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Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques

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Abstract: The many different techniques for maximum power point tracking of photovoltaic (PV) arrays are discussed. The techniques are taken from the literature dating back to the earliest methods. It is shown that at least 19 distinct methods(Algo.) have been introduced in the literature, with many variations on implementation.

Keywords: Maximum power point tracking (MPPT), photovoltaic (PV).

I. INTRODUCTION

One of the major concerns in the power sector is the day-to-day increasing power demand but the unavailability of enough resources to meet the power demand using the conventional energy sources. Demand has increased for renewable sources of energy to be utilized along with conventional systems to meet the energy demand. Renewable sources like wind energy and solar energy are the prime energy sources which are being utilized in this regard. The continuous use of fossil fuels has caused the fossil fuel deposit to be reduced and has drastically affected the environment depleting the biosphere and cumulatively adding to global warming.

Solar energy is abundantly available that has made it possible to harvest it and utilize it properly. Solar energy can be a standalone generating unit or can be a grid connected generating unit depending on the availability of a grid nearby. Thus it can be used to power rural areas where the availability of grids is very low. Another advantage of using solar energy is the portable operation whenever wherever necessary.

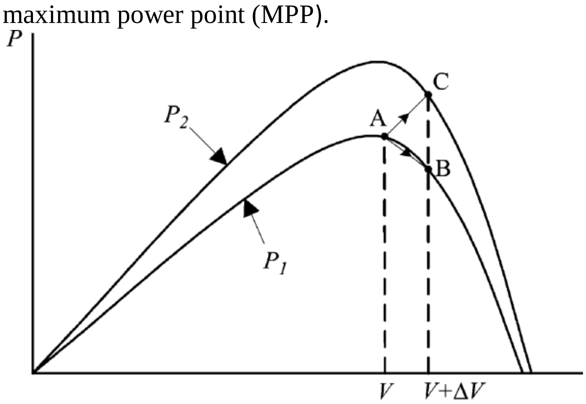
In order to tackle the present energy crisis one has to develop an efficient manner in which power has to be extracted from the incoming solar radiation. The power conversion mechanisms have been greatly reduced in size in the past few years. The development in power electronics and material science has helped engineers to come up very small but powerful systems to withstand the high power demand. But the disadvantage of these systems is the increased power density. Trend has set in for the use of multi-input converter units that can effectively handle the voltage fluctuations. But due to high production cost and the low efficiency of these systems they can hardly compete in the competitive markets as a prime power generation source.

The constant increase in the development of the solar cells manufacturing technology would definitely make the use of these technologies possible on a wider basis than what the scenario is presently. The use of the newest power control mechanisms called the Maximum Power Point Tracking (MPPT) algorithms has led to the increase in the efficiency of operation of the solar modules and thus is effective in the field of utilization of renewable sources of energy. Solar cell operates at very low efficiency and thus a better control mechanism is required to increase the efficiency of the solar cell. In this field researchers have developed what are now called the Maximum Power Point Tracking (MPPT) algorithms.

II. MPPT TECHNIQUES

A. Hill Climbing/P&O

This method is the most common. In this method very less number of sensors are utilized and The operating voltage is sampled and the algorithm changes the operating voltage in the required direction and samplesdP/dV. If dP/dV is positive, then the algorithm increases the voltage value towards the MPP until $dP/dV$is negative. This iteration is continued until the algorithm finally reaches the MPP. This algorithm is not suitable when the variation in the solar irradiation is high. The voltage never actually reaches an exact value but perturbs around the maximum power point (MPP).



Hill climbing and P&O methods can fail under rapidly changing atmospheric conditions as illustrated in Fig. Starting from an operating point A, [1-5]if atmospheric conditions stay approximately constant, a perturbation ΔV in the PV voltage V will bring the operating point to B and the perturbation will be reversed due to a decrease in power. However, if the irradiance increases and shifts the power curve from $P1$ to $P2$ within one sampling period, the operating point will move from A to C.This represents an increase in power and the perturbation is kept the same.

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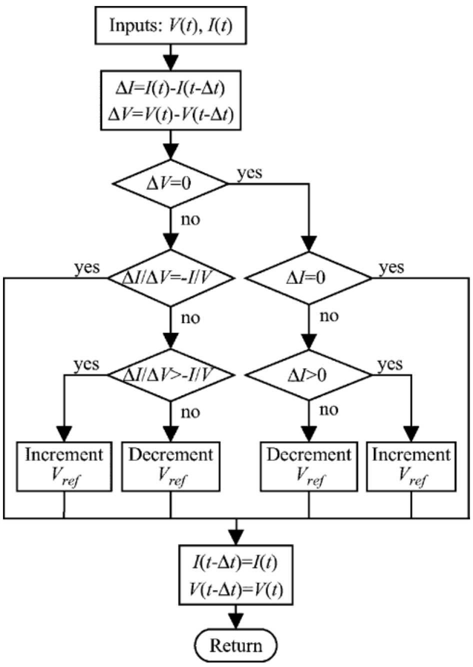
Consequently, the operating point diverges from the MPP and will keep diverging if the irradiance steadily increases. To ensure that the MPP is tracked even under sudden changes in irradiance, [6] uses a three-point weight comparison P&O method that compares the actual power point to two preceding ones before a decision is made about the perturbation sign. In the sampling rate is optimized, while in , simply a high sampling rate is used. In [7], toggling has been done between the traditional hill climbing algorithm and a modified adaptive hill climbing mechanism to prevent deviation from the MPP.Two sensors are usually required to measure the PV array voltage and current from which power is computed, but depending on the power converter topology, only a voltage sensor might be needed as in and [8-12]. In [14-15], the PV array current From the PV array voltage is estimated, eliminating the need for a current sensor. DSP or microcomputer control is more suitable for hill climbing and P&O even though discrete analog and digital circuitry can be used as in [16].

B. Incremental Conductance

The incremental conductance (IncCond) [17], [18-20] method is based on the fact that the slope of the PV array power curve (Fig.) is zero at the MPP, positive on the left of the MPP, and negative on the right, as given by

$dP/dV = 0$, at MPP
$dP/dV > 0$, left of MPP
$dP/dV < 0$, right of MPP

$\Delta I/\Delta V = -I/V$, at MPP
$\Delta I/\Delta V > -I/V$, left of MPP
$\Delta I/\Delta V < -I/V$, right of MPP



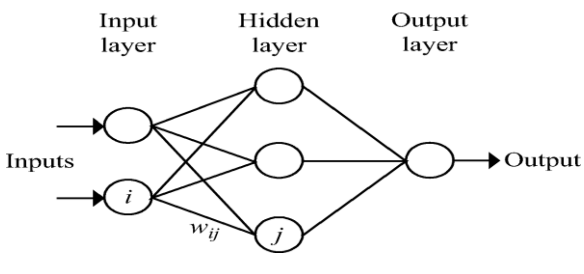
The MPP can thus be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance ($\Delta I/\Delta V$) as shown in the flowchart in Fig. *Vref* is the reference voltage at which the PV array is forced to operate. At the MPP, *Vref* equals to *VMPP*. Once the MPP is reached, the operation of the PV array is maintained at this point unless a change in ΔI is noted, indicating a change in atmospheric conditions and the MPP. The algorithm decrements or increments *Vref* to track the new MPP.

C. Fuzzy Logic Control

Microcontrollers have made using fuzzy logic control [21]–[25] popular for MPPT over the last decade. As mentioned in [26], fuzzy logic controllers have the advantages of working with imprecise inputs, not needing an accurate mathematical model, and handling non linearity. Fuzzy logic control generally consists of three stages: fuzzification, rule base table lookup, and defuzzification. During fuzzification, numerical input variables are converted into linguistic variables based on a membership function similar to Fig. In this case, five fuzzy levels are used: NB (negative big), NS(negative small), ZE (zero), PS (positive small), and PB (positive big). In [27] and [28], seven fuzzy levels are used, probably for more accuracy. In Fig. 5, *a* and *b* are based on the range of values of the numerical variable. The membership function is sometimes made less symmetric to give more importance to specific fuzzy levels as in [29], [30], [31], and [32]. The inputs to a MPPT fuzzy logic controller are usually an error E and a change in error ΔE. The user has the flexibility of choosing how to compute E and ΔE.

D. Neural Network

Along with fuzzy logic controllers came another technique of implementing MPPT—neural networks [33] which are also well adapted for microcontrollers. Neural networks commonly have three layers: input, hidden, and output layers as shown in Fig. The number of nodes in each layer vary and are user-dependent. The input variables can be PV array parameters like *VOC* and *ISC*, atmospheric data like irradiance and temperature, or any combination of these. The output is usually one or several reference signal(s) like a duty cycle signal used to drive the power converter to operate at or close to the MPP.



Example of neural network

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How close the operating point gets to the MPP depends on the algorithms used by the hidden layer and how well the neural network has been trained. The links between the nodes are all weighted. The link between nodes *i* and *j* is labeled as having a weight of *wij* in Fig. . To accurately identify the MPP, the *wij* '*s* have to be carefully determined through a training process, where by the PV array is tested over months or years and the patterns between the input(s) and output(s) of the neural network are recorded. Since most PV arrays have different characteristics, a neural network has to be specifically trained for the PV array with which it will be used. The characteristics of a PV array also change with time, implying that the neural network has to be periodically trained to guarantee accurate MPPT.

E. dP/dV or dP/dI Feedback Control

With DSP and microcontroller being able to handle complex computations, an obvious way of performing MPPT is to compute the slope (*dP/dV* or *dP/dI*) of the PV power curve(Fig) and feed it back to the power converter with some control to drive it to zero. This is exactly what is done in [34]The way the slope is computed differs from paper to paper. In [34], *dP/dV* is computed and its sign is stored for the past

Few cycles. Based on these signs, the duty ratio of the power converter is either incremented or decremented to reach the MPP.A dynamic step size is used to improve the transient response of the system. linearization-based method is used to compute *dP*/*dV*. In sampling and data conversion are used with subsequent digital division of power and voltage to approximate *dP*/*dV*, *dP/dI* is then integrated together with an adaptive gain to improve the transient response. In the PV array voltage is periodically incremented or decremented and $\Delta P/\Delta V$ is compared to a marginal error until the MPP is reached. Convergence to the MPP was shown to occur in tens of milliseconds.

MPPT Technique	PV Array Dependent?	True MPPT?	Analog or Digital?	Periodic Tuning?	Convergence Speed	Implementation Complexity	Sensed Parameters
Hill-climbing/P&O	No	Yes	Both	No	Varies	Low	Voltage, Current
IncCond	No	Yes	Digital	No	Varies	Medium	Voltage, Current
Fractional V_{OC}	Yes	No	Both	Yes	Medium	Low	Voltage
Fractional I_{SC}	Yes	No	Both	Yes	Medium	Medium	Current
Fuzzy Logic Control	Yes	Yes	Digital	Yes	Fast	High	Varies
Neural Network	Yes	Yes	Digital	Yes	Fast	High	Varies
RCC	No	Yes	Analog	No	Fast	Low	Voltage, Current
Current Sweep	Yes	Yes	Digital	Yes	Slow	High	Voltage, Current
DC Link Capacitor Droop Control	No	No	Both	No	Medium	Low	Voltage
Load *I* or *V* Maximization	No	No	Analog	No	Fast	Low	Voltage, Current
dP/dV or *dP/dI* Feedback Control	No	Yes	Digital	No	Fast	Medium	Voltage, Current
Array Reconfiguration	Yes	No	Digital	Yes	Slow	High	Voltage, Current
Linear Current Control	Yes	No	Digital	Yes	Fast	Medium	Irradiance
I_{MPP} & V_{MPP} Computation	Yes	Yes	Digital	Yes	N/A	Medium	Irradiance, Temperature
State-based MPPT	Yes	Yes	Both	Yes	Fast	High	Voltage, Current
OCC MPPT	Yes	No	Both	Yes	Fast	Medium	Current
BFV	Yes	No	Both	Yes	N/A	Low	None
LRCM	Yes	No	Digital	No	N/A	High	Voltage, Current
Slide Control	No	Yes	Digital	No	Fast	Medium	Voltage, Current

III. DISCUSSION

With so many MPPT techniques available to PV system users, it might not be obvious for the latter to choose which one better suits their application needs. The main aspects of the MPPT techniques to be taken into consideration are highlighted in the following subsections

Sensors

The number of sensors required to implement MPPT also affects the decision process. Most of the time, it is easier and more reliable to measure voltage than current. Moreover, current sensors are usually expensive and bulky. This might be inconvenient in systems that consist of several PV arrays with separate MPP trackers. In such cases, it might be wise to use MPPT methods that require only one sensor or that can estimate the current from the voltage as in [22]. It is also uncommon to find sensors that measure irradiance levels, as needed in the linear current control and the *IMPP* and *VMPP* computation methods.

Multiple Local Maxima

The occurrence of multiple local maxima due to partial shading of the PV array(s) can be a real hindrance to the proper functioning of an MPP tracker. Considerable power loss can be incurred if a local maximum is tracked instead of the real MPP. As mentioned previously, the current sweep and the state-based methods should track the true MPP even in the presence of multiple local maxima. However, the other methods require an additional initial stage to bypass the unwanted local maxima and bring operation to close the real MPP.

Costs

It is hard to mention the monetary costs of every single MPPT technique unless it is built and implemented. This is unfortunately out of the scope of this paper. However, a good costs comparison can be made by knowing whether the technique is analog or digital, whether it requires software and programming, and the number of sensors. Analog implementation is generally cheaper than digital, which normally involves a microcontroller that needs to be programmed. Eliminating current sensors considerably drops the costs.

Applications

Different MPPT techniques discussed earlier will suit different applications. For example, in space satellites and orbital stations that involve large amount of money, the costs and complexity of the MPP tracker are not as important as its performance and reliability. The tracker should be able to continuously track the true MPP in minimum amount of time and should not require periodic tuning. In this case, hill climbing/P&O, IncCond, and RCC are appropriate. Solar vehicles would mostly require fast convergence to the MPP. Fuzzy logic control, neural network, and RCC are good options in this case. Since the load in solar vehicles consists mainly of batteries, load current or voltage maximization should also be considered. The goal when using PV arrays in residential areas is to minimize the payback time and to do so, it is essential to constantly and quickly track the MPP. Since partial shading (from trees and other buildings) can be an issue, the MPPT should be capable of bypassing multiple local maxima. Therefore, the two-stage IncCond and the current sweep methods are suitable. Since a residential system might also include an inverter, the OCC MPPT can also be used. PV systems used for street lighting only consist in charging up batteries during the day.

IV. CONCLUSION

Several MPPT techniques taken from the literature are discussed and analyzed herein, with their pros and cons. It is shown that there are several other MPPT techniques than those commonly included in literature reviews. The concluding discussion and table should serve as a useful guide in choosing the right MPPT method for specific PV systems.

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