuit of a solar cell.

From the equation 1 the I-V and P-V characteristics of the solar cell is shown in fig.2.

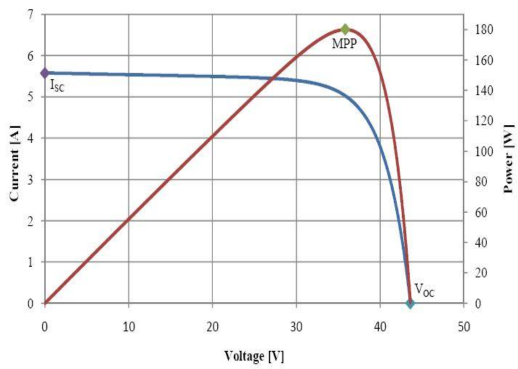


Figure 2. I-V and P-V characteristics of a solar cell.

A PV panel is composed of many solar cells, which are connected in series and parallel so the output current and voltage of the PV panel are high enough to the requirements of the grid or equipment. Taking into account the simplification mentioned above, the output current-voltage characteristic of a PV panel is expressed by equation (2), where $n_p$and $n_s$are the number of solar cells in parallel and series respectively.

$$I \approx n_p I_{ph} - n_p I_0 \left(e^{\frac{q(V-IR_S)}{AkTn_s}} - 1 \right) \quad (2)$$

4. TEMPERATURE AND IRRADIANCE EFFECT ON CHARACTERISTICS OF SOLAR PANEL

Two important factors that have to be taken into account are the irradiation and the temperature. They strongly affect the characteristics of solar modules. The effect of the irradiance on the voltage-current (V-I) and voltage-power (V-P) characteristics is depicted in Figure 3, where the curves are shown in per unit, i.e. the voltage and current are normalized using the $V_{OC}$and the I_{SC}respectively, in order to illustrate better the effects of the irradiance on the V-I and V-P curves. The photon-generated current is directly proportional to the irradiance level, so an increment in the irradiation leads to a higher photo-generated current. Moreover, the short circuit current is directly proportional to the photo-generated current; therefore it is directly proportional to the irradiance. When the operating point is not the short circuit, in which no power is generated, the photo-generated current is also the main factor in the PV current, as is expressed by equations(1) and (2). For this reason the voltage-current characteristic varies with the irradiation. In contrast, the effect in the open circuit voltage is relatively small, as the dependence of the light generated current is logarithmic, as is shown in equation (1).

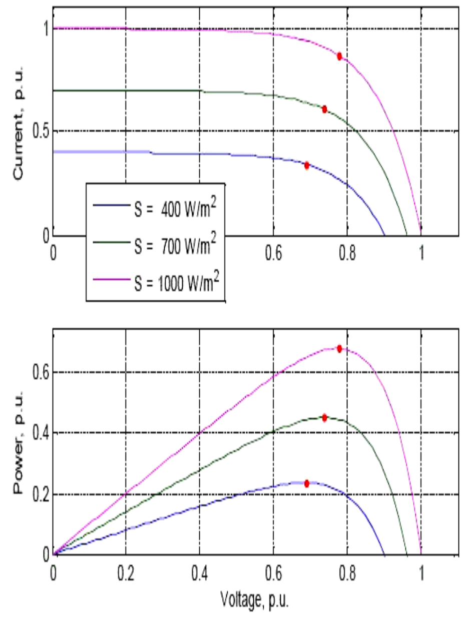


Figure 2. I-V and P-V curves at constant temperature (25°C) and three different irradiation values.

Figure 2 shows that the change in the current is greater than in the voltage. In practice, the voltage dependency on the irradiation is often neglected [10]. As the effect on both the current and voltage is positive, i.e. both increase when the irradiation rises, the effect on the power is also positive: the more irradiation, the more power is generated.

The temperature, on the other hand, affects mostly the voltage. The open circuit voltage is linearly dependent on the temperature, as shown in the following equation:

$$V_{OC}(T) = V_{\alpha}^{STC} + \frac{K_{V\%}}{100}(T - 273.15) \quad (3)$$

According to (3), the effect of the temperature on $V_{OC}$is negative, because *Kv* is negative, i.e. when the temperature rises, the voltage decreases. The current increases with the temperature but very little and it does not compensate the decrease in the voltage caused by a given temperature rise. That is why the power also decreases. PV panel manufacturers provide in their data sheets the temperature coefficients, which are the parameters that specify how the open circuit voltage, the short circuit current and the maximum power vary when the temperature changes. As the effect of the temperature on the current is really small, it is usually neglected [10]. Figure 3 shows how the voltage-current and the voltage-power characteristics change with temperature.

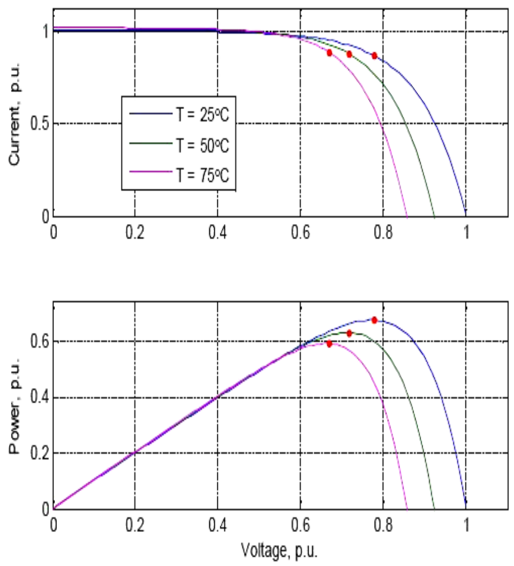


Figure 3. I-V and P-V curves at constant irradiation (1 kW/m2) and three different temperatures.

5. CHARACTERISTICS OF SOLAR ARRAY UNDER PARTIALLY SHADED CONDITIONS: [5]

A number of series/parallel connected SPV modules are used to form a solar array for a desired voltage and current level. The major challenge in using a SPV source containing a number of cells in series is to deal with its non-linear internal resistance. The problem gets all the more complex when the array receives non-uniform irradiance (partially shading). In a solar array spread over vast area, it is likely that shadow may fall over some of its cells due to tree leaves falling over it, birds or bird litters on the array, shade of a neighbouring construction etc. In a series connected string of cells, all the cells carry the same current. Even though a few cells under shade produce less photon current but these cells are also forced to carry the same current as the other fully illuminated cells. The shaded cells may get reverse biased, acting as loads, draining power from fully illuminated cells. If the system is not appropriately protected, hot-spot problem can arise and in several cases, the system can be irreversibly damaged. In conventional SPV systems, those shadows lower the overall generation power to a large degree. Hence the SPV installation cost is increased, because the number of SPV modules will be increased.

5.1 Operation of Series Connected Modules with by-pass Diode

Figure 4 shows the connection diagram of three modules connected in series.

Figure-5 shows the characteristics of SPVA consisting of three series connected modules where each module receives different illumination. The same type of shaded condition (100%, 75% and 25%). The effect of shading in series connected modules is explained with the help of Figure 5. Diodes D_{b1}, D_{b2} and D_{b3} are bypass diodes. In series connection, array characteristics can be obtained by adding the voltage of each module at every current.

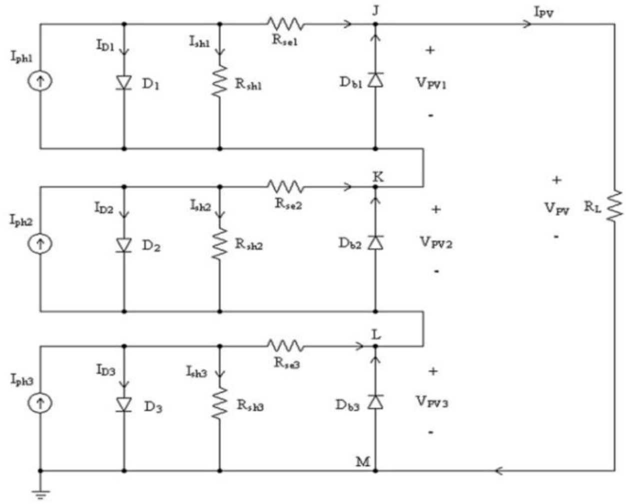
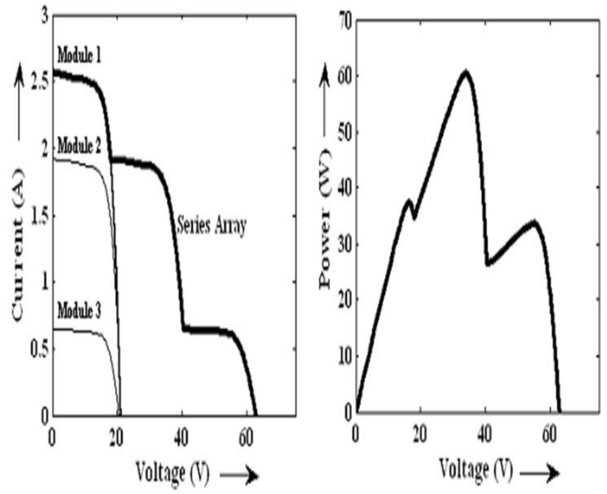


Figure 4. Series Connected SPVA with bypass diodes

In case the array current exceed the short circuit current of a particular module, the voltage of that module will be -0.7 V (the forward cut-in voltage of the bypass diode). I-V characteristics of the array for three non-uniformly illuminated series connected modules plotted in this manner is illustrated in Figure 5.a. P-V characteristic of this array derived from I-V characteristic of Figure 5.a is shown in Figure 5.b.



(a) I-V characteristics (b) P-V characteristics

Figure 5. Characteristics of three series connected panels under partial shading

5.2 Operation of Parallel Connected Modules with Blocking Diode

In parallel connected modules, if one module is severely shaded, or if there is a short circuit in one of the module, the blocking diode prevents the other strings from sending current backwards down the shaded or damaged string. Diodes placed in series with modules can perform the function of blocking currents from flowing back to the modules thus preventing the modules from becoming loads. When the non shaded SPV modules and the shaded SPV modules are connected in parallel, the generation voltage is fixed for each SPV module and is uniform throughout the entire SPV generation system, and the current generated from each SPV module flows without restriction.

To illustrate the performance of parallel connected modules three modules are connected in parallel as shown in Figure 6.

Figure 7 shows the characteristics of SPVA consisting of three parallel connected modules where each module receives different illumination. Let Module-1 receives 100% illumination, Module-2 receives 75% illumination and Module-3 receives 25% illumination. As the output current of the system increases from zero to short circuit current, the operating point of each panel moves. The characteristics reveal that both the shaded and non shaded modules can operate in the area where each module can contribute power.

$$P_{totalmax} = P_{1max} + P_{2max} + P_{3max} \quad (4)$$

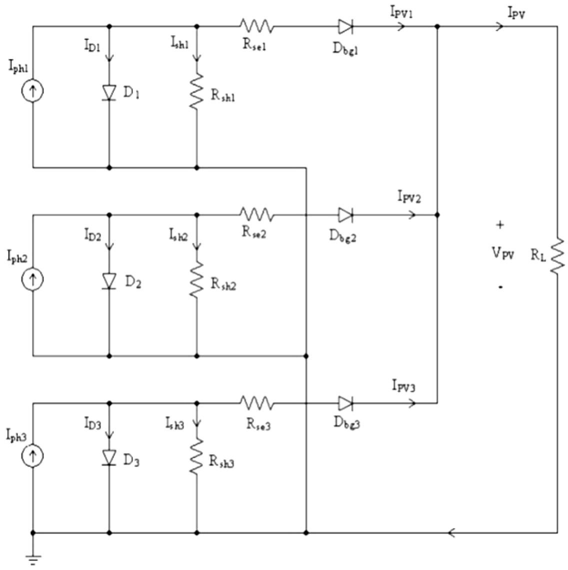


Figure 6. Parallel Connected SPVA with blocking diodes

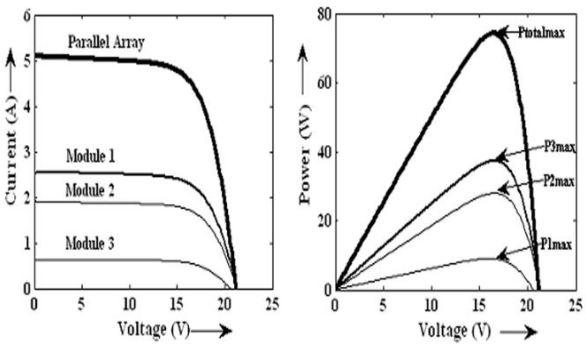


Figure 7. Characteristics of three parallel connected modules under partial shading

6. MAXIMUM POWER POINT TRACKING

As the environmental conditions (temperature, irradiance etc.) vary with time, it is necessary to develop a control logic that continuously monitors the terminal voltage and current and updates the control signal accordingly. Furthermore, for optimal operation of a PV module, its terminal voltage must be equal to the corresponding MPP value. A controller which is used to track value of voltage (Vmpp) for which P is maximum.

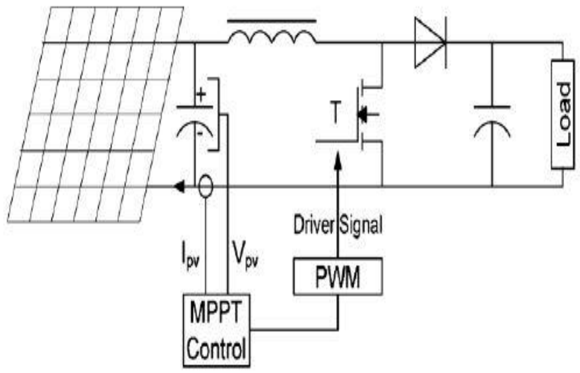


Figure 8. MPPT Control Block-diagram

In this MPPT track an output variable voltage for maximum power and give signal to a PWM (pulse width modulator) signal generator, so that it can develop a gate pulse of perfect duty cycle for variable DC voltage to a constant DC voltage.

6.1 Controlling from Panel side

As shown in Figure.8, MPPT takes 2 input (I & V) from panel side and try to identify maximum power point and then track that continuously. In this case due to change in temperature and irradiation of sun, the variable voltage will be obtained for a maximum power. Using value of that it will calculate duty cycle and give signal to PWM generator block and then a gate pulse is given to DC/DC converter so that we can obtain maximum output power.

6.2 Controlling from Load Side

In real life many times load is changes due to variable demand of electric power so for this case also we need MPPT controller. In this case it takes signal from load side also and generates a regarding duty cycle so that even after variable generation and variable demand we can gain maximum power.

7. CONCLUSION

As was mentioned before, the temperature and the irradiation depend on the atmospheric conditions, which are not constant during the year and not even during a single day; they can vary rapidly due to fast changing conditions such as clouds. This causes the MPP to move constantly, depending on the irradiation, temperature and partial shading conditions. If the operating point is not close to the MPP, great power losses occur. Hence it is essential to track the MPP in any conditions to assure that the maximum available power is obtained from the PV panel. In a modern solar power converter, this task is entrusted to the MPPT algorithms. Some of the practical applications of MPPT techniques are in the solar water pumping system, solar vehicles (car, flights), satellite power supply, off-grid and grid-tied power supply systems, and small electronics applications (mobile charging), etc.

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