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Review Paper

Optimized Maximum Power Point Tracker for Current Environmental Conditions and Sustainable Development

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Abstract

Every photovoltaic cell array has an optimum operating point, called the maximum power point (MPP), which varies depending on cell temperature and the present insulation level. The solar-powered racing vehicle sol train is not yet equipped with such a maximum power point tracking (MPPT) device. Maximum power point tracking (MPPT) techniques are used in PV systems to make maximum utilization of PV array output power which depends on solar irradiation and ambient temperature. The addition of such an operating point controller will yield an estimated 60% increase in power output from the solar cells. This leads to a higher efficiency of the overall system without adding any additional photovoltaic cell surface to the existing array. This paper will introduce a novel approach to analyze, simulate, and evaluate the complete solar power supply system with a digital MPPT controller under varying operating conditions as they are experienced in a moving outdoor vehicle.

Keywords: Solar energy, photovoltaic-cell, MPPT, solar arrays, power train.

Introduction

The generation of energy in our modern industrialized society is still mainly based on a very limited resource: petroleum. As the world's energy demands rise and new sources for petroleum become scarce, the search for alternative energy resources has become an important issue for our time. A large amount of research has been done not only in the area of nuclear power generation but also in the area of unlimited energy sources such as wind power generation and solar energy transformation[1].

This has led to programs and efforts to design low emission (LEV) and zero emission (ZEV) vehicles. Research is being done in highly efficient combustion engines, fuel cell technology, hybrid cars combining conventional propulsion techniques with electrical drive systems and electrical vehicles powered either by batteries or by a solar energy conversion system. This search for alternative energy sources to power individual vehicles led to the decision of a group of Reed College students in the early 90's to build the solar-powered racing car sol train. A solar vehicle is powered by photovoltaic cell arrays which allow for direct conversion of solar radiation into electrical energy[2-4].

Every photovoltaic cell array has an optimum operating point, called the maximum power point (MPP), which varies depending on cell temperature and the present insulation level. The goal of this paper is to find the mechanism best suited for employment in a moving vehicle to optimally track this point of maximum efficiency and adjust the operating point of the solar cell array accordingly. The solar-powered racing vehicle sol train is not yet equipped with such a maximum power point tracking (MPPT) device. The addition of such an operating point controller will yield an estimated 60% increase in power output from the solar cells. This leads to a higher efficiency of the overall system without adding any additional photovoltaic cell surface to the existing array. There are two main groups of MPPTs: those that use analog circuitry and classical feedback control, and others that use a microprocessor to maintain control of the operating point. Analog systems have the advantage of having low cost components, but are more problematic to control. It is difficult to develop a stable system which is able to maintain its accuracy even under extreme operating conditions such as the wide temperature variations that occur in an outdoor vehicle. The digitally controlled MPPT systems have the advantage that a power point tracking algorithm will not be influenced by changes in temperature and therefore will always be very reliable[5-8].

This paper will introduce a novel approach to analyze, simulate, and evaluate the complete solar power supply system with a digital MPPT controller under varying operating conditions as they are experienced in a moving outdoor vehicle. The simulation tool Simulinkr, which is included in The MathWorks's software package Mat lab, enables for the simulation of mixed discrete-continuous systems and therefore allows the direct comparison of the various approaches to maximum power point tracking under the same operating conditions. The digitally controlled MPPT can be directly included in the simulated system, and modifications to improve

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the MPPT performance of conventional MPPT algorithms can be evaluated without having to build and modify an expensive prototype. To be able to properly simulate the complete solar power supply system, detailed mathematical models for all of the system's components are necessary. These components consist of the array of photovoltaic cells, an energy buyer in the form of a parallel-connected battery pack and optionally a dc-to-dc converter.

The Photovoltaic Power System

The power supply system consists of an array of photovoltaic cells, a set of batteries as an energy buffer and optionally some kind of converter to match the voltage of the solar array with the battery voltage (figure-1). If the conversion ratio of the converter is varied by a controller to constantly adjust the operating voltage of the solar panel to its point of maximum power (V_{mp}), it is being operated as a maximum power point tracker (MPPT).

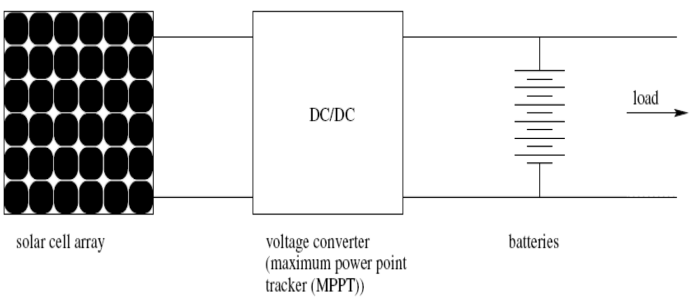

Figure-1
Power train of a solar powered system

Photovoltaic Cells and Solar Arrays

Physical Structure of a Photovoltaic Cell: A solar cell is a semi conducting device that absorbs light and converts it into electrical energy. Today's most common cell is a mass manufactured single p-n junction silicon (Si) cell with efficiency up to about 17%. It consists of a moderately p-doped base substrate and a thin heavily n-doped top layer. Thin metal contacts on the surface and a plain metal layer on the back connect this photovoltaic element to the load (figure-2).

If exposed to radiation, electron-hole pairs are created by photons with an energy greater than the band-gap energy of the semiconductor (hv > Eg). This is called the photovoltaic effect. The newly created charge systemizes in the depletion region are separated by the existing electric field. This leads to a forward bias of the p-n junction and builds up a voltage potential called the photo-voltage. As soon as a load is connected to the cell, this voltage will cause a current (called the photo-current) to ow through the load. In addition the forward bias of the p-n junction also leads to a small diode current Id in the opposing direction of the photo-current. The p-n junction properties and the discussed reaction of the semiconductor to radiation lead to the simplified and idealized equivalent circuit diagram of a photovoltaic cell as shown in figure-3.

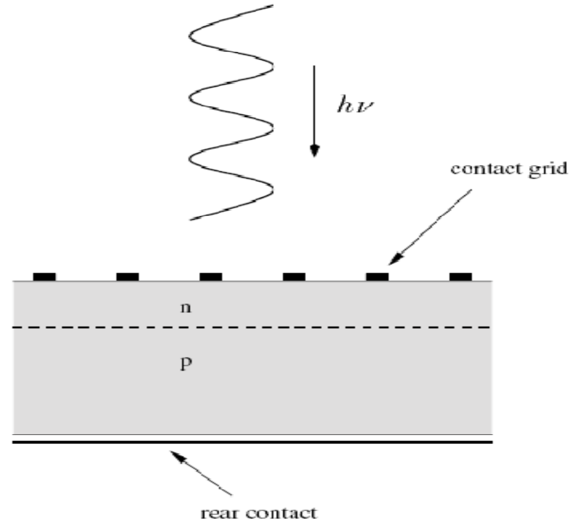

Figure-2
Schematic representation of a standard pn-junction solar cell

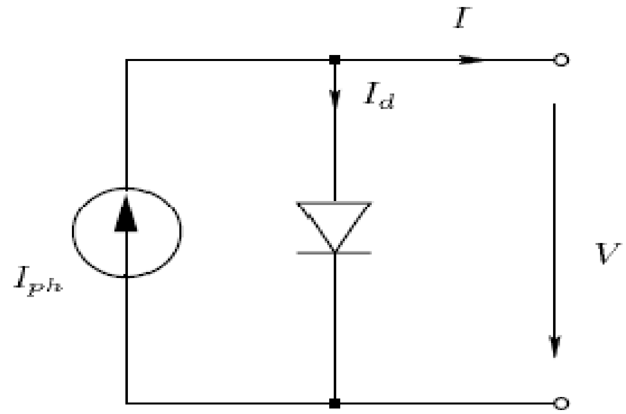

Figure-3
Simple equivalent circuit diagram for a photovoltaic cell

Application of Kirchhoff's law and the exponential diode equation leads to a simple mathematical model for a photovoltaic cell.

$I_d = I_s\,[\,e^{\,q\,v/2\,k\,T} - 1]$ (1)

$I = I_{ph} - I_s\,[e^{\,q\,v/2\,k\,T} - 1]$ (2)

I and V are the output current and voltage of the cell. I_{ph} is the generated photocurrent and I_s is the reverse saturation current of the diode. Furthermore, the characteristics are influenced by the temperature T and by the constant for the elementary charge and Boltzmann's constant k.

With this model in mind it is not surprising that the I-V characteristics of a photovoltaic cell are quite similar to those of a regular diode. The major difference is the existence of an open circuit voltage Voc which leads to a short circuit current Isc visible as a current offset in the characteristic curve (figure-4). A photovoltaic cell in total darkness will perform similar to a regular diode.

Many efforts are being made to increase the efficiency of solar cells by utilizing multi-layer techniques and various semi conducting materials such as gallium arsenide (GaAs), indium phosphide (InP), copper indium selenide (CuInSe2), cadmium telluride (CdTe), copper selenide (Cu2Se), and zinc phosphide (Zn3P2). This increased the cell efficiency to more than 21% for Si and 25% for GaAs solar cells in recent years.

Since a higher complexity of a cell is accompanied by a higher price, research has also been done in the area of low cost mass production which led for example to amorphous polycrystalline thin film solar cells. The thin film configuration greatly reduces material costs and allows for continuous ow processing. The disadvantage of this technique is a reduction in cell efficiency to approximately 10 %-13%.

Equivalent Circuit and Mathematical Model: Actual measurements on real cells under diverse operating conditions, however, show the need for a more sophisticated model. In particular the internal resistance of the device has to be taken into consideration. This leads to the widely used \two-diode model" as shown in figure-5.

Figure 5 is a representation of the mathematical model for the current-voltage characteristic which is given as:

$$I = I_{ph} - I_{s1} [e^{q(V + I Rs) / n_1 k T} -1] - I_{s2} [e^{q(V + I Rs) / n_2 k T} -1] - V + IRs/Rp \quad (3)$$

I and V are the output current and output voltage of the photovoltaic cell, I_{ph} is the generated photo-current, I_s1 and I_s2 are the diodes' reverse saturation currents, n1 and n2 the diode ideality factors, Rs and Rp the series and parallel resistance (respectively), and T is the absolute temperature in Kelvin. The equation also contains the elementary charge constant q and the Boltzmann constant k. The photo-current I_{ph} is equal to its value at maximum insolation1 times the irradiance S in percent (I_{ph} = SI_{ph}; max). It is obvious from equation that the current-voltage characteristic strongly depends on insolation and temperature. The dependency on the temperature is further amplified by the properties for the photo-current I_{ph} and the diodes' reverse saturation currents Is which are given by Burger:

$$I_{ph} (T) = I_{ph} /_{(T = 298 K)} [1+ (T - 298 K) . (5. 10^{-4})] \quad (4)$$
$$I_{s1} = K_1 T^3 e^{-Eq / kT} \quad (5)$$
$$I_{s2} = K_2 T^{5/2} e^{-Eq / kT} \quad (6)$$

Where, Eg is the band-gap energy of the semiconductor and

$$K_1 = 1.2 A/cm^2 K^3 \quad (7)$$
$$K_2 = 2.9. 10^5 A/cm^2 K^{5/2} \quad (8)$$

vary with the manufacturer and depend on the size of the cell surface area. 1Derived from the definition of the standard test conditions (STC) for solar arrays, a maximum insolation of 1000W=m2 is assumed. STC are reference testing values of cell temperature (25^{0}C), in-plane irradiance (1000W=m2) and airmass solar reference spectrum (AM = 1.5) for photovoltaic (PV) module or PV cell testing, defined in IEC 61829 (1995-03).

The Solar Panel

In photovoltaic energy systems, single cells are combined into solar cell arrays by connecting a number of cells in series. Consideration of the equivalent circuit model (figure-5) leads to the equation for a photovoltaic cell array (commonly called a solar panel or solar array) with z photovoltaic cells in series connection.

$$I = Iph - Is_1 [e^{q(V+Iz Rs) / z n_1 kT} -1] - Is_2 [e^{q(V+Iz Rs) / z n_2 kT} -1] - V + Iz Rs/ z Rp \quad (9)$$

These panels then can be further arranged in series or parallel connections to achieve the desired voltage and current values for the system.

Figure-6 shows that the output current I of an array is greatly influenced by the change in insolation S, whereas the output voltage V stays approximately constant. In contrast, for a changing temperature one can see that the voltage varies widely while the current remains unchanged (figure-7). The P-V characteristics for a photovoltaic cell array can be obtained from the I-V characteristics and the relation for the output power P = V I as shown in figures 8 and 9. These figures clearly show how the dependency of output current I and output voltage V on temperature and insolation translate into a dependency of the output power on the same two parameters. Figure-8 confirms the expected behavior of a device that converts solar energy into electrical energy: the power output of a solar panel is greatly reduced for a decreasing insolation.

It can also be seen that the output power of a solar panel not only depends on temperature and insolation, but also very strongly on its operating voltage V. The point of maximum power indicated as MPP (maximum power point) in figure-10 is the desired operating point for a photovoltaic array to obtain maximum efficiency. The corresponding values for voltage and current are called Vmp and Imp, respectively.

The P-V curve shown in figure-10 shares the temperature and insulation dependencies shown in figures 6-9; as a result the value for the optimum operating voltage Vmp will vary constantly with changes in these environmental conditions. In these circumstances a maximum power point tracking (MPPT) mechanism can help to significantly increase the power output of a solar power system by adjusting the system load in such a way that the operating voltage V will always be approximately equal to the optimum operating voltage Vmp:

$$V = V_{mp} + e \quad (10)$$

with being as small as possible.

The importance of keeping the operating voltage as close as possible to Vmp is illustrated in figure-10. If the operating voltage differs from Vmp by about 10% as indicated by V1, it will result in an output power reduction of almost 25 %. Comparison of systems with and without maximum power point tracking devices shows that units with a MPPT output 80-90% of their theoretical maximum power, whereas units without a MPPT only operate at 30% of their maximum power output.

Solar panel consists of a certain number of photovoltaic cells in series. This is necessary to achieve a reasonably high output voltage at the panel. But considering the photovoltaic cell's equivalent circuit diagram (figure-3), the drawback of this configuration becomes clear: as soon as one photovoltaic cell is shaded, it will behave like a diode in reverse direction to the current ow. This result either in almost zero current or, if the voltage is higher than the diode's reverse breakdown voltage, it will eventually even destroy the photovoltaic cell. This can be avoided by placing “bypass" diodes in parallel to the cells (figure-11). It is sufficient to group a number of photovoltaic cells together to be bypassed only by one diode, as long as the voltage of this substring of cells does not exceed the reverse breakdown voltage of one cell of its type.

Additional protective measures indicated in figure-11 are the “blocking" diodes: these diodes are connected in series to the solar array to prevent reverse current ow through the array in case of low or zero illumination. This current ow can be caused by another power source in the system such as the storage batteries. Without the blocking diodes, a reverse current ow through the idle panel could discharge the batteries and even cause thermal damage to the photovoltaic cells[9-30].

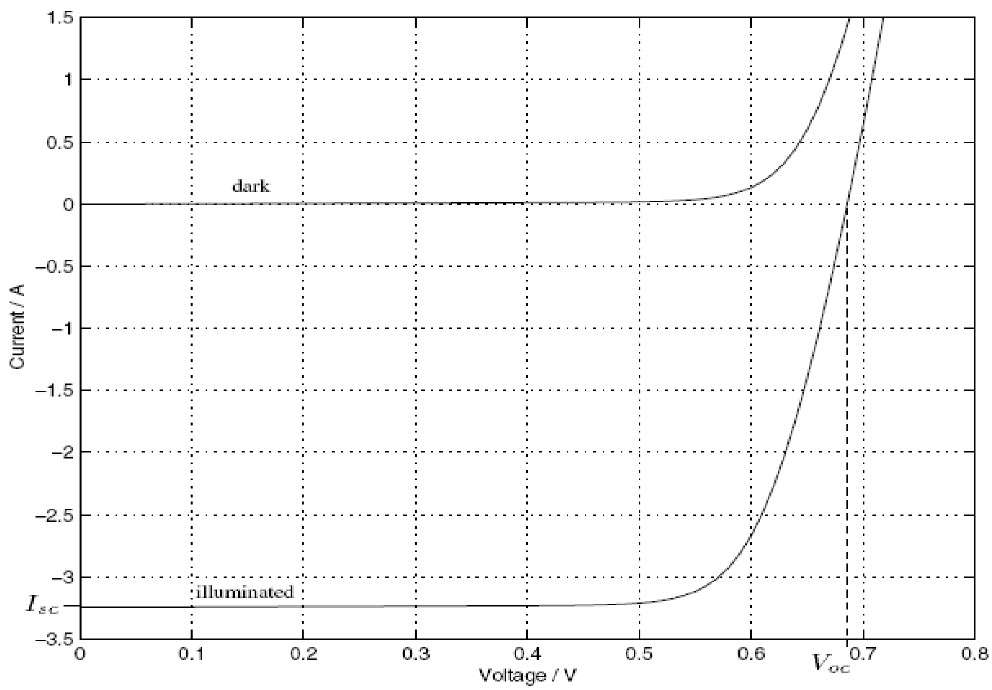

Figure-4
I-V characteristic of a photovoltaic cell

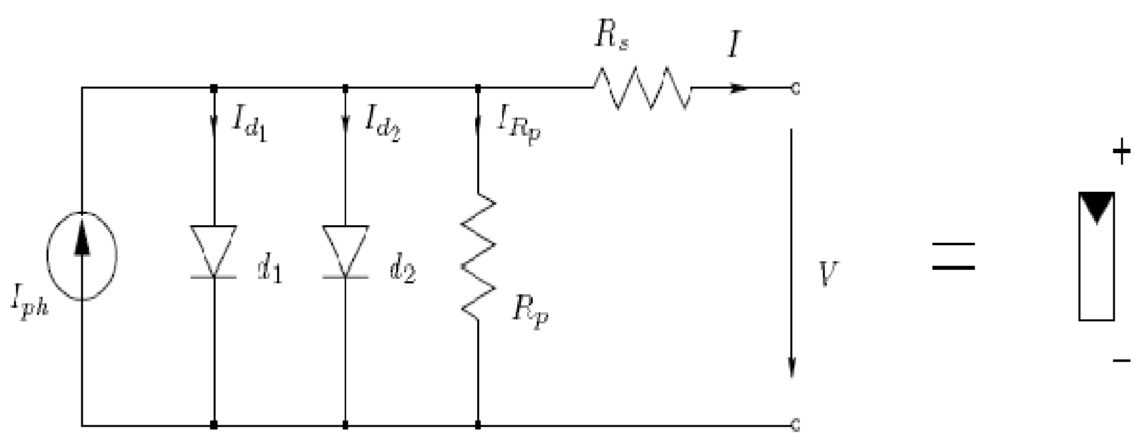

Figure-5
Equivalent two-diode circuit model of a photovoltaic cell and its circuit symbol

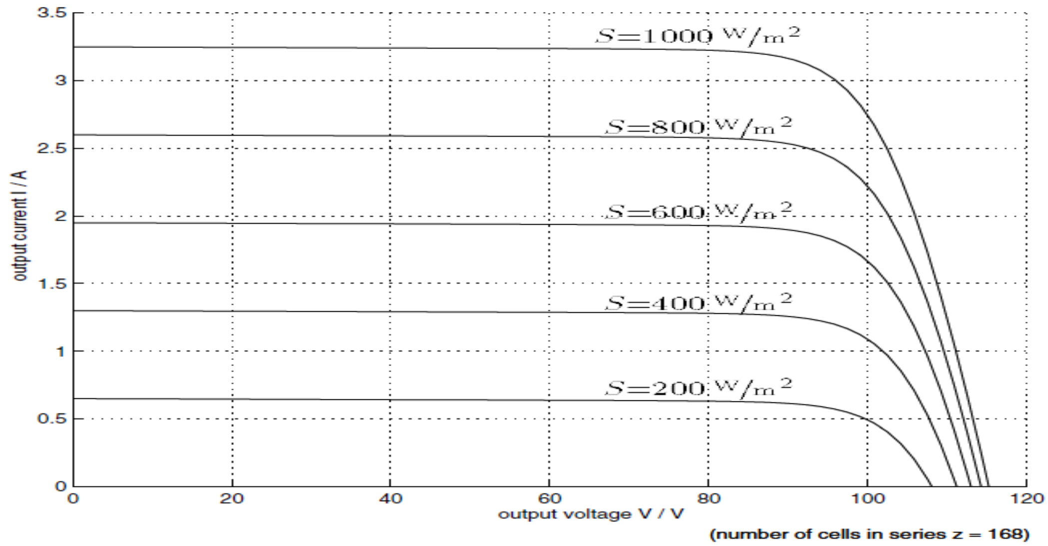

Figure-6
I-V characteristics of a photovoltaic cell array for various values of irradiance S at a temperature of 25^{0}C

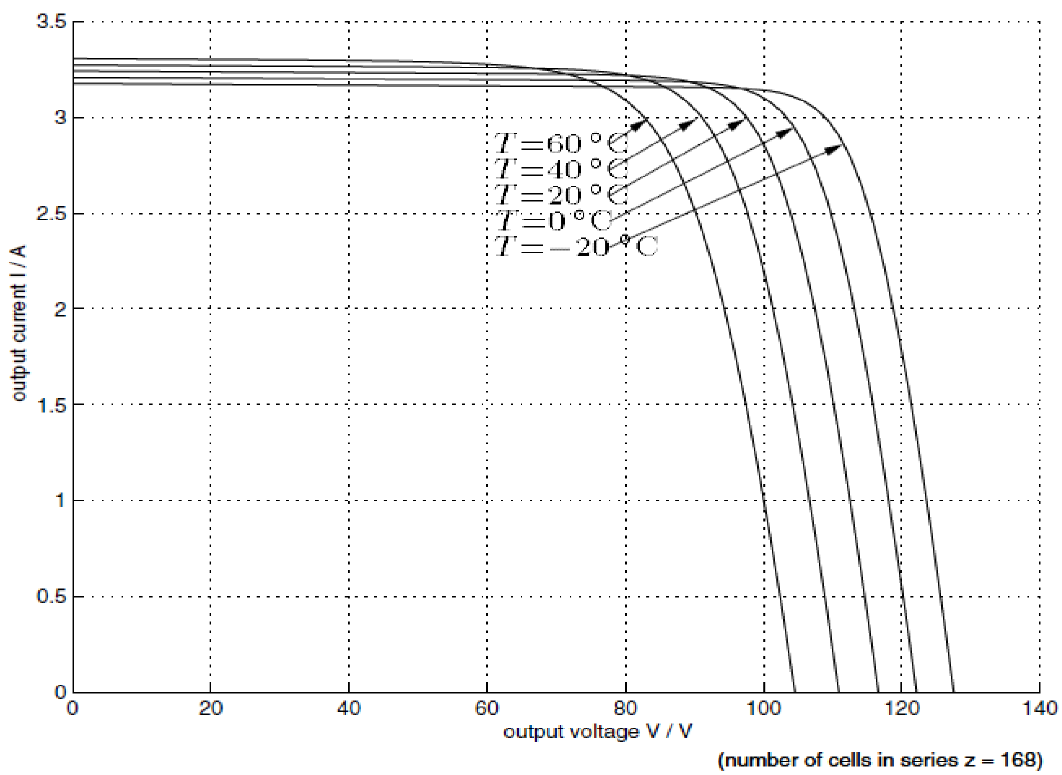

Figure-7
I-V characteristics of a photovoltaic cell array for various values of temperature T at irradiance of 1000W=m2

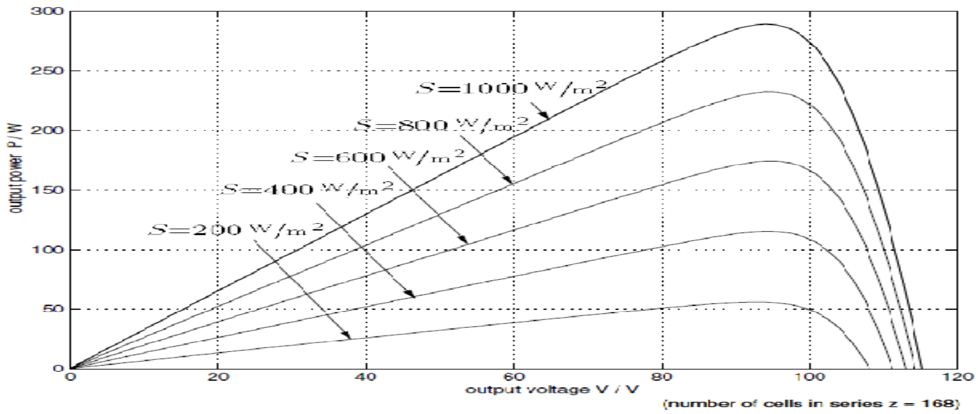

Figure-8
P-V characteristics of a photovoltaic cell array for various values of irradiance S at a temperature of 25 ^{0}C

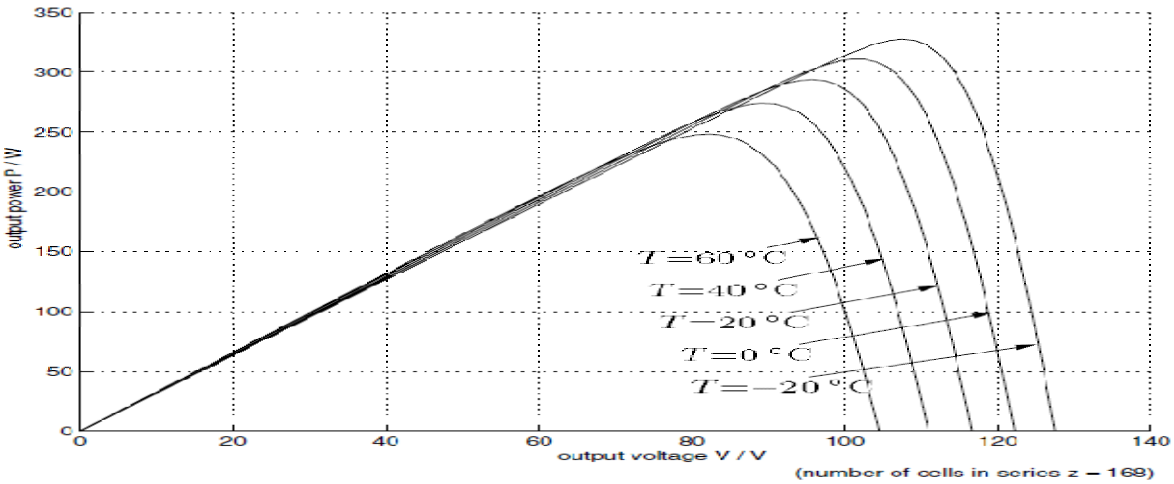

Figure-9
P-V characteristics of a photovoltaic cell array for various values of temperature T at irradiance of 1000W=m2

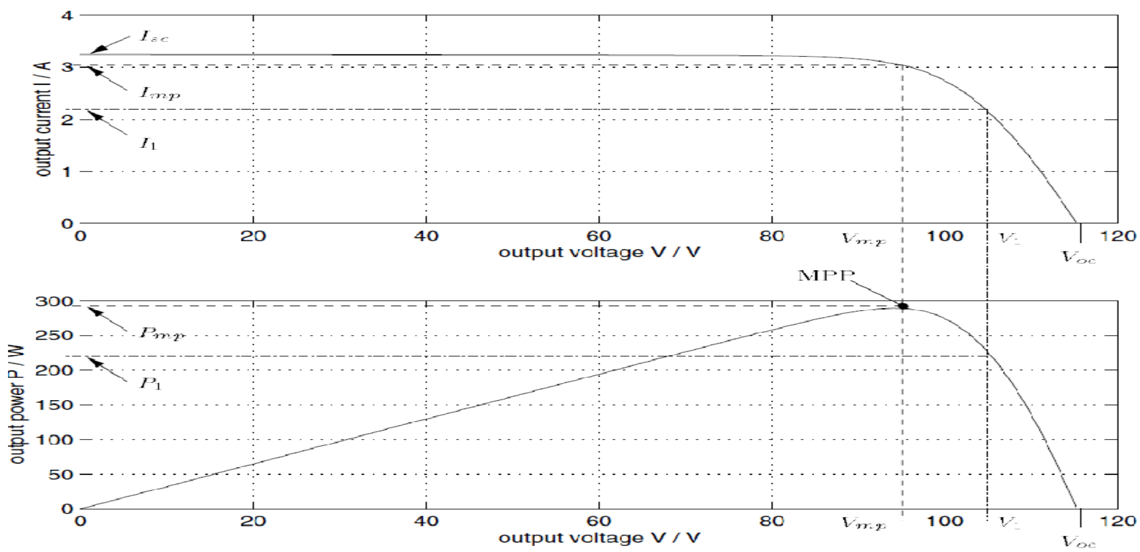

Figure-10
Maximum Power Point MPP and the corresponding voltage Vmp and current Imp for a photovoltaic cell array with 168 cells in series operating at STC

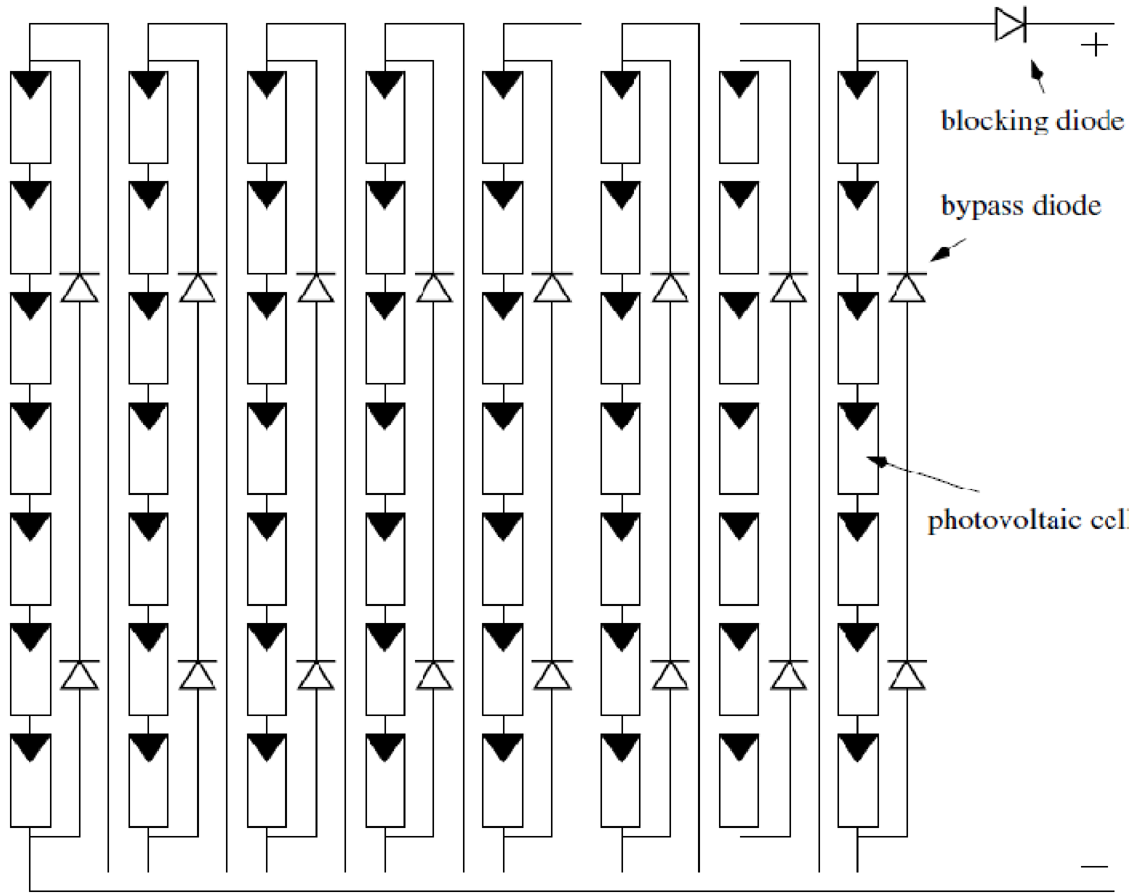

Figure-11
Schematic representation of a solar panel as used in the solar system Sol Train

Conclusion

A detailed analysis of the individual components of the photovoltaic power system was undertaken to evaluate their performance in the complete system under operating conditions characteristic for a moving system. Systems using power feedback and direct control of the dc-to-ac converter's PWM input d, were found to be best suited for a solar system environment. Operation under slowly increasing power levels, caused by moderately rising insolation levels or by decreasing cell temperature, revealed a slight lag behind the other simulated techniques and an associated power loss. This was more than overcome by this technique's extraordinary performance under rapidly increasing insulation levels. Since all existing panels of the solar system Sol Train deifier in their operating point as well as in their mounted angle on the system, they will all need their separate MPPT system. A combination of panels with different mounting angles would yield a difference in the angle of sunlight incidence and therefore lead to multiple local maxima in the panel's P-V curve.

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