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Energy Performance and Cost Comparison of MPPT Techniques for Photovoltaics and other Applications

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Abstract

Maximum Power Point Tracking (MPPT) is a means to extract maximum energy from PV panels at different levels of irradiance. This paper examines some of the MPPT techniques used in PV applications with respect to their energy performance and general costs. It also gives an insight on the factors that should be considered in choosing the appropriate technique for specific applications. The reviews done in this paper are expected to be useful for MPPT users, designers and commercial manufacturers of PV systems.

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Keywords: Maximum Power Point Tracking (MPPT); Photovoltaic (PV).

1. Introduction

It is a smart Engineering idea to include MPPT technique(s) to PV systems designs in order to ensure the transfer of the highest possible and most stable power from source to the load. This is because the power generated by these panels varies continuously varying with weather conditions such as irradiance and temperature, and the power conversion efficiency is very low (only about 15% of the energy converted by sun's light becomes electricity [1]).

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Therefore, maximum power point tracking techniques are included in PV systems in order to ensure maximum power harvest from the solar panels.

PV panel characteristics (I-V and P-V curves) exhibit a nonlinear relationship with temperature and irradiance. However, on this characteristic curve (Figure 1), there is a unique point where the entire system is able to work with maximum efficiency. This point is called the maximum power point MPP, and it requires calculations, tracking and control techniques to make sure the PV system is operating at this unique point, so to achieve the greatest power harvest.

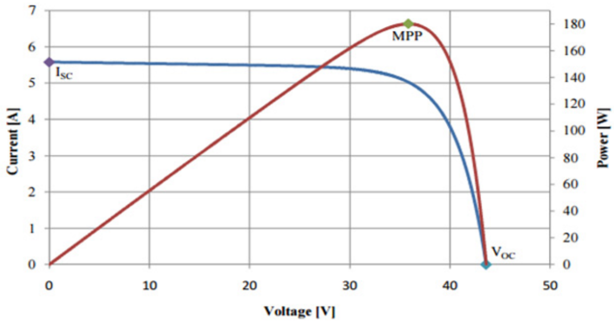

Fig. 1. Characteristic I-V and P-V curves of a solar panel.

Many different techniques have been developed and can be used in optimizing the solar power generation. These techniques differ in complexity, cost, range of effectiveness and speed of tracking, hardware, popularity, etc. Intelligent tracking methods that are more efficient have lower oscillations at MPP, and can track more quickly, have also been developed [2]. Therefore, the power conversion engineer needs to evaluate the various options based on end application, dynamics of irradiance and temperature [3].

2. MPPT control techniques

Many MPPT Techniques exist in literature but this paper will look at some popular techniques, which are as described below:

2.1. Constant voltage technique

The Constant Voltage (CV) technique is one of the simplest MPPT control methods that assumes that insulation and temperature variations on the array are insignificant, and that the constant reference voltage is an adequate approximation of the true MPP. So here, the operating point of the PV array made to match with a fixed reference voltage V_{ref}. The V_{ref} value is set equal to the V_{MPP} of the characteristic PV module or another pre-evaluated best voltage value [4]. In some cases this value is programmed by an external resistor connected to a current source pin of the control IC.

For the CV method therefore, the operating point is never exactly at the MPP and different data have to be adopted for different geographical regions. The CV method does not require any input. However, measurement of the PV array voltage V_{PV} at MPP is necessary in order to set up and adjust the duty-cycle of the DC/DC converter by PI regulator [4]. The CV technique works best at low irradiance levels, and so it is often combined together with other MPPT techniques. At this, it is more effective than both the P&O method and the InCond method.

2.2. Open voltage technique

The Open Voltage (OV) technique is based on the observation that the voltage of the maximum power point V is always close to a fixed percentage of the open-circuit voltage V_{oc}. Temperature and solar insolation levels change the position of the maximum power point within a 2% tolerance band. This technique uses 76% of V_{ov} value as value of the operating voltage V (at which the maximum output power can be obtained) [3]. In general, this value is very close to V_{MPP} of the solar array.

The OV control algorithm requires measurements of the voltage V when the circuit is opened. Here again it is necessary to introduce a static switch into the PV system; for the OV method, the switch must be used to open the circuit. When I_{ov} = 0V, no power is supplied by the PV system and consequently no energy is generated. Also in this method measurement of the PV array voltage V_{PV} is required for the regulator [6].

2.3. Perturb and observe (P&O) technique

The P&O technique is the most commonly used MPPT algorithm. The algorithm uses a simple feedback technique. In this approach, the panel voltage is periodically perturbed and the corresponding output power is compared to that of the previous perturbation cycle [7]. If there is an increase in power, the subsequent perturbation should be kept in the same direction until the MPP is reached. If there is a decrease in power, the perturbation direction is reversed. This process is continued until the MPP is reached and the system oscillates about the MPP.

The drawback in this technique is that under slowly or rapidly varying atmospheric conditions, oscillation occurs and results in power loss in the PV system [8].

2.4. Modified P&O technique

The P&O technique can be modified such as to reduce the steady-state oscillation and mitigate the probability of mis-tracking direction. The algorithm increases or decreases with the duty cycle, and performs an iteration at every pre-set time, say 100miliseconds. The amplitude of the duty cycle is proportional to the ratio of the change in output power to the change in voltage (dP/dV). This modification helps reduce the power loss that occurs during steady state oscillation, and at the same time provides higher response speed. However, this technique is very slow when the irradiance is low because dP/dV will be small but overall efficiency is higher than the conventional P&O technique.

2.5. Incremental conductance technique

The incremental conductance (InCond) technique is based on the fact that the slope of the curve of power vs. voltage (current) of the PV module is zero at the MPP, positive (negative) on the left of it and negative (positive) on the right**.** This is to say that by comparing the conductance at each sampling time, the algorithm will track the maximum power of the solar cell.

$\Delta V/\Delta P = 0$ ($\Delta I/\Delta P = 0$) at the MPP, $\Delta V/\Delta P > 0$ ($\Delta I/\Delta P < 0$) on the left, $\Delta V/\Delta P < 0$ ($\Delta I/\Delta P > 0$) on the right

For both P&O and InCond techniques, the speed at which the algorithm reaches the MPP depends on the size of the increment of the reference voltage. The drawbacks of these techniques are mainly two. The first and main one is that they can easily lose track of the MPP if the irradiation changes rapidly [5] [9]. In case of step changes, they track the MPP accurately because the change is instantaneous. However, when the irradiation changes following a slope, the curve in which the algorithms are based changes continuously with the irradiation, the changes in the voltage and current are not only due to the perturbation of the voltage. As a consequence it is not possible for the algorithms to determine whether the change in the power is due to its own voltage increment or due to the change in the irradiation [5]. The second drawback is that one of the oscillations of the voltage and current around the MPP is in the steady state. This is because the control is discrete and the current and voltage are not constantly on the MPP but oscillating around it [10].

The P&O and InCond techniques, as well as their modifications are the most widely used in PV applications.

2.6. Fuzzy logic control (FLC) technique

The FLC technique is based on a mathematical system, which analyses analogue values in regard to logical values between 2 and 1. FLCs were introduced in the tracking of the MPP in PV systems over the past decade. Fuzzy controllers are robust and can deal with imprecise inputs, does not need an accurate mathematical model and can handle nonlinearity. The FLC consists of three stages: Fuzzification, Inference System (rule base table lookup) and Defuzzification. Fuzzification comprises the process of transforming numerical crisp inputs into linguistic variables based on the degree of membership to certain sets. The interference system is implemented by using the Madani's table method while defuzzification uses the centre of gravity to compute the output of the FLC which is the duty cycle [11].

FLC is faster than both P&O and InCond in the transitional State. Also, in steady-state, it presents a smoother signal with less fluctuation. MPPT using fuzzy logic controllers have been shown to perform well under varying atmospheric conditions. Other applications of FLC include: control systems control systems engineering, industrial automation, robotics, image processing, consumer electronics and optimization. More details on FLC working principles and control strategies can be read in article [12].

2.7. Neural networks technique

Neural Network is the appropriate solution for non-linear and complex systems or random variable systems. They have the potential to provide an improved method of deriving non-linear models which is complementary to the conventional techniques. It is very robust and has a high speed response time. The Neural Network commonly has a three-layer structure, viz. the input layer, hidden layer and output layer. The number of nodes in each layer varies and is user-dependent. The input variables can be PV array parameters such as V_{oc} and I_{sc}, atmospheric data like irradiance and temperature or any combination of those. The output is usually one or several reference signal(s) like duty cycle signal used to drive the converter to operate at or close to MPP [4].

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 can also change with time, implying that the neutral network has to be trained periodically to guarantee accurate MPPT [8]. Other common applications include: character recognition, medicine image compression and security applications. Fuzzy logic and neural network methods are referred to as non-linear methods and more broadly discussed in other literatures. These methods focus on the non-linear characteristics of PV modules. However, they lack the adaptability required especially when upgrading the existing PV systems, and involve rigorous computations [13].

3. Factors to consider when choosing your MPPT technique

Listed and explained below are the important factors that will enable the power conversion engineer make an informed decision on the right MPPT techniques for practical uses:

3.1. Sensors to be used

In PV systems, sensors are used to measure the current and voltage values and in some cases, the level of irradiance. The number of sensors required to implement MPPT also affects the decision process. For a large-scale application, the number of sensors that can be used can affect its complexity and accuracy. Also, the number and type of sensors required depend largely on the MPPT technique. Generally, voltage sensors are less bulky than current sensors and this makes them more desirable for PV applications. The irradiance or temperature sensors are very expensive and uncommon.

3.2. Implementation

Another important consideration should be the simplicity or complexity of the technique when deciding the best MPPT technique to use for what application. While some end-users prefer simple analog circuitry such as Constant

Voltage Technique and Open Voltage Technique, others prefer to work with digital circuitry such as P&O and InCond despite its circuitry complexities and programming requirements.

3.3. Ability to detect Multiple Local Maxima

In many cases, environmental conditions make solar panels partially or fully shaded. This influences irradiance levels and gives rise to the problem of multiple maximum points on the plot. Since partial shading (from trees, flying objects or other buildings) can be an issue, the MPPT should be capable of bypassing multiple local maxima. Also, considerable amount of power is lost if the MPP is mis-tracked. It is therefore important to build a complex, flexible algorithm that has the ability to detect the highest local maximum point in the multiple maximum points that will arise. FLC technique presents a smoother signal with less fluctuation in steady-state.

3.4. Applications

Some MPPT techniques are more suitable for specific applications. For example hill-climbing techniques such as P&O and InCond have shown to be more practical for PV applications. Fuzzy logic control and neural network are good options in the case of solar vehicles because they require fast convergence at MPP. PV systems used for street lighting only consist in charging up batteries during the day. They do not necessarily need tight constraints; easy and cheap implementation might be more important, making constant voltage and open circuit voltage techniques more desirable.

3.5. Convergence Speed and Efficiency of Technique

The time taken for a high-performance MPPT system to converge to the required operating voltage or current should be low. However, if the speed becomes too fast, the actual point tends to bounce around the MPP due to noise present in the power conversion system. Therefore, it is better to first consider accuracy than speed. Certainly, an accurate and fast method would be preferred but then again you will have to consider the cost of implementation.

3.6. Costs

In practice, analog techniques are cheaper than digital techniques. This is because in digital methods, the use of sensors that require microcontrollers and programming is required and comes with system complexities. Voltage sensors are generally costlier than current sensors. This is to say that elimination of sensors reduces the cost of actualization of the PV system. In cost considerations, the number of sensors determine the resources required to set up the system.

4. Cost comparison of the different techniques

An adequate cost comparison of these MPPT techniques can be made by knowing the technique (analog or digital) adopted in the control device, the number of sensors, and the use of additional power components, considering the other costs (power components, electronic components, boards etc.) equal for all the devices [2].

CV and OV Techniques are analogue techniques and therefore cheaper to implement. They can therefore be selected if it is necessary to minimize the control system cost. P&O technique generally use one sensor hence the cost of implementation is usually less than that of the InCond technique, as the latter requires more than one sensor for higher accuracy.

After these considerations, Table 1 summarizes the major characteristics of the discussed MPPT techniques and proposes a simplified classification considering the costs of sensors, microcontroller and the additional power components [13] [14]. Table 1 serves as an easy guide to choosing an appropriate MPPT method.

Table 1. Tabular Comparison of the different Techniques

	MPPT Technique	*Control Complexity*	*Sensed Parameters*	*Cost*	*Implementation Complexity*	*Applications*
1	*Constant Voltage*	*Simple*	*V*	*Inexpensive*	*Simple*	*Stand-alone*
2	*Open (Circuit) Voltage*	*Simple*	*I*	*Inexpensive*	*Simple*	*Stand-alone*
3	*P&O*	*Medium*	*V, I*	*Expensive*	*Medium*	*Stand-alone*
4	*Modified P&O*	*Medium*	*V,I*	*Expensive*	*Complex*	*Stand-alone*
5	*InCond*	*Medium*	*V and I*	*Expensive*	*Complex*	*Stand-alone*
6	*Fuzzy Logic*	*Complex*	*V or I*	*Expensive*	*Complex*	*Grid, Solar Vehicles etc*
7	*Neural Networks*	*Complex*	*V or I*	*Expensive*	*Complex*	*Grid, Pumping, DC motor drives etc.*

5. Conclusion

Maximum power point trackers (MPPT) are used to increase the efficiency of the photovoltaic systems by ensuring the operating parameters of the panel are working at optimal conditions, thereby improving on the efficiency and lowering the cost. From the paper, we have seen that there are many approaches to tracking and finding this power point for PV cells or groups of cells. For many systems, it is best to use a combination of methods (hybriding). For instance, OV technique can be first used to find the starting point for the algorithm and the iterative methods like P&O or InCond then used to track the algorithm more accurately. In some cases, changing from one method to another based on the level of irradiance is possible. At low levels of irradiance, methods like CV and OV techniques may be more appropriate as they can be more immune to noise. The iterative techniques such as P&O and InCond and their modifications offer better solution when a portion of the panel is shaded or when panels do not have the same angle of incidence, and searching algorithms are needed.

6. Future work

Further research could focus on experimental comparisons of these techniques for mismatched conditions such as partial shading, non-uniformity of PV panel temperatures, damages to panel glass and dust or shadow effects for specific applications. The reviews done in this paper are expected to be useful for MPPT users, designers and commercial manufacturers of PV systems.

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