Maximum Power Point Tracking Method for Multiple Photovoltaic Systems

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Abstract

The goal of this paper is to find the optimum mechanism for extracting the maximum possible power out of a given set of solar panels. There are many different approaches to this problem. A huge variety of concepts leads to an even larger variety of circuits and mechanisms for operating photovoltaic panels as close as possible to the point of maximum power and efficiency. Some of the concepts are very robust and simple, whereas other approaches require very sophisticated logic devices such as microprocessors combined with high-power high-efficiency switching converters. In this study different approaches to operating a solar panel at or close to its maximum power point are analyzed and their suitability to the environment of a solar system is examined.

Keywords: MPPT, solar energy, photovoltaic, microprocessors, converters.

Introduction

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 occurs 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. Additionally, the use of an algorithm allows for additional control modes to cope with certain system states such as a fully charged battery buyer. The main challenge in designing a microprocessor-controlled MPPT is the combination of the strongly nonlinear continuous-time system of the photovoltaic cell array with a discrete-time control device. This union makes it impossible to evaluate such important factors as system performance and stability with the classical approach of closed-form transfer-function analysis. 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.

Material and Methods

Maximum Power Point Tracking: The energy extracted from a solar panel is strongly limited by the physical constraints of photovoltaic cells. The approximate power density of the insolation on a sunny day is around 1000W=m2. In combination with solar cell efficiencies between 15% and 17% this yields a maximum possible power output between 150W=m2 and 170W=m2. There are two ways to increase the power coming from a photovoltaic array: first can add more panels to the array, which means an increase in area requirements and a great increase in cost for material. Second can also attempt to make the existing array always work at its highest possible efficiency. If the array is operated at this point with its corresponding values for current Imp and voltage Vmp, the maximum possible efficiency is achieved.

Simple Panel-Load Matching: To achieve the goal of operating the photovoltaic cells close to their point of maximum power, the method of simple load matching can be used. In this method the optimum operating point of the solar panel is determined either in theory or under average operating conditions by a series of measurements. After the corresponding values for maximum power current and voltage (Imp and Vmp) are found, a matching load is designed. Such a system is usually designed such that the average load voltage is close to the average Vmp. The advantage of this configuration is its simplicity. Since no additional circuitry is used, the risk of component failure is kept low for the whole system and the power loss between panel and load is reduced to the conductor losses.

The discrepancy between the maximum power voltage Vmp and the nominal battery voltage Vb (108 V) was found to be higher

than 50% for some of solar panels (table). This yields a significantly reduced power output. Table 1 shows the values for the short-circuit current Isc and the open circuit voltage Voc for the different solar panels on the system at two different temperatures. It is apparent that Isc and Voc are sensitively dependent on changes in operating conditions. The changes in the open-circuit voltage Voc are mainly caused by the indicated temperature difference of approximately 25^0C.

Semi-Dynamic Load Matching: A number of individually controllable battery cells are connected in series. Depending on the desired operating voltage of the photovoltaic array, the number of battery cells in series can be changed. By rearranging the series and parallel connections between the different panels, the matching between load and photovoltaic cell array is improved. This enables the system to react to changes in environmental conditions such as temperature and irradiance and therefore operate closer to the actual MPP.

Both these approaches require extra circuitry and wiring. In addition, the stepwise increase or decrease in operating voltage does not permit accurate tracking of the MPP. These methods might be sufficient for use with a stationary photovoltaic system to provide two or more operating modes for different times of the day or different seasons.

The Voltage-Feedback Method: If no battery is present in the system to tie the bus voltage to an almost constant level, a simple control system can be applied. A dc-to-dc converter can be used to convert the voltage level at a photovoltaic cell array to another voltage level at the load. Feedback of the panel voltage and comparison with a constant reference voltage can be used to continuously adjust the duty ratio of the converter to operate the solar panel at a predefined operating point close to the MPP. This method makes it possible to operate a solar array under unknown or changing load conditions and still be able to choose a desirable operating point for the panel (figure 1).

The Power-Feedback Method: Methods overall goal is to increase the power output of the systems solar array. Sullivan and Powers point out, the maximization of the power to a motor as a load may lead to a maximization of the power dissipated in its windings and not to a maximization of its mechanical power output. To have a design, which is independent of the load type, it is therefore preferable to pursue a maximization of solar panel output power. If actual MPP tracking is to be achieved, it is necessary to get information about the actual power extracted from the photovoltaic array. This can be done by measuring the panel output voltage V and the panel output current I and then multiplying these two parameters to get the actual value for the panel output power P = V I. Given these values there are various methods of tracking the actual MPP of the array.

The Perturbation and Observation Method (P and O): The P and O method is a widely used approach to MPPT. It employs a microprocessor with the values for panel voltage V and panel

current I as its input values and the desired operating voltage Vref as its output value. The notation used for the desired operating voltage Vref alludes to the fact that this system can then be inserted in the already discussed voltage-feedback controller to supply vref. Another possible configuration is to have the microprocessor directly controlling the dc-to-dc converter's PWM input variable d. This makes the extra voltage control feedback loop dispensable. Figure 2 shows a ow chart diagram of the P and O algorithm as it is implemented in the controlling microprocessor. With this algorithm the operating voltage V is perturbed with every MPPT cycle. As soon as the MPP is reached, V will oscillate around the ideal operating voltage Vmp. This causes a power loss, which depends on the step width of a single perturbation. If the step width is large, the MPPT algorithm will be responding quickly to sudden changes in operating conditions with the tradeoff of increased losses under stable or slowly changing conditions. If the step width is very small the losses under stable or slowly changing conditions will be reduced, but the system will be only able to respond very slowly to rapid changes in temperature or insolation. The value for the ideal step width is system dependent and needs to be determined experimentally.

Assuming that the system has been oscillating around the MPP, it can be seen in figure that a continuous perturbation in one direction will lead to an operating point far away from the actual MPP. This process continues until the increase in insolation slows down or ends.

The Incremental Conductance Method (IncCond): To avoid the drawbacks of the PandO MPPT method, Hussein and others developed the incremental conductance MPPT algorithm (IncCond). It is based on the fact that the derivative of the output power P with respect to the panel voltage V is equal to zero at the maximum power point (MPP). The solar panel's P-V characteristics in figure 4 show further that the derivative is greater than zero to the left of the MPP and less than zero to the right of the MPP. This leads to the following set of equations:

$$dP/dV = 0 \qquad \text{for } V = Vmp, \qquad (1)$$
$$dP/dV > 0 \qquad \text{for } V < Vmp, \qquad (2)$$
$$dP/dV < 0 \qquad \text{for } V > Vmp. \qquad (3)$$

The fact that P = V I and the chain rule for the derivative of products yields
$$dP/dV = d (V I)/dV = I dV/dV + V dI/dV = I + V dI/dV \quad (4)$$

Combining equations (1) and (4) leads to the MPP condition (V = Vmp) in terms of array voltage V and array current I:
$$dI/dV = - I/V. \qquad \text{------ (5)}$$

This shows that with equations (1) and (4) enough information is gathered to determine the relative location of the MPP by measuring only the incremental and instantaneous array conductance dI dV and I V, respectively (figure 3).

Table-1
The solar panels and the corresponding measured values for Isc and Voc at different temperatures

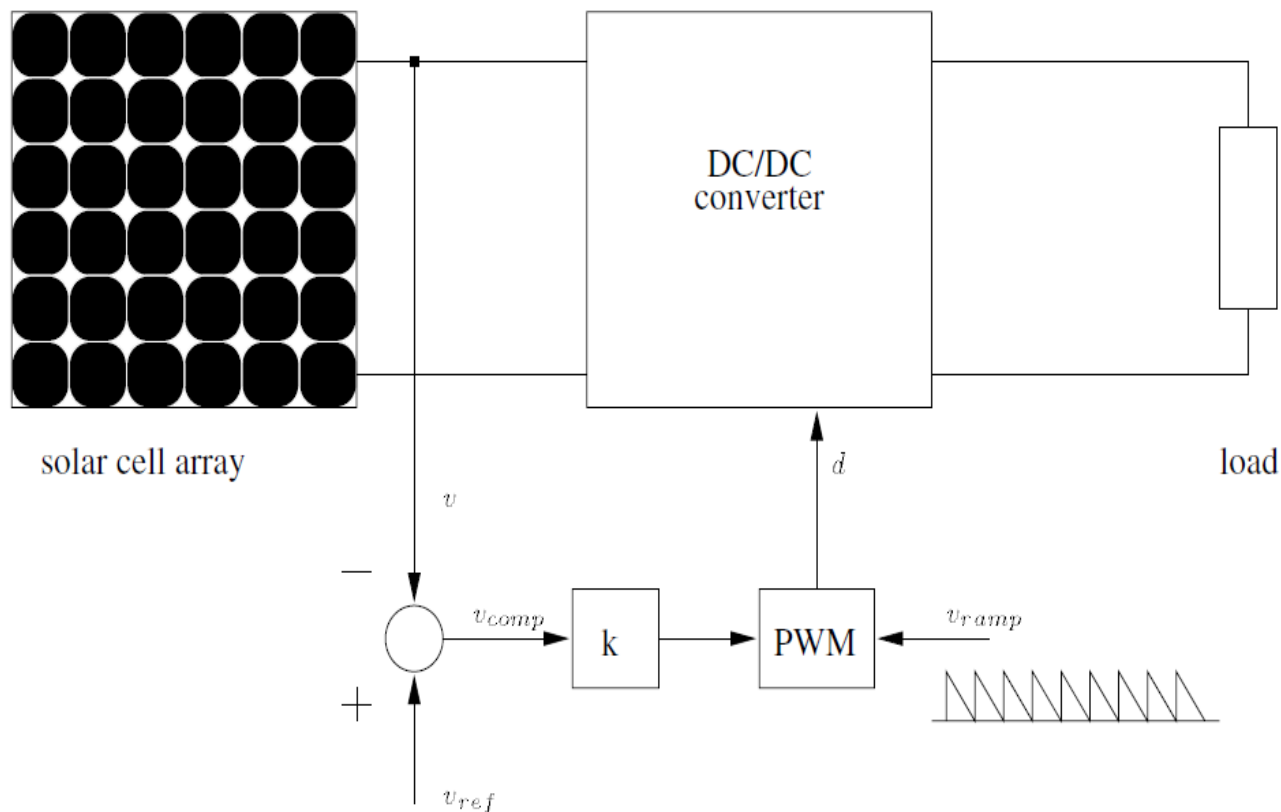| Panel Name and location	$T \approx 50\ ^0C$				$T = 25\ ^0C$			
	V_{oc} (V)	I_{sc} (A)	V_{mp} (V)	$V_b - V_{mp}/V_b$ (%)	V_{oc} (V)	I_{sc} (A)	V_{mp} (V)	$V_b - V_{mp}/V_b$ (%)
[a] starboard (cells)	108.9	1.75	82.76	23.4	128.6	2.34	97.75	9.5
[b] starboard (shards)	119.1	0.26	90.25	16.2	Nil	Nil	Nil	Nil
[c] starboard wing	104.7	0.14	79.75	26.3	Nil	Nil	Nil	Nil
[d] top front	61.0	1.48	46.36	57.1	67.0	2.39	50.92	52.9
[e] top middle	114.9	1.75	87.32	19.1	135.2	2.37	102.75	4.9
[f] top back	112.4	1.72	85.42	20.9	137.8	2.32	104.73	3.0
[g] port (cells)	107.3	1.88	81.55	24.5	120.4	2.33	91.50	15.3
[h] port (shards)	109.1	0.27	82.92	23.2	Nil	Nil	Nil	Nil
[i] port wing	104.5	0.17	79.42	26.5	Nil	Nil	Nil	Nil

Figure-1
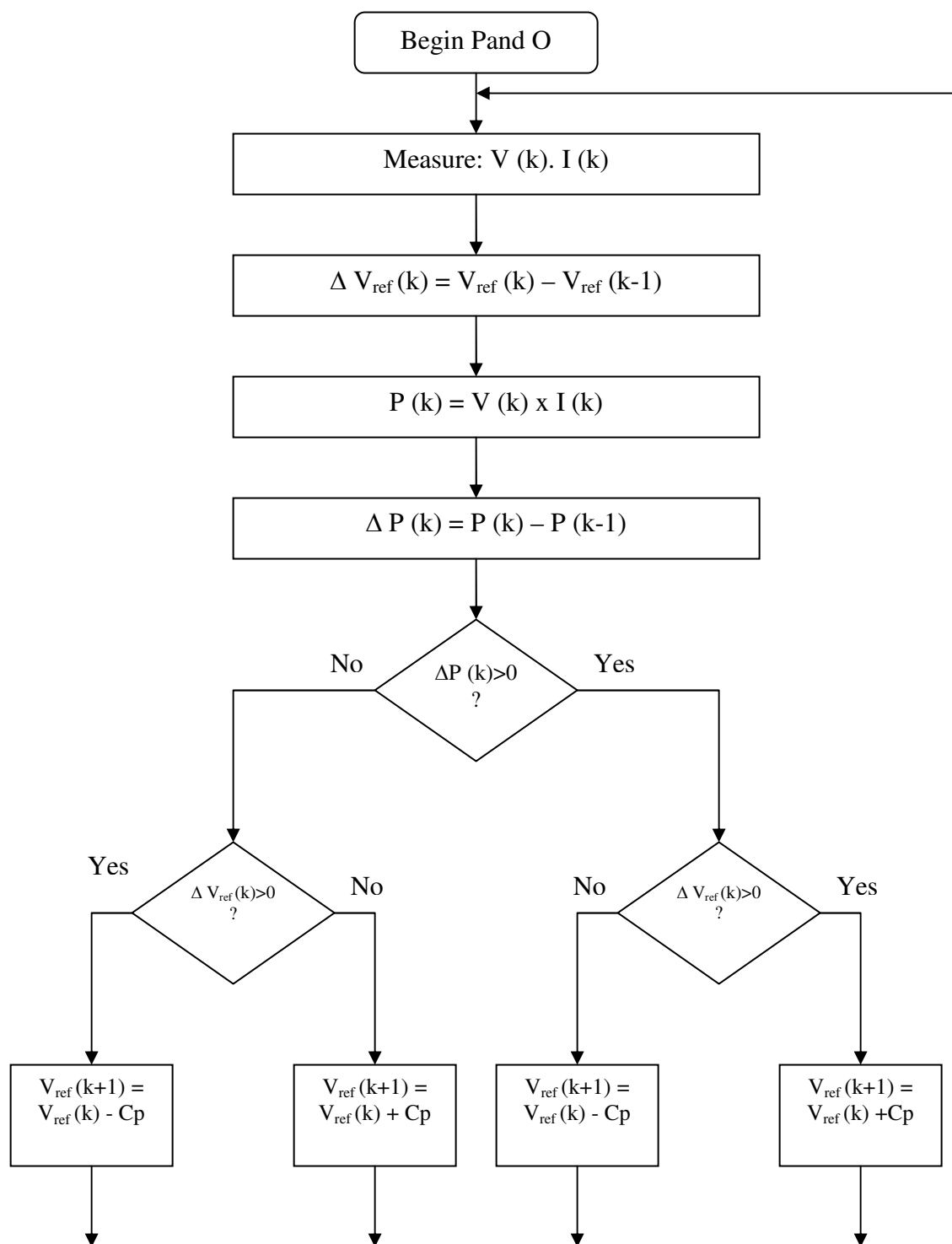**Voltage-feedback with pulse width modulation (PWM) on a dc-dc converter**

Figure 2
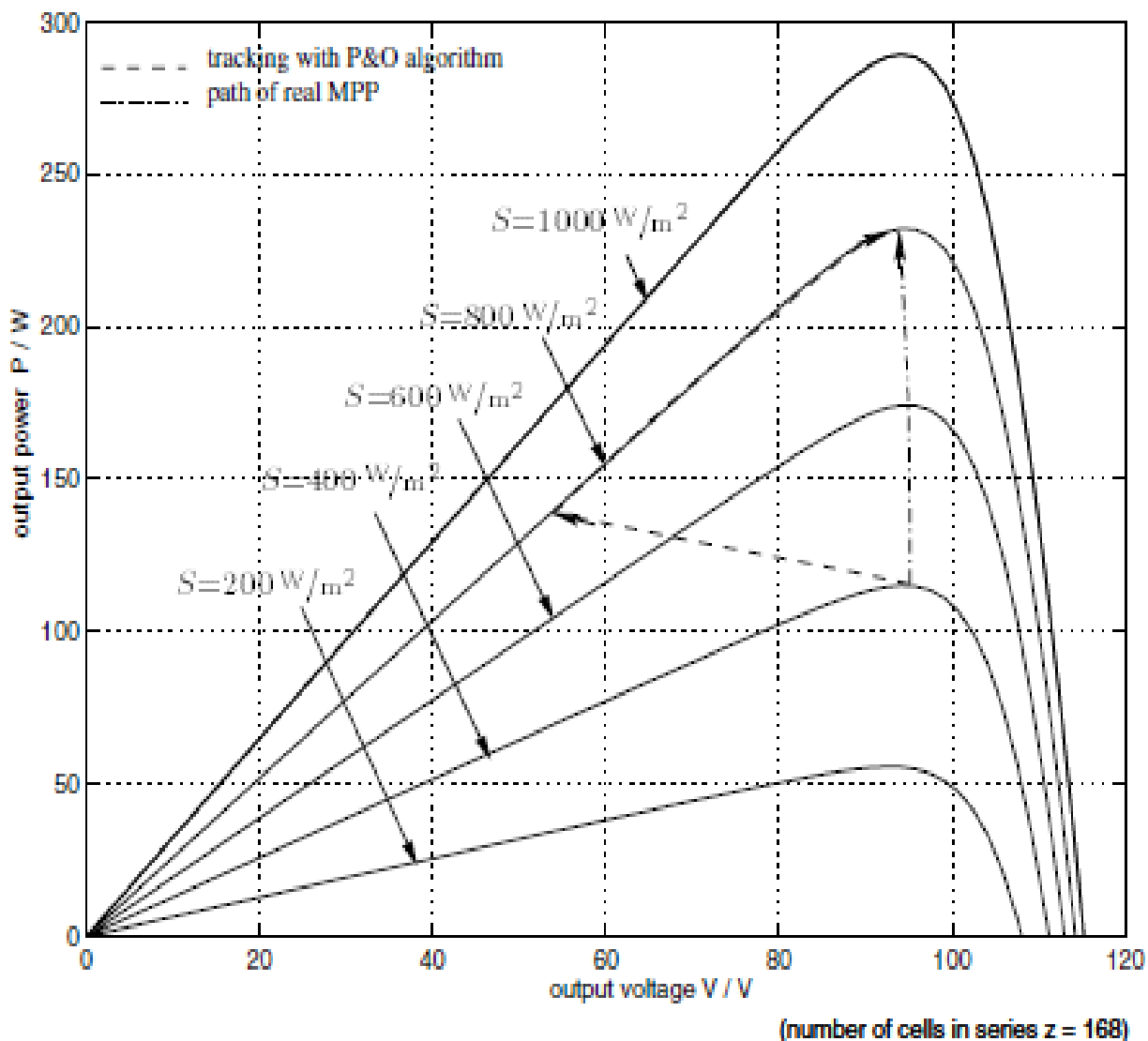**Flow chart of the PandO MPPT algorithm, Cp is the perturbation step width**

Figure-3
Deviation from the MPP with the P and O algorithm under rapidly changing insolation levels S

Forced Oscillation | Auto Oscillation: In all of the MPPT methods discussed so far, the derivative of the solar panel's output power was used in various ways to determine the relative location of the MPP. Appropriate adjustment of the operating voltage eventually led to an operating point closely oscillating around the MPP. These oscillations were automatically generated by the utilized feedback control. A new method with a forced oscillation of the operating point is introduced by Cocconi and Rippel in the GM Sunracer Case History. Figure 7 shows how a modulation of the array voltage causes a ripple in the output power. If this modulation occurs in the area below the MPP (denoted A), the voltage and the power ripple will be perfectly in phase. If the modulation occurs at an operating point in the area above the MPP (denoted B), the output power ripple will be 180 degrees out of phase (figure 5).

The drawback of this method is the difficulty in evaluating very low signal amplitudes. The ac component of the output power signal is much smaller than the dc component and will contain a high noise level due to the switching dc-to-dc converter. This noise can be filtered out using higher order band pass filters, but this will lead to further losses in the signal's amplitude. When the operating point finally approaches the MPP, the signal's amplitude will further decrease and will make it difficult for the synchronous detector to maintain a stable output signal. An increase in the amplitude of the modulating signal to improve the signal to noise ratio will also lead to higher oscillations at the MPP and therefore increase power losses even under stable environmental conditions.
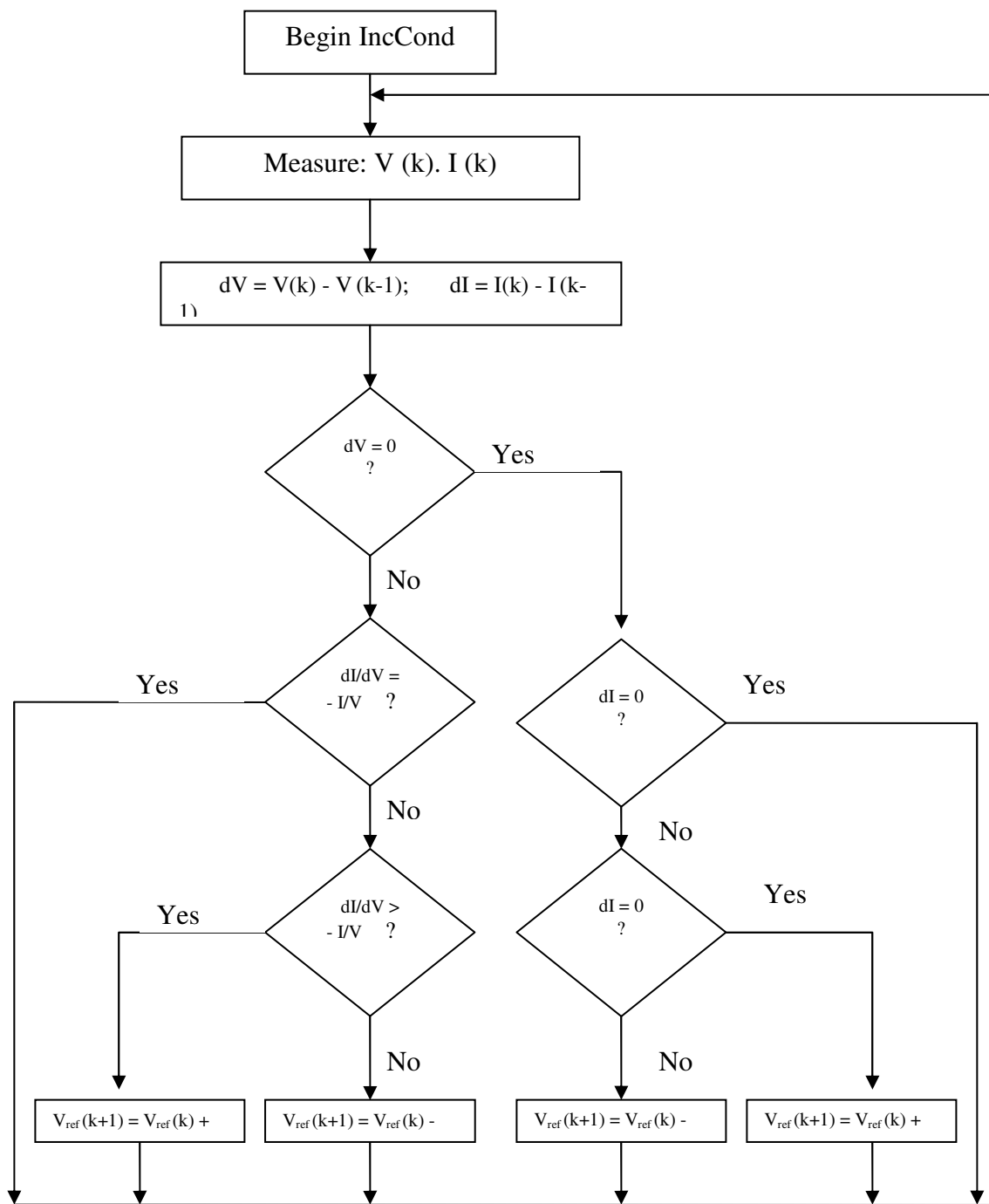
Figure-4
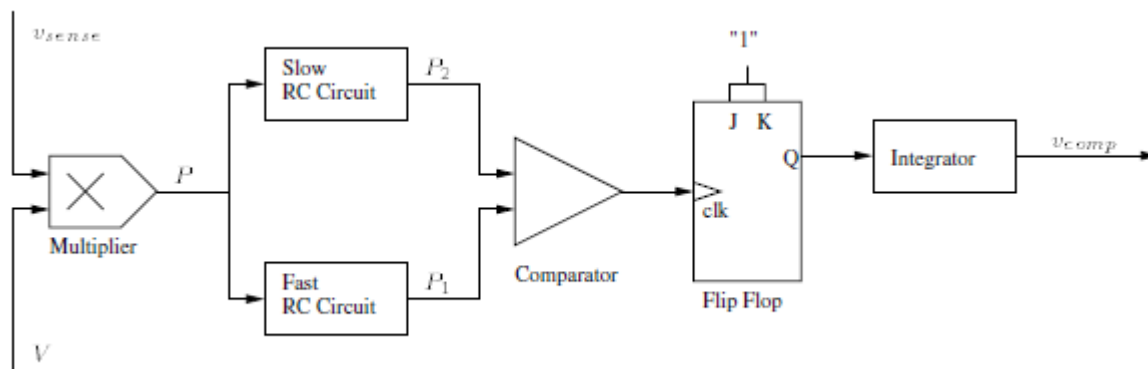**Flow chart of the IncCond MPPT algorithm, Ca is the adjustment step width**
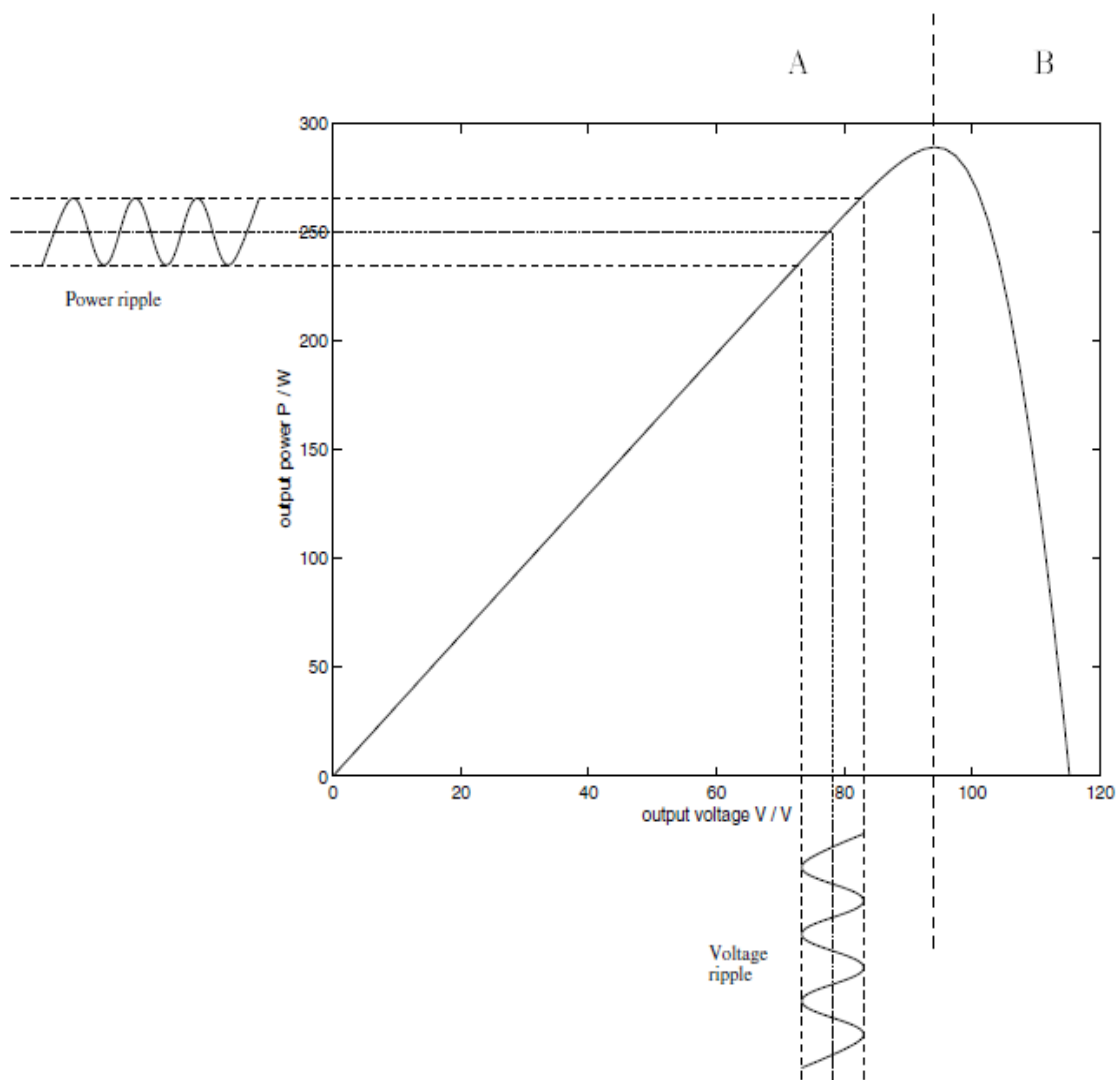
Figure- 5
Analog MPPT mechanism

Figure-6
P-V curve for the solar array with the power ripple caused by the array voltage modulation

The letter A denotes the area for an operating point below the MPP, B the area above the MPP.

The Current-Feedback Method: In all of the real MPPT methods presented so far, a measurement of I and V was used to get information about the present panel output power. Based on this information the MPPT mechanism adjusted the panel output voltage V to move the operating point of the solar cells closer to their MPP. Sullivan and Powers as well as Burger present a new method of MPPT using only a current measurement to get information on the system's present operating point. Their method is based on the assumption that the system's battery pack always operates at a nearly constant voltage level. Therefore a maximization of the power fed into the battery would be equal to maximizing the battery charge current Ib.

The advantage of this method is that it does not require the complexity, cost and power necessary to sense and multiply two different operating parameters. Since the maximized battery input current Ib equals the dc-to-dc converter's output current, this approach has the same restrictions as techniques maximizing the dc-to-dc converter output power: it is dependent on a battery as a load. The risk of maximizing the power dissipation in the windings of a dc-motor load has already been mentioned. But there are further problems occurring without a battery buffer tying the voltage to an almost constant level: maximizing power is only equivalent to maximizing current if a rise in current is always associated with a rise in power. In mathematical terms this means that the derivative dPb dIb must be bounded and strictly greater than zero. This can be expressed as:

$$0 < Vb/Ib + d\ Vb/\ d\ Ib < \infty \qquad (6)$$

This will always be the case for a plain resistive load or a battery load. But if the load consists of another PWM dc-to-dc converter for example controlling a dc-motor (as with the Sol Train), the derivative dPb dIb would be ideally equal to zero, which would result in the impossibility of finding the MPP in the measured current signal[1-25].

Conclusion

Valuable information on the performance of the individual MPPT techniques was gathered to allow the specification of a method, which will significantly increase the efficiency of the solar MPPT. 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. Analog MPPT systems were not further investigated since they only permit the realization of very basic MPPT techniques. The implementation of the proposed improved PandO MPPT method in combination with a well-designed buck-boost converter would increase the Sol Train's efficiency significantly. The solar system is currently operating with the simple panel load matching method

at an efficiency of approximately 30%. With the proposed MPPT method this efficiency can be raised to above 95%. This more than threefold increase will substantially improve the range and the dynamics of the system.

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