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# A review study of photovoltaic array maximum power tracking algorithms

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**Abstract**

There are numerous maximum power point tracking (MPPT) algorithms for improving the energy efficiency of solar photovoltaic (PV) systems. The main differences between these algorithms are digital or analog implementation, simplicity of the design, sensor requirements, convergence speed, range of effectiveness, as well as hardware costs. Therefore, choosing the right algorithm is very important to the users, because it affects the electrical efficiency of PV system and reduces the costs by decreasing the number of solar panels needed to get the desired power. This paper provides the comparison of 62 different techniques used in tracking the maximum power based on literature survey. This paper is intended to be a reference for PV systems users.

**Keywords:** Maximum power point tracking system (MPPT), Photovoltaic (PV), System efficiency

## Background

Recently, renewable energy technology has been swiftly developed where it has an important role in clean energy application. An important type of renewable energy is solar energy that produces electrical energy directly using PV modules supported by MPPT algorithm to maximize the output power. The objective of obtaining MPP in PV systems is to regulate the actual operating voltage of PV panels to the voltage at MPP, by adjusting the output power of the inverter (Libo et al. 2007).

In literature, there are plentiful MPPT methods as in (Esram and Chapman 2007; Ali et al. 2012; Jusoh et al. 2014; Kamarzaman and Tan 2014; Liu et al. 2015; Lyden and Haque 2015). Kamarzaman and Tan (2014) used four categories to review MPPT algorithms as follows: conventional MPPT algorithms (perturb and observation P&O and incremental conductance IC); hill-climbing (open circuit voltage and short circuit current); ripple correlation current; and stochastic-based MPPT algorithms (particle swarm optimization, fuzzy logic controller, artificial neural network, and differential evolution). Liu et al. (2015) gave a review of MPPT techniques for use in partially shaded conditions. Lyden et al. (2015) divided the tracking techniques to three types: conventional MPPT techniques, global MPPT techniques, and power electronics-based approaches.

This paper presents a brief comparison between different techniques to help the users to choose an MPPT technique for a particular application. The comparison between the MPPT methods includes cost, analog or digital implementation, sensor dependence, convergence speed, hardware complexity, and effectiveness.

Second section illustrates the statement of the problem. Comparison between different MPPT techniques is given in third section. In fourth section, the methodology is presented followed by the fifth section in which results are introduced and three most popular algorithms are presented. Finally, the conclusion is presented in the last section.

## Statement of the problem

In medium- and large-scale systems, sun tracking or MPPT or both are used to obtain maximum power (Tse et al. 2002). MPPT systems are considered the most popular in all PV systems. MPPT systems are used to reach MPP automatically from solar modules. That is the PV system will work at its maximum efficiency. The amount of energy gained by PV system depends on several

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factors including level of irradiance, temperature, and partial shading. Thus, these algorithms should consider the changes in these factors. The characteristic current–voltage curve and power–voltage curve are displayed in Fig. 1. These characteristic curves present the parameters that describe the operation of the PV cell such as the open-circuit voltage $V_{OC}$, short circuit current $I_{SC}$, and the cell voltage, current, and power at the maximum power point, $V_{MPP}$, $I_{MPP}$, and $P_{MPP}$, respectively.

In addition, the fill factor *FF* and efficiency $\eta$ are considered. *FF* measures the quality of the PV array. It is the ratio of the actual MPP ($P_{MAX}$) to the product of $V_{OC}$ and $I_{SC}$ as in (1) (Chen 2011).

$$FF = \frac{P_{MAX}}{P_T} = \frac{I_{MP}V_{MP}}{I_{SC}V_{OC}} \qquad (1)$$

While the efficiency, $\eta$, of a solar cell is defined as the ratio of the output electric power over the input solar radiation power under standard illumination conditions at the maximum power point (Chen 2011).

## Comparison between MPPT techniques

The MPPT techniques vary in many aspects, which might help the users to decide the system that suits their unique applications. These parameters include hardware implementation, sensor, convergence speed, multiple local maximum, cost, application, and dependency on array parameter. Hardware implementation is simply the type of circuit: analog or digital (Esram and Chapman 2007). Sensors and their numbers affect the decision makers to decide which MPPT to use. The more precise MPPT requires more sensors (Reported issued by National Instruments 2009). Usually, it is easier to sense voltage than current. The irradiance or temperature sensors are very expensive and uncommon (Faranda and Leva 2008).

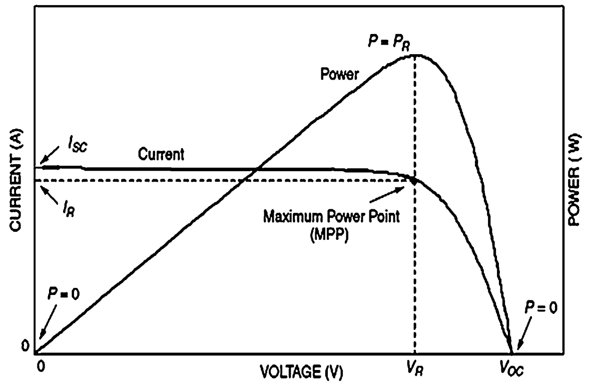

**Fig. 1** Characteristic power–voltage and current–voltage curves (Tse et al. 2002)

Convergence speed is the time taken to reach the MPP (Walker et al. 2011). For a high-performance MPPT system, the time taken to converge to the required operating voltage or current should be low. The lower time and periodic tuning taken to reach the *MPP* minimize power losses and maximize efficiency.

The ability to detect multiple local maxima when the system is under different irradiance levels is another important parameter. The power loss can reach 70 % under partial shading condition, if a local maximum is tracked instead of the real MPP (Reported issued by National Instruments 2009; Ji et al. 2009).

Performance cost is another parameter that concerns the users. It is usually cheaper to use analog system than digital system. Moreover, the number and type of sensors, using other power or electronic components, add extra cost to the system (Faranda and Leva 2008).

Different MPPTs are suitable for various applications. Depending on the application, different aspects may be considered important when choosing the PV system. As an example, in space satellites and orbital stations applications that involve a 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 (Khatib et al 2010).

The MPPT system might be independent (direct) or dependent (indirect) on array parameters. The direct methods use *PV* voltage and/or current measurements. These direct methods have the advantage of being independent from the prior knowledge of the *PV* array configuration and parameter values for their implementation. Thus, the operating point is independent of irradiance, temperature, or degradation levels. The indirect methods are based on the use of a database of parameters that include data of typical *P*–*V* curves of PV systems for different irradiances and temperatures, or on the use of mathematical functions obtained from empirical data to estimate the MPP (Khatib et al. 2010; Jain and Agarwa 2007). Table 1 summarizes the most important characteristics of MPPT algorithm that is used to compare between different techniques.

**Table 1 Parameters used to compare MPPT algorithms**

| Parameters | Statement |
|---|---|
| PV array dependent/ independent | Methods can be applied to any PV array with or without the knowledge of its configuration and parameter values |
| True MPPT | The MPPT algorithm can operate at maxima or others. If the actual MPP is not the true MPP, then the output power will be less than the expected one actually |
| Types of circuitry | Analog or digital |
| Periodic tuning | Is there an oscillation around the MPP or not |
| Convergence speed | It is the amount of time required to reach MPP |
| Implementation complexity | This standard describes the method in general |
| Sensors | It depends on the number of variables under consideration |

## Methodology

In this work, we conducted a literature review to what is available in terms of MPP tracking algorithms. We analyzed theoretically the work presented in each paper and fetch the parameters as indicated in Table 1. We collected 45 different algorithms. The differences between 45 MPPT algorithms are listed in Table 2. Table 2 is an extended work to what have been presented in (Ali et al. 2012). Further, algorithms are collected from other resources.

## Results

The comparison between 62 algorithms is shown in Table 2. According to the table, the most common algorithms are perturb and observe (P&O)/"hill-climbing," incremental conductance algorithm, and fuzzy logic controller (FLC).

Below is a quick review of these three well-known algorithms.

### Perturb and Observe (P&O)/"hill-climbing"

The P&O is the most popular for its low cost, ease of implantation, simple structure, and few measured parameters, which are required. It only measures the voltage ($V$) and current ($I$) of the PV array. PV system controller changes PV array output with a smaller step in each control cycle. The step size is generally fixed, while mode can be increased or decreased. Both PV array output voltage and output current can be the control object; this process is called "perturbation." It depends on the fact that the derivative of power with respect to voltage is zero at MPP point (Sera et al. 2006; Busa et al. 2012). This method fails under rapidly changed atmospheric conditions and has a slow response speed oscillation around the MPP (Sera et al. 2006).

### Incremental conductance algorithm

The incremental conductance method is based on the fact that the sum of the instantaneous conductance ($I/V$) and the incremental conductance is zero at MPP. Figure 2 shows the slope of the PV array power curve compared to ($I/V$). Thus, incremental conductance can determine that the MPPT has reached the MPP and stop perturbing the operating point of the PV array as explained in Fig. 2.

Although incremental conductance is an improved version of P&O, it can track rapidly increasing and decreasing irradiance conditions with higher accuracy than P&O. However, this algorithm is more complex than P&O. This increases computational time and slows down the sampling frequency of the array voltage and current (Esram and Chapman 2007; Chen 2011; Yadav et al. 2012; Rashid 2011; Zainudin and Mekhilef 2010).

### Fuzzy logic controller (FLC)

FLC consists of four categories as fuzzification, inference engine, rule base, and defuzzification. The numerical input variables are converted into fuzzy variable known as linguistic variable based on a membership function similar to Fig. 3. In this case, five fuzzy levels are used: NB (negative big), NS (negative small), ZE (zero), PS (positive small), and PB (positive big). For more accuracy seven fuzzy levels are used. In Fig. 3, a and b are based on the range of values of the numerical variable. Conventional fuzzy MPPT consists of two inputs and one output. The two input variables are the error ($E$) and the error change ($\Delta E$), at sampled times $k$. The input $E$ ($k$) shows if the load operation point at the instant $k$ is located on the left or on the right of the maximum power point on the PV characteristic, while the input $\Delta E(k)$ expresses the moving direction of this point (Esram and Chapman 2007; Ali et al. 2012; Faranda and Leva 2008; Brito et al. 2013).

## Conclusion

In this work, we presented a comparison of 62 MPPT algorithms. In the comparison, we used several parameters including the complexity of the system, number of sensors, kind of circuitry (digital or analog), tuning, convergence speed, and the dependency of the parameters. The results are shown in the table to serve the users to

**Table 2 Comparison between different MPPT algorithms (*V* voltage, *I* current, *Ir* irradiance)**

| | MPPT technique | PV array dependence | True MPPT | Analog/digital | Periodic tuning | Convergence speed | Implementation complexity | Sensors |
|---|---|---|---|---|---|---|---|---|
| 1. | Hill-climbing P&O (Sera et al. 2006; Busa et al. 2012; Jusoh et al. 2014; Kamarzaman and Tan 2014) | No | Yes | Both | No | Vary | Low | *V* and *I* |
| 2. | Incremental conductance (Esram and Chapman 2007; Yadav et al. 2012; Rashid 2011; Zainudin and Mekhilef 2010; Jusoh et al. 2014; Kamarzaman and Tan 2014) | No | Yes | Digital | No | Vary | Medium | *V* and *I* |
| 3. | Fractional $V_{oc}$ (Kumari and Babu 2011; Lee 2011; Jusoh et al. 2014; Kamarzaman and Tan 2014) | Yes | No | Both | Yes | Medium | Low | *V* |
| 4. | Fractional $I_{sc}$ (Kumari and Babu 2011; Lee 2011; Jusoh et al. 2014; Kamarzaman and Tan 2014) | Yes | No | Both | Yes | Medium | Medium | *I* |
| 5. | Fuzzy logic control (Ali et al. 2012; Rezaei and Gholamian 2013; Takun et al. 2011; Rahmani et al. 2013; Jusoh et al. 2014; Kamarzaman and Tan 2014). | Yes | Yes | Digital | Yes | Fast | High | Varies |
| 6. | Neural network (Ali et al. 2012; Kamarzaman and Tan 2014) | Yes | Yes | Digital | Yes | Fast | High | Varies |
| 7. | RCC (Ali et al. 2012; Jusoh et al. 2014) | No | Yes | Analog | No | Fast | Low | *V* and *I* |
| 8. | Current weep (Ali et al. 2012) | Yes | Yes | Digital | Yes | Slow | High | *V* and *I* |
| 9. | DC link capacitor droop control (Ali et al. 2012) | No | No | Both | No | Medium | Low | *V* |
| 10. | Load *I* or *V* maximization (Ali et al. 2012) | No | No | Analog | No | Fast | Low | *V* and *I* |
| 11. | dP/dV or dP/dI feedback control (Ali et al. 2012) | No | Yes | Digital | No | Fast | Medium | *V* and *I* |
| 12. | β method (Ali et al. 2012) | Yes | Yes | Digital | No | Fast | High | *V* and *I* |
| 13. | System oscillation method (Ali et al. 2012) | Yes | Yes | Analog | No | N/A | Low | *V* |
| 14. | Constant voltage tracker (Ali et al. 2012; Coelho et al. 2010) | Yes | No | Digital | Yes | Medium | Low | *V* |
| 15. | Lookup table method (Ali et al. 2012; Abdulmajeed et al. 2013) | Yes | Yes | Digital | Yes | Fast | Medium | *V*, *I*, *T*, and *Ir* |
| 16. | Online MPP search algorithm (Ali et al. 2012) | No | Yes | Digital | No | Fast | High | *V* and *I* |
| 17. | Array reconfiguration (Ali et al. 2012; Israel 2015) | Yes | No | Digital | Yes | Slow | High | *V* and *I* |
| 18. | Linear current control (Ali et al. 2012) | Yes | No | Digital | Yes | Fast | Medium | *Ir* |
| 19. | IMPP and VMPP computation (Morales 2010) | Yes | Yes | Digital | Yes | N/A | Medium | *Ir* and *T* |
| 20. | State based MPPT (Ali et al. 2012) | Yes | Yes | Both | Yes | Fast | High | *V* and *I* |
| 21. | OCC MPPT (Ali et al. 2012) | Yes | No | Both | Yes | Fast | Medium | *I* |
| 22. | BFV (Ali et al. 2012) | Yes | No | Both | Yes | N/A | Low | None |
| 23. | LRCM (Esram and Chapman 2007) | Yes | No | Digital | No | N/A | High | *V* and *I* |
| 24. | Slide control (Esram and Chapman 2007; Ali et al. 2012; Tse et al. 2002; Chen 2011; Reported issued by National Instruments 2009; Faranda and Leva 2008; Walker et al. 2011; Ji et al. 2009; Khatib et al. 2010; Jain and Agarwa 2007; Sera et al. 2006; Busa et al. 2012; Yadav et al. 2012; Rashid 2011; Zainudin and Mekhilef 2010; Kumari and Babu 2011; Lee 2011; Rezaei and Gholamian 2013; Takun et al. 2011; Rahmani et al. 2013; Coelho et al. 2010; Abdulmajeed et al. 2013; Israel 2015; Morales 2010; Ghazanfari and Farsangi 2013) | No | Yes | Digital | No | Fast | Medium | *V* and *I* |
| 25. | Temperature method (Ali et al. 2012; Faranda and Leva 2008; Brito et al. 2013) | Yes | Yes | Digital | Yes | Medium | Low | *V* and *T* |

**Table 2 continued**

| | MPPT technique | PV array dependence | True MPPT | Analog/digital | Periodic tuning | Convergence speed | Implementation complexity | Sensors |
|---|---|---|---|---|---|---|---|---|
| 26. | IC Based On PI (Brito et al. March 2013; Lyden and Haque 2015) | No | Yes | Digital | No | Fast | Medium | *V* & *I* |
| 27. | Three point weight comparison (Ali et al. 2012)(Walker et al. 2011; Jiang et al. 2005). | No | Yes | Digital | No | Low | Low | *V* and *I* |
| 28. | POS control (Ali et al. 2012) | No | Yes | Digital | No | N/A | Low | *I* |
| 29. | Biological swarm chasing MPPT (Ali et al. 2012) | No | Yes | Digital | No | Varies | High | *V*, *I*, *T* and *Ir*, |
| 30. | Variable inductor MPPT (Ali et al. 2012) | No | Yes | Digital | No | Varies | Medium | *V* and *I* |
| 31. | INR method (Ali et al. 2012) | No | Yes | Digital | No | High | Medium | *V* and *I* |
| 32. | Parasitic capacitances (Zainudin and Mekhilef 2010; Rekioua and Matagne 2012; Hohm and Ropp 2003). | No | Yes | Analog | No | High | Low | *V* and *I* |
| 33. | dP-P&O MPPT (Sera et al. 2006; Mastromauro et al. 2012) | No | Yes | Digital | No | High | Medium | *V* and *I* |
| 34. | Modified INC algorithm (Mastromauro et al. 2012) | No | Yes | Digital | No | Medium | High | *V* and *I* |
| 35. | Pilot cell (Kumar et al. 2013) | Yes | No | Both | Yes | Medium | Low | *V* and *I* |
| 36. | Modified Perturb and Observe (Liu et al. 2004) | No | Yes | Digital | No | High | Medium | *V* and *I* |
| 37. | Estimate, Perturb and Perturb (Liu et al. 2004; Yafaoui et al. 2007) | No | Yes | Digital | No | High | Medium | *V* and *I* |
| 38. | Numerical method quadratic interpolation (QI) (Hu et al. 2009) | No | Yes | Digital | No | High | Medium | *V* and *I* |
| 39. | MPP locus characterization (Israel 2015) (Vladimir et al. 2009) | | Yes | | | High | Low | *V* and *I* |
| 40. | CVT + INC CON (P&O) + VSS method (Go et al. 2011) | Yes | Yes | Both | No | High | Medium | *V* |
| 41. | Piecewise linear approximation with temperature compensated method (Yang and Yan 2013) | Yes | Yes | Both | Yes | High | Low | *V*, *I*, *T*, and *Ir*, |
| 42. | Particle swarm optimization PSO algorithm (Mandour and Elamvazuthi 2013; Lyden and Haque 2015) | No | Yes | Digital | No | High | Low | *V* and *I* |
| 43. | PSO-INC structure (Mandour and Elamvazuthi 2013) | No | Yes | Digital | No | High | Low | *V* and *I* |
| 44. | Dual carrier chaos search algorithm (Zhou et al. 2012) | No | Yes | Digital | No | High | Medium | *V* and *I* |
| 45. | Algorithm for stimulated annealing (SA) (Rahman et al. 2013) | Yes | Yes | Digital | No | High | High | *V* and *I* |
| 46. | VH-P&O MPPT algorithm (Abdalla et al. 2011) | No | Yes | Digital | No | Medium | Medium | *V* |
| 47. | Artificial neural network (ANN) based P&O MPPT (Amrouche et al. 2007; Kamarzaman and Tan 2014) | No | Yes | Both | No | High | Medium | *V* and *I* |
| 48. | Ant colony algorithm (Qiang and Nan 2013) | No | Yes | Digital | No | High | Medium | *V* and *I* |
| 49. | Variable DC link voltage algorithm (Lee and Lee 2013) | No | Yes | Digital | No | Medium | Medium | *V* |
| 50. | Extremum seeking control method (ESC) (Reisi et al. 2013) | No | Yes | Both | No | Fast | Medium | *V* and *I* |
| 51. | Gauss–Newton method (Xiao et al. 2007) | No | Yes | Digital | No | Fast | Low | *V* and *I* |
| 52. | Steepest-descent method (Xiao et al. 2007) | No | Yes | Digital | No | Fast | Medium | *V* and *I* |
| 53. | Analytic method (Rodriguez and Amaratunga 2007) | Yes | No | Both | Yes | Medium | High | *V* and *I* |
| 54. | Azab method (Azab 2008) | Yes | Yes | Digital | Yes | Medium | Low | – |
| 55. | Newton-like extremum seeking control method (Zazo et al. 2012) | No | Yes | Analog | No | Fast | High | *V* |
| 56. | Sinusoidal extremum seeking control method (Leyva and Olalla 2012) | No | Yes | Analog | Yes | Fast | High | *V* and *I* |

**Table 2 continued**

| | MPPT technique | PV array dependence | True MPPT | Analog/ digital | Periodic tuning | Convergence speed | Implementation complexity | Sensors |
|---|---|---|---|---|---|---|---|---|
| 57. | low-power (<1 W) (Lapeña et al. 2010) | Yes | Yes | Analog | No | Fast | Low | *V* |
| 58. | GA-optimized ANN (Kulaksiz and Akkaya 2012) | No | Yes | Digital | Yes | Fast | High | *V*, *T* and *Ir* |
| 59. | Differential evolution (DE) (Kamarzaman and Tan 2014) | No | Yes | Digital | No | Fast | Low | *V* and *I* |
| 60. | Ripple correlation control (Lyden and Haque 2015) | No | No | | No | Fast | Low | – |
| 61. | Chaos search (Lyden and Haque 2015) | No | Yes | | No | Fast | Medium | – |
| 62. | Simulated annealing (Lyden and Haque 2015) | No | Yes | | No | Varies | Low/moderate | – |

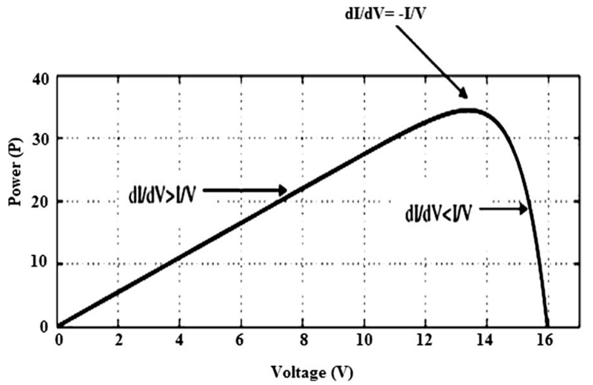

**Fig. 2** Slope of the P–V array power curve (Yadav et al. 2012)

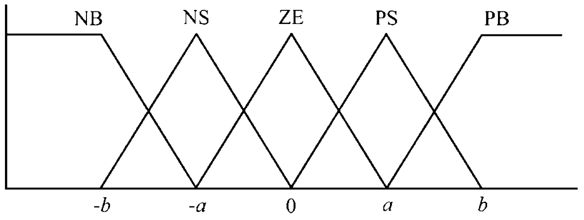

**Fig. 3** Membership function (Esram and Chapman 2007)

choose the suitable system that suits their specific applications. Moreover, we presented a summary of three most common MPPT algorithms.

### Authors' contributions

HJE and TS originated the problem idea. KM collected and demonstrated the idea. RE contributed in writing and reviewing the paper. All authors read and approved the final manuscript.

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### Competing interests

The authors declare that they have no competing interests.

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