A Competitive Study on MPPT Techniques Employed in Solar PV Systems

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Abstract. Integration of maximum power point tracking (MPPT) with photovoltaic (PV) systems is a necessity to track and deliver maximum power available. This paper focuses on comparing the tracking efficiencies of Perturb and Observation method (P&O), Incremental Conductance (IC) and Fuzzy-Logic System based MPPT technique. Change in atmospheric condition such as varying irradiance causes the output power to continuously vary over time. IC as well as P&O based MPPT techniques exhibit poor dynamic responses and so operating points keeps fluctuating. Variation in solar irradiance over a day at constant temperature is given as input to the solar PV module. The algorithm used here implements tracking over the period of a day. All the simulation study are implemented with the use of MATLAB/SIMULINK.

Keywords: Maximum Power Point Tracking, Fuzzy Logic System, Efficiency Tracking, DC-DC Boost Converter

1. Introduction

Non-Conventional sources of energy such as renewables are presently used as alternative paths to generate electricity. Sources of renewable energy include tidal, solar, wind and geothermal energy. With the increasing usage of electricity, the dependency on renewables is also increasing. Among the various available sources, solar energy is undergoing large researches and development. A major advantage of solar energy is that it is scalable. Solar plants can be installed in any area depending on the energy need and so the investment will be limited based on the generation required. One of the major disadvantages of PV energy generation is that the output could exhibit non-linear characteristics due to reasons such as a change in solar radiation pattern, temperature variations, partial shading and nature of the connected load. Implementation of MPPT is necessary as varying nature of solar and wind energy causes fluctuations in the output power. Configuration setup in a PV system can differ with its relation with the battery bank, off-grid and grid connected loads. MPPT is implemented in many ways including direct and indirect methods but these produce varying results and trends based on factors such as hardware configuration, speed of response, ripples present and efficiency [1] [2]. The highest power transfer does vary based on the changes happening in the climatic conditions and load connected [3] [4]. Maximum power point (MPP) is the load characteristic at which the efficiency of the system gets optimized [5]. To keep the power transfer efficiency high, load characteristics keep changing. Any MPPT algorithm aims to find the MPP point and keeps the load characteristic at that point for maximum power tracking [6]. Voltage and current control in bidirectional power flow with grid-connected PV system is analysed and studied [7]. Different PV
arrays connected will lead to mismatching conditions and this will directly affect the MPP. MPPT techniques used for analysis includes Centralized MPPT (CMPPT) and reconfiguration MPPT (RMPPT) [8].

The hill climbing method or commonly known as P&O is a widely implemented strategy due to its simple algorithm and easy integration in PV systems [9][10]. Fuzzy logic-based MPPT control can achieve higher energy conversion efficiency by adopting intelligent control techniques. This paper aims to make a comparative study on the tracking efficiency of P&O, IC and fuzzy-logic based MPPT techniques by using Matlab/Simulink software.

2. SYSTEM DESIGN AND MODELLING

2.1. Modelling of PV Array
Base component of solar module is a PV cell. These are arranged in various combinations to form a module. The equivalent circuit of a cell is presented in figure 1.

![Equivalent Model of a cell](image)

These individual cells are connected in different arrangements to produce the required level of output voltage and power. Series resistance (Rs) of the cell is wired in series with a parallel combination of photovoltaic current (Iph) which depends upon the cell temperature and solar radiation, diode (D) and shunt resistance (Rsh).Ipv and Vpv represent the current and voltage generated from PV cell respectively. To show the non-linear characteristics of the system under varying operating conditions, 1Soltech 1STH-215W panel comprising of 4 modules each having 60 cells each are connected with two in series and other two in parallel was chosen for study. The module specifications of the solar panel under standard conditions is as seen in Table 1.

| Parameter                | Symbol | Value |
|--------------------------|--------|-------|
| Output Power             | Rp     | 215 W |
| Voltage at open circuit  | Vc     | 37.3 V|
| Current at short circuit | Is     | 8.66 A|
| Voltage at MPP           | Vmp    | 30.7 V|
| Current at MPP           | Imp    | 8.15 A|
| Cells in series          | Ns     | 60    |
| Cells in parallel        | Np     | 0     |
Characteristic curves are plotted using Simulink tool for the chosen solar panel with varying conditions in atmosphere. The variation of output is presented in figure 2.

![I-V and P-V Curves](image)

**Figure 2. I-V and P-V Curves**

PV array exhibit varying performance characteristics throughout its operation based on the change in operating conditions during a particular time and this causes a change in the output power.

MPPT is a requisite to track that the PV array operates at peak power point under varying atmospheric conditions. The system efficiency is improved as MPPT repeatedly tracks the voltage at which maximum power is generated by the PV array and ensures that the system continues to operate at this point throughout. Many MPPT algorithms have been studied in literature each having its advantages. The main units of an MPPT system are the power circuit (converter) and the MPPT control algorithm as shown in figure 3.

![Block Representation of Tracking System](image)

**Figure 3. Block Representation of Tracking System**

2.2. **DC to DC Boost converter design**

MPP is followed up between a photovoltaic panel and load by interfacing it with DC-DC converters. To extract maximum power from a PV panel the load has to match with the current and voltage from the panel. This power converter steps us the voltage output of a system to desired level. Design components of a converter include inductors, input and output capacitors, diode, and an IGBT switch to which the gate pulse is provided. By controlling the switching operation duty ratio is varied and the
Output voltage is controlled. In equation (1) the conversion ratio at steady state for a boost converter is presented.

\[ V_o = V_i \div (1 - D) \] (1)

The converter output voltage is tracked with respect change in input. Duty cycle is used in the system for the purpose of tracking. Duty cycle is incremented or decremented to provide gate pulse to switch. Equation (2) shows input and output voltage relation.

\[ V_i = (1 - D) \ast V_o \] (2)

The change in operating conditions causes variation in input voltage and duty ratio is adjusted using equation (3).

\[ \Delta V_i = \Delta D \ast V_o \] (3)

Where \( \Delta V_i \) and \( \Delta D \) are variation of output voltage and converter duty variations. To minimize the possible voltage variations around the MPP the duty ratio step change is adjusted. The initial value of \( \Delta D \) is chosen as 0.001. The capacitance and inductance value are designed based on the input and output voltage parameters with equations (4) and (5).

\[ L = \frac{V_i(V_o - V_i)}{\Delta I \ast F_S \ast V_o} \] (4)

\[ C = \frac{I_o + D}{F_S \ast \Delta V_o} \] (5)

Design parameters and its values are presented in Table 2

| Design Specification     | Notation | Value |
|--------------------------|----------|-------|
| Input Side Voltage       | Vi       | 60 V  |
| Output Side Voltage      | Vo       | 120 V |
| Load Resistance          | R-load   | 20 Ω  |
| Capacitance              | C        | 100 µF|
| Inductance               | L        | 2000µHz|
| Switching Frequency      | FS       | 5 KHz |

A Boost or step-up converter is chosen as the power converter due to its advantage of fast response and fewer components needed, which will also reduce implementation cost.

3. Comparison of MPPT Techniques

MPPT module integrated with the PV system makes it possible for the load connected to the system to operate at maximum efficiency by effectively tracking under varying operational conditions. Different MPPT techniques employ different tracking algorithms [11] [12]. Direct and indirect approaches are usually employed for tracking purposes. Three of those methods are discussed in this section.

3.1. Hill Climbing Method (P&O)

The hill-climbing method or commonly known as the P and O algorithm is a direct method used to implement MPPT. The main aim of the P&O method is to track and maintain the voltage (\( V_{mpp} \)) at which solar power produces maximum power [12]. The algorithm used is presented in figure 4.
The algorithm used in this paper is based on incrementing and decrementing the duty ratio based on the difference in power calculated from the instantaneous panel voltage and current and the previous value of power. The duty ratio is incremented if the difference between powers are is positive and decremented if negative until the power reaches a maximum point or voltage is at $V_{mpp}$. Once the MPP or $V_{mpp}$ is reached the systems continuously holds around that point.

3.2. Fuzzy logic method

Fuzzy logic-based MPPT takes into account multivariable considerations and it is a multi-value based approach. The aim of this approach based on fuzzy logic control system is to generate a duty cycle
based on inputs from the PV panel which are the voltage and current. Fuzzy based MPPT technique is a non-linear tracking approach and does not contain mathematical equations [13]. The fuzzy controller simulation design is presented in figure 5.

\[ E(n) = \frac{P(n)_{pv} - P(n-1)_{pv}}{V(n)_{pv} - V(n-1)_{pv}} \]  
\[ CE(n) = E(n) - E(n - 1) \]

The inputs \( E(n) \) shows whether the PV operating point at an instant of time is on the right or left of MPP while the other input \( CE(n) \) represents the direction of movement required to reach the MPP [13]. An algorithm relating to fuzzy based MPPT is presented as a flow chart in figure 6.

3.2.1. Fuzzification
Fuzzy membership functions are used in process of fuzzification to convert actual inputs to the system (CE and E) into linguistic fuzzy sets. Member functions are user-defined linguistic variable like Negative Large (NL), Zero (ZE), and Positive Small (PS).
3.2.2 Rule Base and Inference
The rule base is a set of if then statements which sets the rules and contains information for controlling the output parameters. It is tabulated based on the experience and operation of system control. Twenty-five rules are defined in the proposed system. This rule base is presented in Table 3.

| E/CE | NL | NS | ZE | PS | PL |
|------|----|----|----|----|----|
| NL   | PS | PL | NL | NL | NS |
| NS   | PS | PS | NS | NS | NS |
| ZE   | ZE | ZE | ZE | ZE | ZE |
| PS   | NS | NS | PS | PS | PS |
| PL   | NS | NL | PL | PL | PS |

Inference engine formulates logical decisions on basis of the rules from the rule base and modifies it into fuzzy based semantic output.

3.2.3 De-fuzzification
The fuzzy based semantic output is modified to a numeric value by forming the union of output resulting from each rule. The de-fuzzification technique used for output duty cycle control is Centre of Area (COA). If Error I is NL and change of error (CE) is zero then Duty (D) will be PL.

3.3. Incremental conductance method
This section discusses the principle and algorithm relating to MPPT using incremental conductance. Variation in MPP is determined by evaluating and comparing incremental conductance and instantaneous conductance. Power delivered will be maximum at the point where incremental conductance is equal to instantaneous conductance [14]. The derivative of PV system conductance is used to determine the operating point for MPP. The output power of solar module is given by \( P = V * I \). MPP occurs when the ratio \( \frac{\partial I}{\partial V} \) is equal to zero. The relation between instantaneous and incremental conductance is derived as shown in equation (8) and equation (9).

\[
\frac{\partial P_{pv}}{\partial V_{pv}} = \frac{\partial (V_{pv}I_{pv})}{\partial V_{pv}} = V_{pv} \frac{\partial I_{pv}}{\partial V_{pv}} + I_{pv} 
\]

\[
\frac{\partial I_{pv}}{\partial V_{pv}} = -\frac{I_{pv}}{V_{pv}}
\]

If \( \frac{\partial V_{pv}}{\partial V_{pv}} = 0 \) and \( \frac{\partial I_{pv}}{\partial V_{pv}} = 0 \) then the operating point shall be at the MPP region. If \( \frac{\partial V_{pv}}{\partial V_{pv}} = 0 \) and \( \frac{\partial I_{pv}}{\partial V_{pv}} > 0 \) which indicates MPP voltage has increased due to rise in irradiance. In this situation voltage is incremented and tracking is done. The algorithm developed using inbuilt blocks in Matlab is presented in figure 7.

![IC Algorithm Implementation Model](image)
The flowchart of IC algorithm used in the comparative study is presented in figure 8.

**Figure 8. Flow Diagram of IC Algorithm**

4. Results and Discussion

All the MPPT tracking techniques explained in section III were simulated with varying irradiance over the period of a day and constant temperature as inputs to the selected PV panel. The varying irradiance pattern was generated using a signal generator block. Perturb and Observe, Fuzzy Logic Control and, Incremental Conductance MPPT techniques were simulated and analysed to compare the tracking efficiencies. The output of the same is being discussed in this section. Figure 9 shows the pattern of variation in irradiance. The curve is plotted using a signal builder block in Simulink. It depicts a rough pattern of change in irradiance over a day.

**Figure 9. Variation of solar irradiance used in simulation**
Simulation results of different tracking methods are discussed in this section at constant temperature (25°C) and under conditions of varying irradiance.

Figure 10. Voltage at Input and Output of MPPT technique employing P&O Method

Figure 11. Current at Input and Output of MPPT System employing P&O Method

Figure 12. Power at Input and Output of MPPT System employing P&O Method
Figure 13. Voltage at Input and Output of MPPT System employing IC algorithm

Figure 14. Current at Input and Output of MPPT System employing IC algorithm

Figure 15. Power at Input and Output of MPPT System employing IC algorithm
Figures 10 to 18 represent all the major outputs relating to the MPPT techniques used for comparison. There is some amount of ripples in voltage and current outputs of P&O and IC algorithm as seen in figures 11, 13 and 15 due to continuous change in irradiance at the input side. Even though ripples are present, the output power of all the MPPT methods tracks the input power from panel which is proved in figures 12, 15 and 18. The output and input power of each of the MPPT techniques under consideration is given as input to mean efficiency block developed using Simulink and then mean efficiency is plotted. Mean efficiencies of all the MPPT techniques under consideration were plotted using Simulink. These plots are presented in figures 19, 20 and 21.
Figure 19. Mean Efficiency for MPPT using P&O Method

Figure 20. Mean Efficiency for MPPT using IC Method

Figure 21. Mean Efficiency for MPPT using Fuzzy Method

P&O based tracking shows a high efficiency of about 99% as seen in figure19. The tracking efficiencies are high even with continuous changes in irradiance. IC method showed low tracking efficiency at the beginning but as we can see from figure20 the efficiency reaches almost 97 % and then continues to exhibit the same tracking efficiency from then on. From the mean efficiency plot in figure 21, it is clear that the Fuzzy based MPPT approach has a lower tracking speed and efficiency.
This method showed variations in tracking along the mean efficiency curve and the efficiency value is nearly 96%. The reason for having such high tracking efficiencies is because only irradiance change is considered in this study while values of temperature variations and other factors are kept in to match with that of standard test conditions. Ripples are present in the plots due to slow dynamic response and lack of fine-tuning in response to varying atmospheric conditions.

4. Conclusion

This paper presents a comparison of three different MPPT techniques used for tracking the maximum power point of a PV system at varying solar irradiance and a constant temperature. Designing the system and the corresponding algorithms were implemented using Matlab/Simulink for analysing the tracking performance. Graphical outputs demonstrate the mean tracking efficiencies of P&O, IC and Fuzzy-Logic based MPPT techniques. Fine-tuning of control parameters is necessary to reduce the ripples at the input and output of the system.

References

[1] S. Selvakumar, M. Madhusmita, C. Koodalsamy, S. P. Simon and Y. R. Sood, High-Speed Maximum Power Point Tracking Module for PV Systems, IEEE Transactions on Industrial Electronics, vol. 66, no. 2, Feb. 2019, pp. 1119-1129
[2] S. Pant and R. P. Saini, Comparative Study of MPPT Techniques for Solar Photovoltaic System, International Conference on Electrical, Electronics and Computer Engineering (UPCON), 2019, pp. 1-6
[3] P. T. Pillai, R. S. Sreelakshmi and M. G. Nair, A PV panel model considering temperature and irradiance effect on panel resistances, 2017 International Conference on Technological Advancements in Power and Energy (TAP Energy), 2017, pp. 1-6
[4] P. K. Sahu, M. Manjrekar and R. Bhatt, Maximum power point tracking for solar panel companion inverters, 2017 IEEE 18th Workshop on Control and Modelling for Power Electronics (COMPEL), 2017, pp. 1-7
[5] H. Choutapalli, Bharath K. R., and Dr. P. Kanakasabapathy, A Review on Advanced MPPT methods for SPV system under Partial Shaded Conditions, International Conference on Control, Power, Communication and Computing Technologies (ICCP CCT), 2018
[6] G. Prakash and S. Pradeepa, Design and Modeling of MPPT for Solar Based Power Source, 2018 4th International Conference on Electrical Energy Systems (ICEES), 2018, pp. 624-629
[7] O. Ibrahim, N. Z. Yahaya, N. Saad and M. W. Umar, Matlab/Simulink model of solar PV array with perturb and observe MPPT for maximising PV array efficiency, 2015 IEEE Conference on Energy Conversion (CENCON), 2015, pp. 254-258
[8] Baba, S, Armstrong, M. and Pickert, V. (2014) Overview of Maximum Power Point Tracking Control Methods for PV Systems. Journal of Power and Energy Engineering, 2, pp. 59-72
[9] P. K. Vineeth Kumar and C.A. Asha, An efficient solar power converter with high MPPT tracking accuracy for rural electrification, International Conference on Computation of Power, Energy, Information and Communication, ICCPEIC 2014, pp. 383-389
[10] M. A. G. de Brito, L. Galotto, L. P. Sampaio, G. d. A. e Melo and C. A. Canesin, Evaluation of the Main MPPT Techniques for Photovoltaic Applications, IEEE Transactions on Industrial Electronics, vol. 60, no. 3, March 2013, pp. 1156-1167
[11] K. Poojitha, L. Ashwini, B. S. Anjali and J. Ramprabhakar, Solar tracker using Maximum Power Point Tracking Algorithm, 2019 International Conference on Intelligent Computing and Control Systems (ICCS), 2019, pp. 1528-1531
[12] D. S. Saravanan and Anand Rajendran, Solar PV System for Energy Conservation Incorporating an MPPT Based on Computational Intelligent Techniques Supplying Brushless DC Motor Drive, Circuits and Systems, vol. 7, no. 8, 2016, pp. 1635-1652
[13] S. Samal, P. K. Barik and S. K. Sahu, Extraction of maximum power from a solar PV system using fuzzy controller based MPPT technique, *Technologies for Smart-City Energy Security and Power (ICSESP)*, 2018, pp. 1-6

[14] Abdulkadir, M. et al. A new approach of modelling, simulation of mppt for photovoltaic system in simulink model, *ARPN journal of engineering and applied sciences*, vol. 8 (2013): 488-494.