



Analysis of Solar Maximum Power Point Tracking Algorithms and Hardware Architectures

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Abstract: This paper shows the comparison of the different maximum power point tracking (MPPT) techniques in order to assess them and give the PV industry a conclusive document to choose the best technique for their requirements. Numerous research articles are presented and their hardware commercialized which is only based on MPPT. Due to which PV users are confused as to what is the best choice for their need. For this reason detailed analysis and review of all the MPPT techniques available has been done so as the users can easily select the best possible option. The comparison is done on the basis of efficiency, sensing, size, cost, speed, control variables and response time so that this paper should serve a reference for PV users, researchers and developers.

Keywords: Solar Cell, Photovoltaic, Maximum Power Point Tracking, Offline, Online

1. **INTRODUCTION**

Renewable energy is obtained from renewable sources. Any energy source which can either be recycled naturally, e.g., the potential energy of water in hydro power stations are used to spin the turbine and then it flows into the sea. Through a natural cycle it turns to clouds and rain and again can be utilized at hydro power station. Energy sources which are infinite, e.g., the energy taken from the Sun, are all renewable sources (Ameli *et al.*, 2008). Renewable energy systems are getting popular because of their infinite nature and green energy image. The international community is showing great interest towards the development of clean and renewable energy sources. These days' consumers are shifting towards the clean development Mechanisms (Amrouche *et al.*, 2007). The renewable energy requires onetime investment whereas the price of fossil fuels is increasing with every passing day as the reservoirs are being depleted.

2. **SOURCES OF RENEWABLE ENERGY**

2.1 **Solar Power**

The energy of the sun can be used to fulfill our requirements. It was first found by the British astronomer John Herschel who used thermal collector to cook his food. This is one way to use solar energy, i.e., to store the heat and then use the heat for our activities. The other way to use solar energy is to convert solar radiations into electrical energy. This is done by using photovoltaic cells (Bidyadhar *et al.*, 2013) or with concentrating solar power plants.

2.2 **Hydro Power**

Micro hydro power stations (up to 10MW) are considered as renewable energy source (Chowdhury and Saha 2010). They convert the kinetic energy of water i.e., flowing river or the potential energy of water, i.e.,

the energy of a waterfall or of the water stored in a dam into electrical energy.

2.3 **Biogas**

Plants prepare their food by the process of photosynthesis which has the term "photo" showing that the process involves light. During this process the sun's energy is stored in the plants. The biomass works as a natural cycle to store the sun's energy (Chen *et al.*, 2003). This energy is released when the plant is burned, digested by herbivores animals, or decomposed by an aerobically.

2.4 **Geothermal**

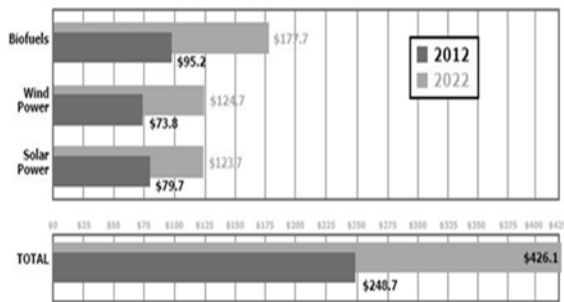
Geothermal energy is generated in the earth's crust and stored in its layers (Amrouche *et al.*, 2007). To extract this energy from the core of the earth the gradient is used. Geothermal energy is generally used to heat water and to produce steam which is further used to produce electricity. Its limited availability is its biggest disadvantage as it is specific to areas near tectonic plate boundaries (Bidyadhar *et al.*, 2013)

3. **SOLAR AND PHOTOVOLTAIC**

Clean energy is getting the attention it deserves all across the globe. In the last decade (since 2002) great breakthroughs are done in this field and organizations developing or promoting clean energy have flourished. The point of view of Sloyndra and other green tech critics that clean energy cannot compete in the market without the help of government subsidies. Green technology supporters or tree huggers are caught off guard and the energy giants and major US oil producing companies are giving them a hard time (Esram and Chapman 2007). **Table-1** shows the growth of clean energy during period 2011-2012. A big reason for this tremendous growth is the focus of the community towards clean and green energy.

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Table 1: Global Clean-Energy Projected Growth 2012-2022 (\$ US Billions)

4. A MPPT TECHNIQUES

Cost per watt and low conversion efficiency is the weak point of solar power systems (Femia *et al.*, 2006). Now there are many ways to increase the efficiency of PV systems (Hua and Shen 1998). But the one giving immediate results which doesn't require any expansive hardware upgrades is the maximum power point tracking technique. This can be achieved mechanically or using a solid state circuit. Mechanical tracking is easy to implement and cost effective but it is not reliable or long lasting. On the other hand solid state circuits are reliable and long lasting. Due to advancement in technology the cost of solid state trackers is decreased day by day such that it has completely outcast the mechanical method in small industry, which are only used in large PV projects. MPP can be tracked by online, offline and hybrid techniques.

This paper would be a helpful tool in the regard that it would give a brief comparison of the different techniques available on the basis of cost, efficiency, response time etc.

4.1 Offline MPPT Techniques

Those MPP techniques in which it is necessary to disconnect the source from the load or the PV panels from the load to calculate the MPP are called offline MPPT techniques. Some of the available techniques are explained below:

4.1.1 Curve Fitting Technique

The technique makes use of the power voltage curve of the module for tracking the MPP. Mathematical techniques are used to find the voltage at which the maximum power is delivered. Its implementation is complex and it is also not very accurate but it is very cost effective.

4.1.2 Fractional Short-Circuit Current Technique

The performance of the solar systems depends greatly on the atmosphere. Its performance changes with changing irradiance and temperature which means that their MPP would also change relative to the change in atmospheric conditions. According to this technique the

MPP lies near 65-85% of the short circuit current which is calculated from irradiance of from the panel.

4.1.3 Fractional Open-Circuit Voltage (FOCV) Technique

Fractional Short-Circuit Current (FSCI) Technique determines the MPP by making use of the short circuit current whereas according to Fractional open-circuit voltage lies near 78-92% of the open circuit voltage which is determined by the temperature of from the panel.

4.1.4 Current Sweep Technique

In this technique the power voltage and the current voltage of the PV module is determined and the MPP calculated (Femia *et al.*, 2006).

In this technique the real time P-V and I-V of the PV module is computed and the maximum power point is estimated using equation of (Jiao *et al.*, 2010). The MPP is computed at regular intervals more after at the end.

4.2 Online MPPT Techniques

Online MPPT techniques are those during which the load is connected to the source to calculate the maximum power point. Some of the techniques are discussed below:

4.2.1 Look-up Table Technique

In this technique a database is stored in the memory of the MPP controller. The database contains previously calculated maximum power points for different environmental conditions. These techniques are expensive and their implementation time consuming. Also they are not very accurate as no PV technologies have the same MPP for the same conditions.

4.2.2 One-Cycle Control (OCC) Technique

Instead of feeding the battery, this technique connects the PV source to the load (grid or motor) through an inverter. The output current of the inverter is varied according to the voltage produce by the PV panel. This technique is expensive and dependent upon the AC load. The main advantage is accuracy and compatibility with large scale PV systems. These techniques are suitable for solar water pumps.

4.2.3 Defereential Technique

The MPP is calculated by the following formula:

$$\frac{dP}{dt} = \frac{d(IV)}{dt} = I \frac{dV}{dt} + V \frac{dI}{dt} = 0 \quad (1)$$

The voltage and current and the change in voltage and current is for a very short time and then by MPP is determined by using equation. These techniques are very accurate but have very high costs and low speeds. To increase the speed of operation expansive processors are used (Femia *et al.*, 2006).

4.2.4 Feedback Voltage or Current Technique or Reference Voltage or Current Technique

These techniques are used where there is not battery bank, so a simple way to track the MPP is to fix the bus voltage (Amrouche *et al.*, 2007). Feedback of such techniques is current or voltage whereas duty cycle of the converter is adjusted according to the previous values of voltage to get the maximum output power.

4.2.5 Feedback of power with Voltage techniques

According to this technique MPP lies where the rate of change of current with respect to voltage is zero. So in order to achieve the maximum power condition the voltage is varied. It is easy to implement such techniques but the response time is very slow. Also another disadvantage is that the output is not fixed but slides across the MPP condition (Lapea *et al.*, 2010). Output voltage is increased to reach the MPP and then reduced when MPP is crossed.

4.2.6 Feedback of Power Variation with Current Technique

The maximum power point is where the differential of power with respect to voltage is zero (Mathew, *et al.*, 2006). So the load current is varied until the MPP is reached. Such techniques are easy to implement but response is slow and output is not fixed but swings around the maximum value. Such techniques are good for cloudy weather where there are fast current variations.

4.2.7 Perturbation and Observation (P&O) And/Hill-Climbing Technique

The maximum power point of a PV module is calculated by calculating the power P1 on a specific duty cycle and then calculating power P2 by perturbing the duty cycle of the DC-DC converter. Both the powers are compared if P2 is greater is greater than P1 it means MPP has not been reached yet. If on the other hand P2 is less than P1 it means that the MPP has been crossed. (Jiao *et al.*, and Lapea *et al.*, 2010). The main disadvantage of P&O or hill climbing is that the MPP is not fixed and swings around the maximum value in changing weather conditions. The perturbation size is also a crucial decision in this technique (Mathew, *et al.*, 2006; Noguchi, and Matsumoto 2003). The solutions is provided in which propose a fast P&O technique by variable perturbation for fast changing conditions, this is named adaptive hill climbing technique.

4.2.8 Incremental Conductance (Inc-Cond) Technique

The MPP is the point where both the current and voltage are at their maximum values. Voltage varies with temperature of the panel and current varies with irradiance, so such techniques should be used to observe the variation caused by both temperature and irradiance. MPP is tracked by calculating dI/dV where dI/dV is

zero; the fact is calculated from the following equations (Femia *et al.*, 2006; Jiao *et al.*, 2010).

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V \frac{dI}{dV} = I + V \frac{\Delta I}{\Delta V} \quad (1)$$

$$\frac{\Delta I}{\Delta V} = \frac{-I}{V} \text{ at MPP} \quad (2)$$

$$\frac{\Delta I}{\Delta V} > \frac{-I}{V} \text{ at left of MPP} \quad (3)$$

$$\frac{\Delta I}{\Delta V} < \frac{-I}{V} \text{ at right of MPP} \quad (4)$$

These techniques perform best in changing conditions. The accuracy of P&O and Incremental conductance is the same and as with P&O perturbation size is crucial (Piegari and Rizzo 2010). Also the hardware is complex and expensive.

4.2.9 Forced Oscillation Technique

According to this technique a sinusoidal signal with frequency equal to the switching frequency is introduced and the panel terminal voltage and the components are compared.

4.2.10 Ripple Correlation Control Technique

Maximum power point is reached by using the ripples of the panels. The PV panel is forced to generate ripples by the switching element of the DC-DC converter. These ripples unlike the self-made perturbations are sensed for MPP. The maximum power point lies where the ripples are zero. The duty cycle and switching frequency of the DC-DC converter are changed according to the ripples of the panels (Noguchi, and Matsumoto 2003).

4.2.11 Estimated-Perturb-Perturb Technique

A little advancement is done in the ordinary P&O method to find MPP during quickly varying conditions. The non-linear curve is tracked to find the MPP. Its response time is better than that of P&O but the controller becomes very complex.

4.2.12 Parasitic Capacitance Technique

Parasitic capacitance has been discussed in (Saha 2010), and is related to the incremental conductance method. The difference between the Inc-Con and parasitic capacitance is that this method makes use of the solar cell's PN junctions capacitance. The current produced by this capacitance is included to calculate the MPP.

$$I = I_{pv} - I_o \left[\exp\left(\frac{V+IR_s}{aV_t}\right) - 1 \right] - \frac{V+IR_s}{R_{sh}} + C_p \frac{dv}{dt} \quad (1)$$

4.2.13 Load Current/Load Voltage Maximization Technique

In this technique the load is connected to the panels and is varied with the MPP as MPP cannot be tracked with constant load. It uses current and voltage of DC-

DC converter instead of PV module hence simplifying the controller (Noguchi, and Matsumoto 2003).

4.2.14 DC Link Capacitor Drop Control Technique

DC-link capacitor drop control technique is given in (Amrouche *et al.*, 2007), it is designed for such systems which are connected parallel to the PV system. The duty ratio (d) of ideal boost converter is a ratio of PV voltage (V) to the dc link Voltage (V_{link}) and minus one. The maximum power point is achieved where the both voltages V & V_{link} becomes equal. The inverter gates switch according to the required input voltage to AC loads. This technique has limitations because they can be applied on the systems which are connected parallel to the PV system such as solar Pumps.

4.2.15 Linearization-Based MPPT Technique

What makes tracking the MPP difficult is the non-linear nature of the PV panel and the DC-DC converter. This technique uses mathematical techniques to deal linearly with the non-linear nature of the panel and converter making it easy to track the MPP. A liner MPP locus is obtained based on voltage and current of the panel and is related to electrical parameter of the panel (Mathew *et al.*, 2006; Noguchi and Matsumoto 2003).

4.3 INTELLIGENT MPPT TECHNIQUES

4.3.1 Fuzzy Logic (FL)-Based MPPT Technique

Intelligent MPPT techniques promise a lot. Their performance in terms of efficiency, size, speed and reliability to changing environmental conditions is very good. Knowledge of the PV model is not required in the Fuzzy logic based MPPT (Noguchi and Matsumoto 2003; Piegari and Rizzo 2010). These trackers have one output and two inputs (Lapea *et al.*, 2010).

4.3.2 Artificial Neural Network (ANN)-Based MPPT Technique

These techniques don't require information about the working PV module (Lapea *et al.*, 2010). These are fast, efficient and intelligent. W_{ij} is the weight of link between i^{th} and j^{th} node and is adjusted with respect to the input and output. Input of such techniques can be any combination of voltage, current, temperature and irradiance whereas the output is the duty cycle and is varied by the weights according to the MPP. MPP is tracked in real time after temperature and irradiance variations are provided and relationship of these with the MPP is found (Mathew, *et al.*, 2006; Noguchi, and Matsumoto 2003; Piegari, and Rizzo 2010; Salas, *et al.*, 2006).

4.3.3 Particle Swarm Optimization-Based MPPT (PSO-MPPT)

There are some conditions in which there might be more than one MPP. For example in partly shaded conditions some part of the PV panel would be in shade and some of it will be in light. So there will be more than one MPP and tracking the MPP is great challenge. A technique called the PSO was proposed to solve this problem and is very effective in rapidly changing conditions (Esram and Chapman 2007). Some techniques are proposed in (Saha 2010), but are not very economical for commercial purposes.

4.4 Hybrid MPPT Techniques

Such techniques are the combination of the rest of the intelligent MPPT techniques and combine the qualities of each of them to give better results. For example PSO works great in changing conditions and FL have very small size, so these two are combined to get a controller which is cost effective as well as can handle fast varying conditions. The cost of such techniques would be greater than that of the cost of individual MPPT techniques. Such techniques are discussed in (Jiao *et al.*, 2010).

5. ANALYSIS OF MPPT TECHNIQUES

In this research paper, analysis of MPPT techniques have been made on the basis of cost, efficiency, control variable (Current and voltage), size, implementation, Direct output to the load, operation in rapidly changing environment (Partial shading), speed of tracking maximum power point and output accuracy (Amount of voltage and current ripples in output).

6. CONCLUSION

Several MPP tracking techniques were analysed on the basis of cost and power efficiency and their scope of commercialization was also studied. On the basis of input control signal MPP techniques were classified into three categories. Then each technique was studied for power losses, max and min size, cost/unit, accuracy, max power rating, life of device, effects of partial shading, control variable and response time. This paper can also be reviewed for standalone and grid tie systems and the preferable converter for each MPPT technique can be selected. Latest MPPT techniques are also included in the study. The study also reviews the effects of mismatch conditions (changing weather, dust, internal temperature etc.) on the performance of PV systems. Efficiency calculations for different MPPTs have also been done. The study should be useful not only for research community, but also for the users and producers of PV systems.

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