

Application of MPPT Algorithm Based on Lyapunov Stability for Photovoltaic Systems

Heroual Samira¹, Belabbas Belkacem¹, Allaoui Tayeb¹, Meraouah Mustapha¹, Chibani Houaria¹, Slimani Amira²

¹Electrical Engineering Department, Ibn Khaldoun University
Tiaret, Algeria

²Electrical Engineering Laboratory of Biskra LGEB University of Biskra
Biskra, Algeria

*Corresponding author; Email: samira.heroual@univ-tiaret.dz

Article Info

Article history:

Received , 12/02/2024
Revised , 15/09/2024
Accepted , 20/11/2024

Keywords:

Maximum power point tracking
backstepping controller
perturb and observe

ABSTRACT

Maximum power point tracking (MPPT) plays a vital role in photovoltaic (PV) systems to utilize PV energy efficiently given the high cost and low efficiency of a PV system, it must run at maximum power point (MPP), which varies with load fluctuations and weather conditions. This article describes the design comparison between the fuzzy logic controller and a non-linear backstepping controller for a DC-DC converter used to extract the greatest power from photovoltaic systems (PV). The converter's duty cycle regulation accomplishes this. The backstepping control is utilized to create the controller. The perturb and observe approach supplies the backstepping controller with the output reference voltage PV. The result confirms the robustness of the backstepping controller with good performance in decreasing oscillations in the solar panels, tracking maximum power under irradiance variations, and achieving MPPT.

I. Introduction

The energy consumption of every country is increasing in proportion to the growth of its population and its economy. Countries are increasingly relying on energy from renewable sources such as solar, wind, tidal, and biomass, to name but a few, due to the depletion of fossil fuels and their negative impact on the environment. Unlike other means, harnessing energy from the sun has become easier and more affordable [1]. For that purpose, solar photovoltaic (PV) technology has huge, proven potential [2].

Photovoltaic generation is becoming increasingly important as a renewable energy source due to advantages such as the absence of fuel costs, low maintenance, and the absence of noise and noise and wear due to the absence of moving parts [3]. However, two major factors limit the implementation of photovoltaic systems: high cost and low efficiency in energy conversion. In photovoltaic systems, the PV module accounts for 57% of the total cost of the system, and the storage system accounts for 30% of the cost. Other system components, such as inverters and MPP trackers contribute only 7% (Hua and Lin, 2003)[2],[4].

To increase the power output, PV modules are therefore connected in series-parallel combinations. Here, power electronic interfaces or power optimizers such as DC-DC converters are used to increase the DC output voltage of PV arrays to voltage levels required for utility load applications [5]. Furthermore, DC output voltages vary due to factors such as varying solar irradiance, ambient temperature, shading, or even panel cleanliness [1], [3]. This

leads to the need for an efficient DC-DC boost converter that can efficiently regulate the low and unstable voltage output of the PV array [6]. Photovoltaic systems are designed to continually extract the maximum power from the modules, independent of load voltage or weather, to maximize the ratio between output power and installation cost. Systems called maximum power point trackers, or MPP-trackers for short, run PV modules to maximize power. An MPP tracker is an electronic system that modifies the electrical operating point of the modules so that they can provide maximum power, as opposed to a mechanical tracking system that "physically moves" the modules to point more directly at the sun. It is compatible with mechanical tracking systems; however, they work with whole separate systems, [4][7]. The main purpose of the utilization maximum power point trackers (MPPT) algorithm is to adjust the effective working point of PV panels on their maximum power [2].

In previous studies [5],[6] have presented the mathematical modelling of a PV and its design. In the present scenario, A single-diode model of the solar cell is used, following the mathematical model implemented in Villalva et al. The literature has a variety of MPPT techniques for calculating the MPP of PV panels that use various dc/dc converter topologies coupled to PV modules as presented in [7] but it suffers from oscillation and decreases in term performance.

A sophisticated control circuit is required for a fuzzy logic technique this approaches have drawbacks, including high costs, complexity, and instability. In this research, we propose a novel controller called Backstepping Controller based on MPPT type perturb and observe for extracting the maximum power of solar panels and ensuring the efficient transfer of energy from the photovoltaic panels to the load under various scenarios of irradiation. In Section 2, a model of the solar PV system. The design of the DC-DC controller is depicted in Section 3. An overview of various MPPT tracking techniques are demonstrated in Section 4. An overall discussion about the discussed methods after reviewing them is also detailed in Section 4. Finally, the paper concludes in Section 5.

II. System Description

Figure 1 shows the photovoltaic (PV) system distinguished by integrating a Maximum Power Point Tracking (MPPT) mechanism and a DC-DC converter type boost, which function together to improve energy conversion and usage efficiency. Photovoltaic panels are the major energy source, converting solar energy into direct current (DC). These panels generate voltage and current that change with solar intensity and environmental conditions. To ensure peak performance, an MPPT controller continually monitors the voltage and current outputs of the panels. The MPPT algorithm identifies the most economical operating point and creates a control signal, called the duty cycle, which is sent to the DC-DC converter to control it. This converter, a power electronic device, modifies the voltage and current output from the PV panels by the MPPT signal, thereby facilitating maximum power extraction and satisfying the load's need for power [6],[8].

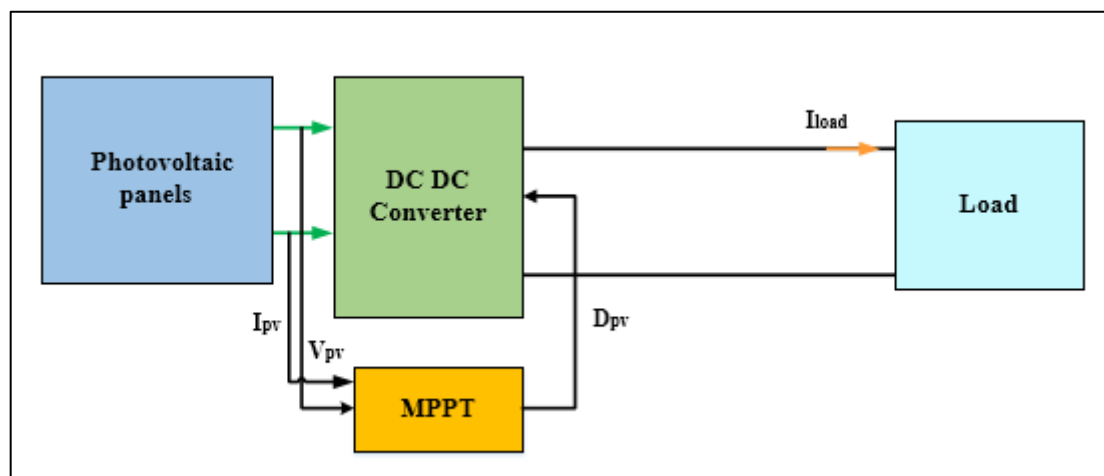


Figure 1: schematic diagram of the stand-alone photovoltaic system [9].

III. Modeling of Photovoltaic System

The existing literature presents various models for representing a photovoltaic (PV) cell, with the single-diode model being the most widely utilized. This model is favoured for its balance of accuracy and simplicity; Figure 2 illustrates the equivalent circuit of the single diode model for the PV cell. In this representation, the PV cell is depicted as a current generator, which is analogous to a current source in parallel with a diode. Additionally, this diagram incorporates two resistors. These equations below can be used to display the PV panel's mathematical model

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad (1)$$

$$I_{ph} = [I_{rs} + K_i(T - T_r)] \cdot \frac{G}{G_r} \quad (2)$$

$$I_{pv} = I_{ph} - I_{sat} \left(e^{\frac{q(V_{pv} + R_s I_{pv})}{n \cdot k \cdot T \cdot N_s}} - 1 \right) - N_p \left(\frac{q(V_{pv} + R_s I_{pv})}{R_s \cdot R_{sh}} \right) \quad (3)$$

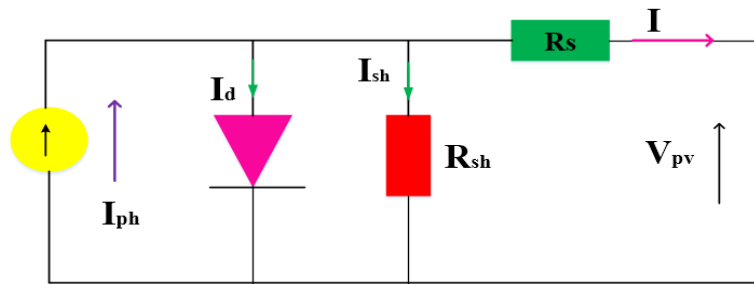


Figure 2 : The equivalent circuit of the PV panel [5].

The Boost Converter is a DC-DC power converter that increases the input voltage to produce a greater output voltage and serves as an adapter between the source and the load [2]. It usually comprises a power switch (a transistor, MOSFET, or IGBT), an inductor, a diode, and a capacitor as depicted in Figure 3. The mathematical model of a Boost Converter includes equations describing the relationships between input voltage, output voltage, inductor current, and duty cycle (control signal). Boost converters operate in two phases based on their condition [8].

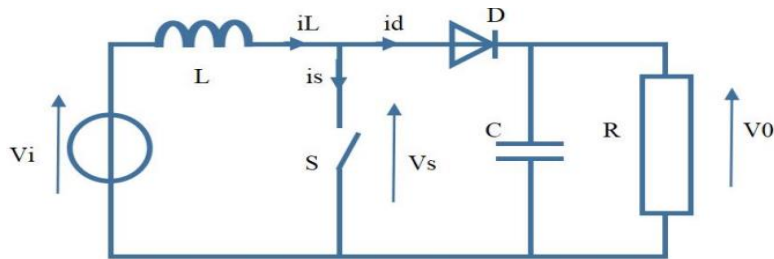


Figure 3: Design of boost converter [8].

- **First period**

When the switch is closed as depicted in Figure 4, the current flowing through the inductor will rise, resulting in the storage of energy as magnetic energy. At this time, the diode is in a reverse-biased state.

$$\frac{di_L}{dt} = \frac{V_i}{L} \quad (4)$$

$$\frac{dV_c}{dt} = \frac{1}{C} \left(\frac{V_o}{R} \right)$$

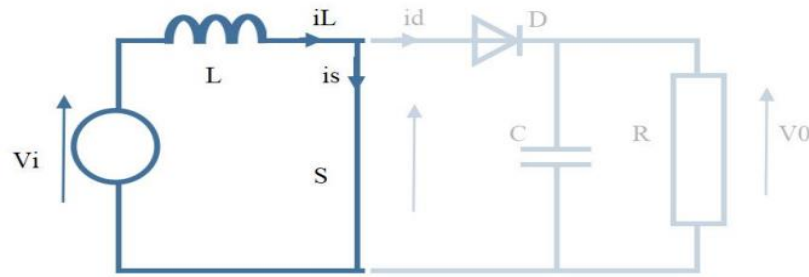


Figure 4: Boost Converter (ON state).

- **Second period**

When the switch is opened, the diode becomes forward-biased, allowing the energy stored in the inductor to be transferred to the capacitor.

$$\begin{aligned} di_L &= \frac{1}{L}(V_i - V_o) \\ \frac{dV_o}{dt} &= \frac{1}{C}\left(i_L - \frac{V_o}{R}\right) \end{aligned} \quad (5)$$

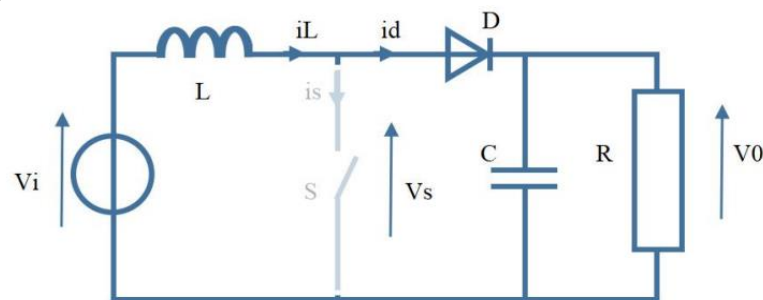


Figure 5: Boost Converter (Off state).

Determining the inductor specifications for a boost converter is a vital aspect of electronic design. While datasheets usually offer inductor values within a defined range, engineers often need to estimate these values when such information is lacking [8],[9]. This estimation process takes into account several critical parameters, including the target output voltage, switching frequency, duty cycle, and inductor current ripple. Precise estimation of the inductor is crucial for ensuring the converter's stability and efficiency, allowing it to function within the desired performance parameters [3],[9].

- The expression of the inductance [9]:

$$L = \frac{DV_{in}}{f\Delta_i} \quad (6)$$

- The expression of the capacity:

$$C = \frac{DV_{out}}{f\Delta_v R} \quad (7)$$

the waveforms of voltage and inductor current in the operation of boost converter shown in Figure 6 :

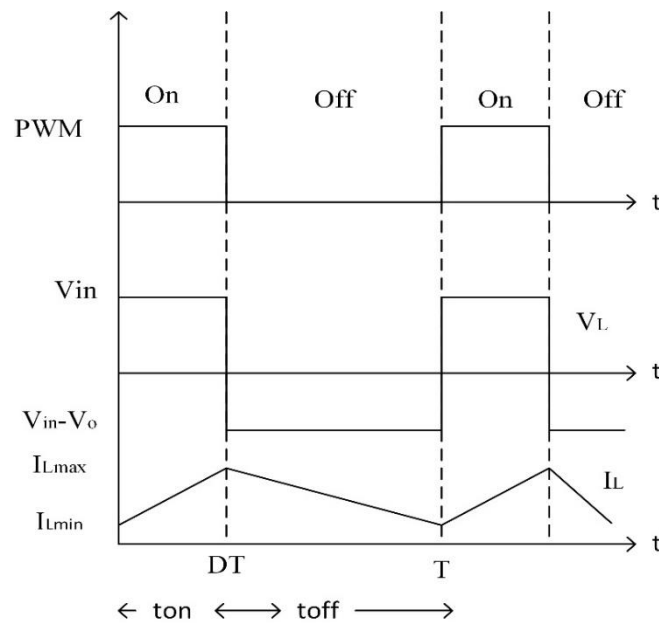


Figure 6: The inductor voltage and current waveform of the boost converter.

IV. Maximum Power Point Tracker

A maximum power point (MPPT) is utilized for obtaining the maximum power from the solar panel and transferring maximum power from the PV module to the load. To transmit the greatest amount of power from the PV module to the load, a DC-to-DC converter acts as an interface between the load and the module. [1], [5],[10] In this paper we used two type of MPPT:

- MPPT Fuzzy logic.
- MPPT Perturb and Observe (P&O).

IV.1 The Proposed MPPT Fuzzy Logic Base Method

There are several uses for fuzzy logic controllers in renewable energy applications. Over the past ten years, fuzzy logic controllers have become increasingly popular due to their ease of use, ability to manage nonlinearity, deal with imprecise inputs, and lack of necessity for a correct mathematical model [10]. The maximum power that the PV modules can produce in response to varying weather conditions may be obtained by using FLC as a controller. The process of FLC

can be classified into three stages: Fuzzification, rule evaluation, and Defuzzification [3],[7] as shown in Figure 7.

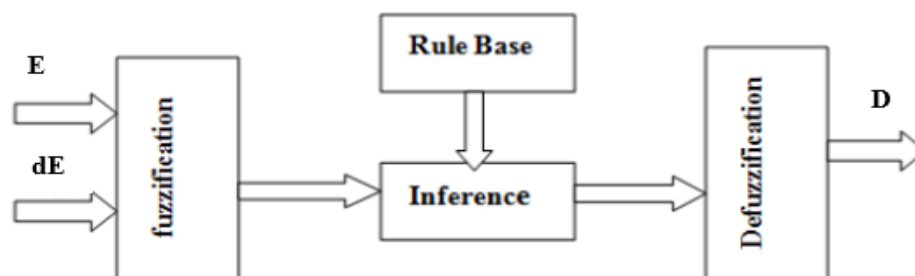


Figure 7. Block diagram of Fuzzy Logic Controller

- *Fuzzification*: Fuzzification aims to translate input signals to prescribed field values in a proportional manner, employ colloquial variation to express physical quantities and assess the relative attribution of language values.
- *Fuzzy inference*: The fuzzy inference process is crucial to the fuzzy control method, simulating human fuzzy thinking [11]. Fuzzy logic and inference laws determine fuzzy control actions. Figure 9 depicts the fuzzy control rule for a signal with two inputs and one output.
- *De-fuzzification*: This technique converts fuzzy outputs to crisp outputs based on specified fuzzy sets and membership degrees.

Since fuzzy logic controllers are resilient, rather easy to develop, and don't require precise model knowledge, they have been used to track the maximum power of photovoltaic systems [5]. This research proposes a novel FLC-based approach to track the PV module's maximum power under varying weather circumstances.

The theoretical design of the rules is based on the fact that if the change in the voltage causes the power to increase, the moving of the next change is kept in the same direction otherwise the next change is reversed. After the theoretical design, all the MFs and the rules were adjusted by trial and error to obtain the desired performance [9].

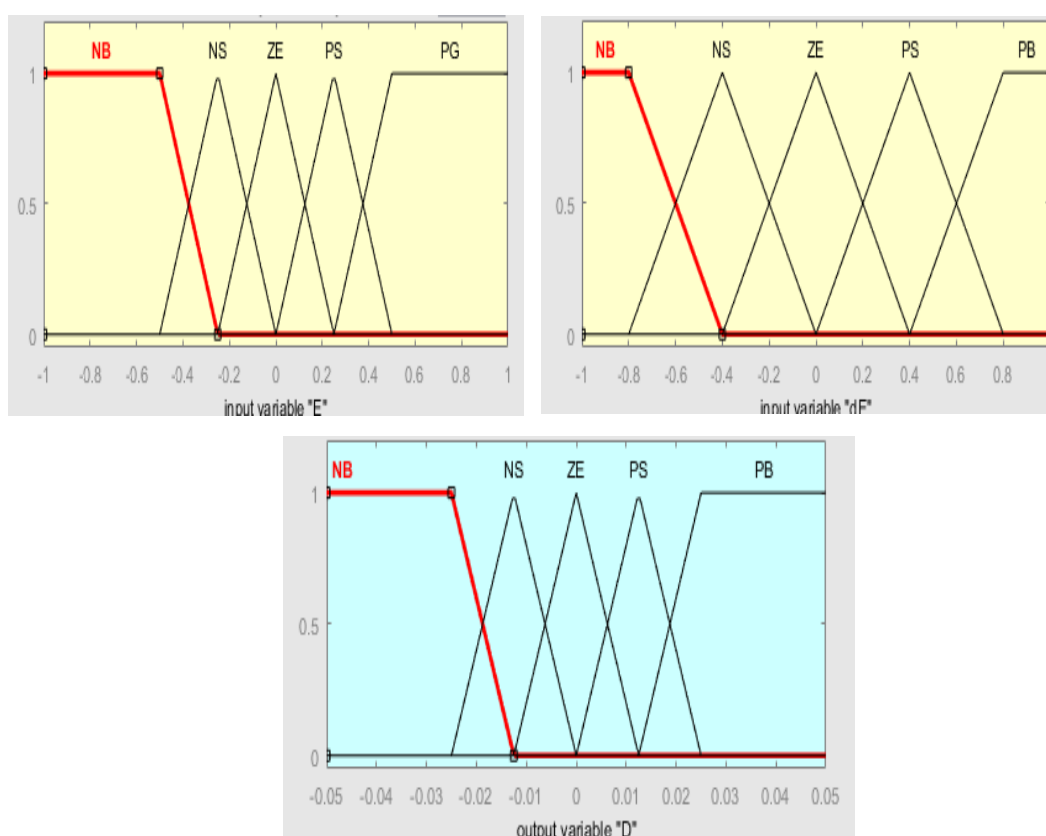


Figure 8: The Membership function of the input variable (E), (dE),(D).

The fuzzy rule editor is shown in Figure 9, in which rules are selected according to user visualizing. The membership functions are selected by taking account the system limits.

The Limitation of Fuzzy logic : One of the inputs of the fuzzy controller is the change of error, which requires a differentiation operation that increases the complexity of the calculations and can generate errors when measuring small powers that are sensitive to noise and more oscillation with less performance [4],[10].

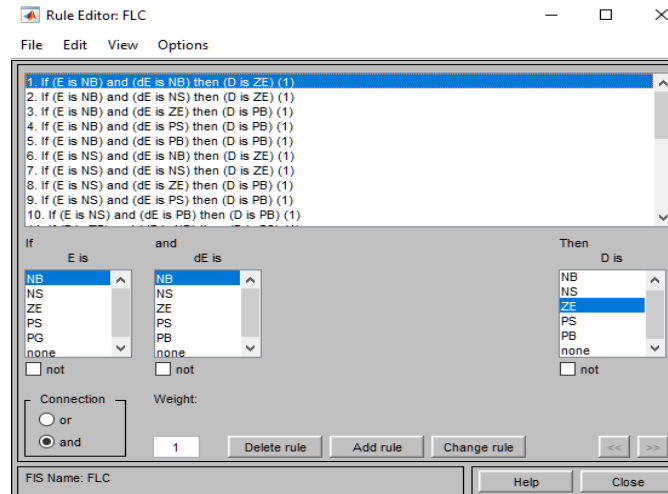


Figure 9. Two-inputs, single-output fuzzy control rules.

IV.2 The Proposed Backstepping Controller Based On Perturb And Observe (P&O)

The Backstepping controller, a synthesis of the nonlinear controller described in this section, employs the dynamics of the converter to drive the photovoltaic system to the reference point after receiving a reference voltage from the perturb and observe algorithm as depicted in Figure [3], [7].

Using the integral backstepping approach, created using the Lyapunov theory [23], we can achieve the maximum power of the photovoltaic power board for various weather conditions. This work proposes the MPPT controller based on the backstepping approach. The panel's output voltage needs to be controlled and converge to the V_{pv_ref} value provided by the (P&O) MPPT controller, as shown in Figure 11 [8].

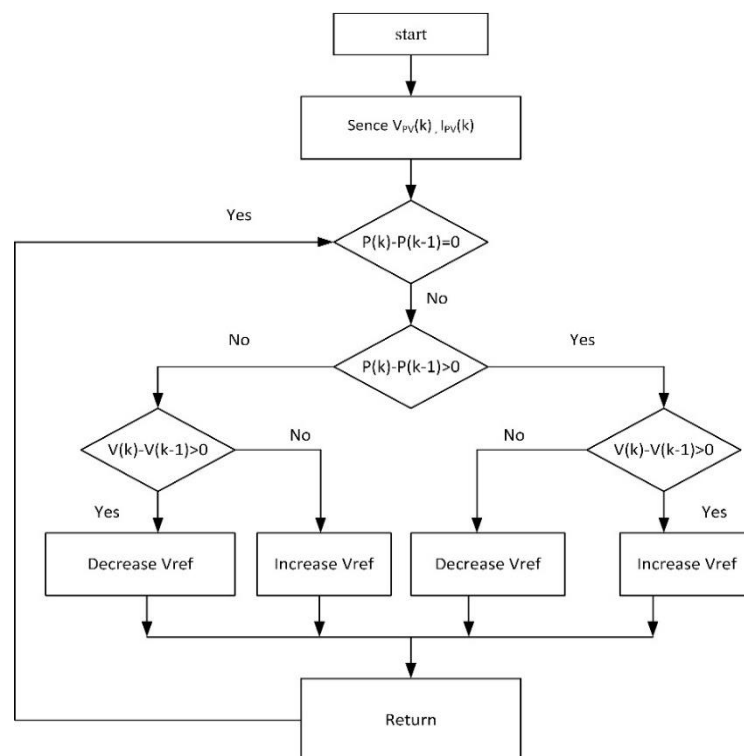


Figure 10 : MPPT Perturb and observe (P&O).

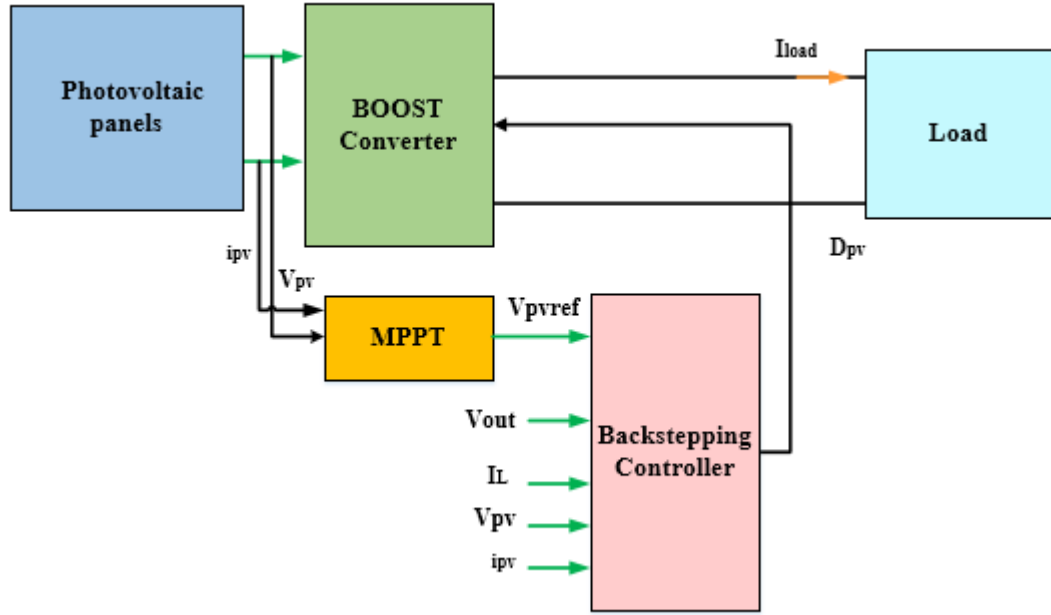


Figure 11: Control Scheme with Backstepping Controller using MPPT (P&O) Algorithm [4].

The dynamic equations of the converter are derived from the inductance current and the voltage of the photovoltaic generator, where the state model is [9]:

$$\begin{cases} \dot{x}_1 = \frac{1}{C_1} i_{pv} - \frac{1}{C_1} x_2 \\ \dot{x}_2 = \frac{1}{L} x_1 - \frac{1}{L} (1 - D) V_{out} \end{cases} \quad (8)$$

Where $[x_1 \ x_2]^T = [V_{pv} \ I_L]^T$

The first error variable is:

$$e_1 = x_1 - V_{pvref} \quad (9)$$

Using the system (4,5), the tracking error derivative is written as follows [7]:

$$\dot{e}_1 = \dot{x}_1 - \dot{V}_{pvref} = \frac{1}{C_1} (i_{pv} - x_2) - \dot{V}_{pvref} \quad (10)$$

The candidate Lyapunov function is considered:

$$V_1(e_1) = V_1 = \frac{1}{2} e_1^2 \quad (11)$$

This function is positive definite, the derivative versus time using equation (6) is:

$$\dot{V}_1 = e_1 \dot{e}_1 = e_1 \left(\frac{1}{C_1} (i_{pv} - x_2) - \dot{V}_{pvref} \right) \quad (12)$$

relevant choice of α_1 allows to write $\dot{e}_1 = -\lambda_1 e_1^2$, $\dot{V}_1$ is negative semi-definite function for that its must be:

$$\alpha_1 = i_{pv} + C_1(\lambda_1 e_1 - \dot{V}_{pvref}) \quad (13)$$

To guarantee the stability of the subsystem, λ_1 is a positive constant that represents a design parameter of the rollover controller.

The second error variable, which is defined as the difference between the state x_2 and its desired value α_1 , is expressed as:

$$e_2 = x_2 - \alpha_1 \quad (14)$$

After deducing the equations of the system in the error space (e_1, e_2) below:

$$\begin{aligned} \dot{e}_1 &= i_{pv} + \frac{1}{C_1}(\alpha_1 + e_2) + \frac{1}{C_1}i_{pv} - \dot{V}_{pvref} \\ \dot{e}_2 &= \frac{1}{L}(x_1 - (1 - D_1)V_{out}) - \dot{\alpha}_1 \end{aligned} \quad (15)$$

The new Lyapunov function:

$$V_2(e_1, e_2) = V_1 + \frac{1}{2}e_2^2 \quad (16)$$

The derivative function is expressed by:

$$\begin{aligned} \dot{V}_2(e_1, e_2) &= \dot{V}_2 \\ \dot{V}_2 &= e_1 \left(\frac{1}{C_1}e_2 - \lambda_1 e_1 \right) + e_2 \left(\frac{1}{L}(x_1 - (1 - D_1)V_{out}) - \dot{\alpha}_1 \right) \\ \dot{V}_2 &= -\lambda_1 e_1^2 + e_2 \left(-\frac{1}{C_1}e_1 + \frac{1}{L}(x_1 - (1 - D_1)V_{out}) - \dot{\alpha}_1 \right) \end{aligned} \quad (17)$$

In this step the command choosing D_1 to obtain the following expression:

$$\left(-\frac{1}{C_1}e_1 + \frac{1}{L}(x_1 - (1 - D_1)V_{out}) - \dot{\alpha}_1 \right) = -\lambda_2 e_2 \quad (18)$$

the backstepping controller produces the expression of command D_1 by this:

$$D_1 = 1 - \frac{1}{V_{out}} \left[x_1 - L\dot{\alpha}_1 - L \left(\frac{1}{C_1}e_1 - \lambda_2 e_2 \right) \right] \quad (19)$$

With $\lambda_2 > 0$ leads to a negative derivative of the Lyapunov function:

$$\dot{V}_2 = -\lambda_1 e_1^2 - \lambda_2 e_2^2 \quad (20)$$

It ensures that the error variables (e_1, e_2) converge asymptotically towards the origin, which implies that x_2 converges asymptotically towards the origin (V_{pvref}), thus allowing the maximum power extraction from the PV system [10].

V. Simulink Result

To test the effectiveness of the proposed Fuzzy MPPT and backstepping MPPT approach based on Lyapunov stability under varying irradiation inputs as illustrated in Figure 12, A photovoltaic system with a DC-DC converter connected to DC load simulation based on SIMULINK/MATLAB is conducted.

Figures 13(a) and (b), show The solar system's voltage and current, and the power of the output DC converter regulated by the fuzzy logic MPPT algorithm is shown in Figure (c).

From 0 to 0.5s the input irradiation $G = 1000 \text{ w/m}^2$ provides a sufficient power $P_{pv} = 40 \text{ kw}$, however, the current and voltage have a large band full of oscillation from perturb and observation, as well as the present power of the photovoltaic system with integral backstepping controller control, are displayed in Figure 14(a), (b), (c), and (d) thus, the current and voltage contain less band of oscillation also for the power under $G = 1000 \text{ w/m}^2$ provide more power equals $P_{pv} = 45 \text{ kw}$, indicates value then P&O this result shows the important and validate the effectiveness of backstepping control to attract the maximum of power.

In instance 1s, the irradiation increases from 1000 to 500, in the first test with Fuzzy MPPT attract power equals 20kw inferior to the power achieved by the Backstepping controller equals 24 kw. Also at 1.5 s the novel backstepping is controlled by perturbing and observed to attract superior of maximum power in a short time of response than MPPT Fuzzy.

The simulation findings, however, show that the MPPT (P&O) control strategy based on a backstepping controller performs noticeably better when the temperature and sun irradiance of the external environment abruptly change. According to simulation research, the suggested controller combination technique performs much better overall than the fuzzy method in terms of quicker reaction times, reduced output power fluctuation, and system stability in the face of quickly shifting weather circumstances. Although the system's effectiveness somewhat declines when the outside weather changes, the tracking speed to identify a new MPP is accurately and successfully increased.

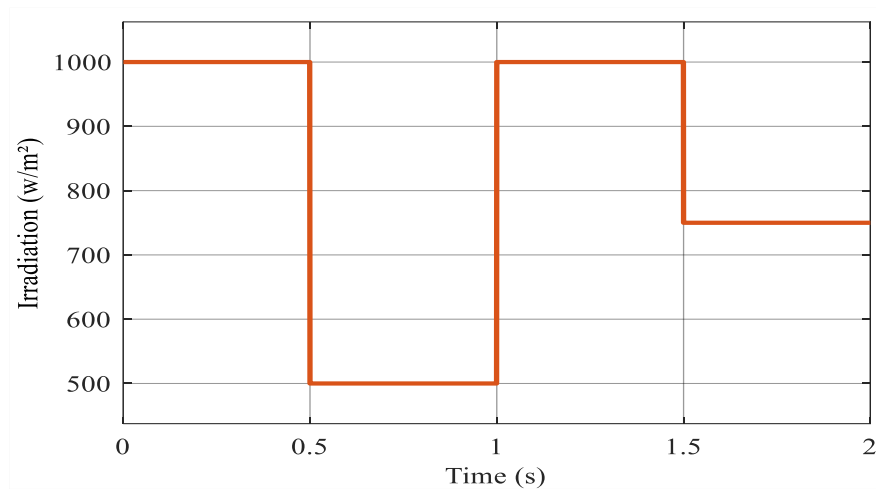


Figure 12: Irradiation profile

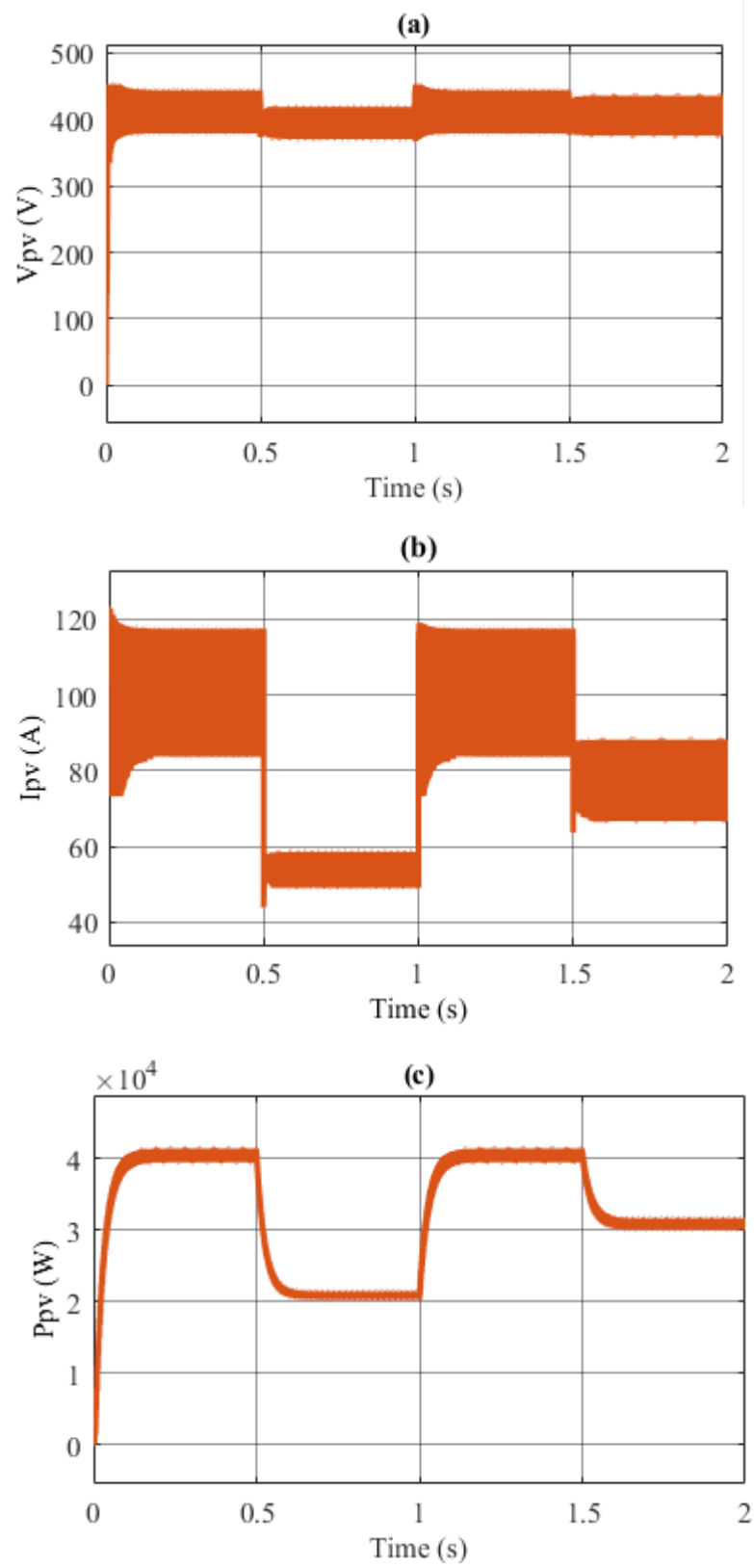


Figure 13 :(a)(b)(c) respectively PV Voltage, current, and the power of the boost output with the fuzzy logic algorithm.

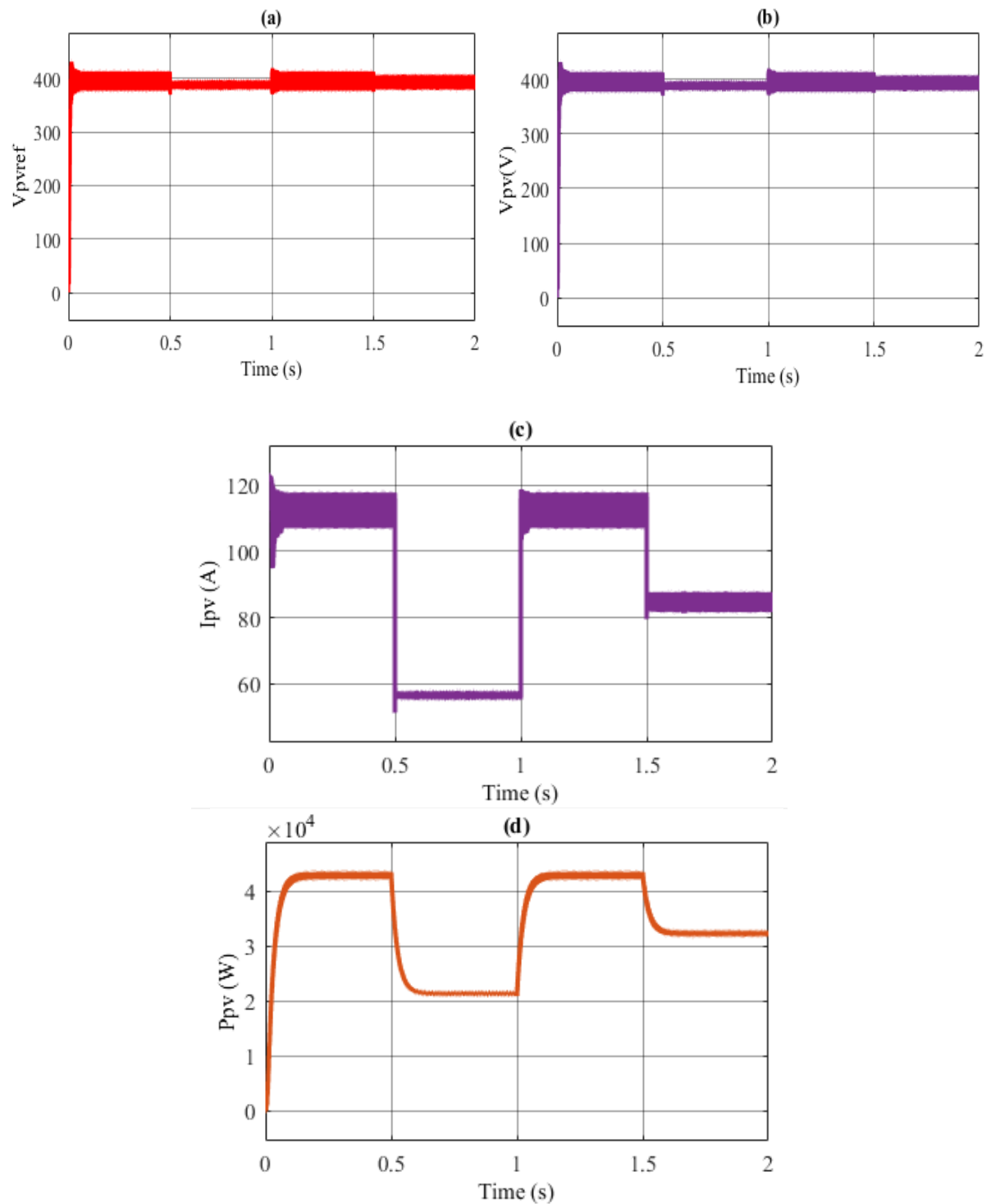


Figure 14: (a)(b)(c) and (d) respectively referential voltage of Perturb and observe, the current, voltage, and power of the boost output with backstepping controller

VI. Conclusion

The energy generated using a photovoltaic (PV) system depends mainly on meteorological factors such as solar radiation using maximum power point tracker systems MPPT adopts several algorithms that control the converter's duty cycle to retrieve the maximum power. This paper deals with a comparative study between two control methods for maximum power point tracking (MPPT) algorithms in photovoltaic (PV) systems. The two MPPT controllers considered in this chapter are the Fuzzy Logic Controller (FLC) and the backstepping control. The input parameters are the voltage and the current, the duty cycle is used to generate the optimal MPP under different operating conditions. The result of the simulations shows the process that MPPT controlling by fuzzy logic has less oscillation with a smaller band and then only a local maximum is reached. And shows the robustness and effectiveness of the developed controller backstepping in terms of rapidity. Thus, maximum power is achieved with excellent precision under changing atmospheric conditions hence improving the efficiency of the PV system.

Reference

- [1] A. Ostadrahimi and Y. Mahmoud, "Curve Computation MPPT Method Based on Simple Modeling of the Photovoltaic Modules," 2020 International Conference on Smart Grids and Energy Systems (SGES), Perth, Australia, 2020, pp. 819-825, doi: 10.1109/SGES51519.2020.00151.
- [2] Z F. Raziya, M. Afnaz, S. Jesudason, I. Ranaweera and H. Walpita, "MPPT Technique Based on Perturb and Observe Method for PV Systems Under Partial Shading Conditions," 2019 Moratuwa Engineering Research Conference (MERCon), Moratuwa, Sri Lanka, 2019, pp. 474-479, doi: 10.1109/MERCon.2019.8818684.
- [3] D. Ghislain and X. Li, "Combination Result of Two MPPT Techniques (Fuzzy Logic and Perturb and Observe Method): Comparison with The Conventional Perturb and Observe Method," 2021 IEEE 5th Conference on Energy Internet and Energy System Integration (EI2), Taiyuan, China, 2021, pp. 4323-4327, doi: 10.1109/EI252483.2021.9712951.
- [4] W. Hayder, D. Sera, E. Ogliari and A. Abid, "Hybrid MPPT method based on Neural Network and Perturb & Observe for PV systems," 2022 19th International Multi-Conference on Systems, Signals & Devices (SSD), Sétif, Algeria, 2022, pp. 1401-1408, doi: 10.1109/SSD54932.2022.9955860..
- [5] M. N. Nazirbhai and R. R. Gajjar, "Comparative Analysis of Perturb & Observe, Incremental Conductance and Fuzzy Logic Based Maximum Power Point Tracking Methods," 2023 IEEE Renewable Energy and Sustainable E-Mobility Conference (RESEM), Bhopal, India, 2023, pp. 1-6, doi: 10.1109/RESEM57584.2023.10236212..
- [6] G. Jayachitra, V. H. A, S. Reddy H.R and R. Sinha, "Fuzzy Based Perturb & Observe MPPT Algorithm for Grid Tied PV System," 2023 IEEE International Conference on Distributed Computing, VLSI, Electrical Circuits and Robotic), Mangalore, India, 2023, pp. 123-127, doi: 10.1109/DISCOVER58830.2023.10316736.
- [7] R. Divya, A. R. Nair, S. Harisankar, V. G. S. Sai and M. G. Nair, "Illustration of Maximum Power Point Tracking of Photovoltaic Array with Boost Converter Via Perturb and Observe Algorithm," 2022 4th Asia Energy and Electrical Engineering Symposium (AEEES), Chengdu, China, 2022, pp. 992-996, doi: 10.1109/AEEES54426.2022.9759789..
- [8] Bjaoui, Marwen, et al. "Practical implementation of the backstepping sliding mode controller MPPT for a PV-storage application." *Energies* 12.18 (2019): 3539.
- [9] ALI, Kamran, KHAN, Laiq, KHAN, Qudrat, et al. Robust integral backstepping based nonlinear MPPT control for a PV system. *Energies*, 2019, vol. 12, no 16, p. 3180..
- [10] B. E. Youcefa, A. Massoum, S. Barkat, and P. Wira, 'Backstepping Predictive Direct Power Control of Grid- Connected Photovoltaic System Considering Power Quality Issue', vol. 14, no. 1, 2020.