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Critical Study of Several MPPT Techniques for Photovoltaic Systems

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Abstract: This paper presents a critical study of Maximum Power Point Tracking (MPPT) techniques for photovoltaic systems. After a brief introduction of the key factors for power extraction of photovoltaic panels, a review of commonly used MPPT techniques is presented and detailed with a holistic approach. Then, a comparison of these techniques is made according to several parameters such as robustness, response time, cost ... In the last part, the advantages and disadvantages of each of the MPPT techniques considered are presented. This article can serve as a quick guide to panel selection and MPPT technique for specific applications.

Keywords: Maximum Power Point Tracking, Boost Converter, Photovoltaic Generator

Introduction

Oil and fossil fuel reserves are falling day after day due to abusive and non-standardized use. Several countries import a large part of their energy needs from abroad. In Morocco, 88.5% of the necessary energy resources are imported from abroad (Wikipedia).

Renewable energies, especially photovoltaics, have had a great advantage in recent decades. This is why many researchers and scientists have conducted a great deal of research to improve and promote this energy (WBG, 2017).

Oil and fossil fuel reserves decline day by day as a result of misuse and non-standard use. Several countries import most of their energy demand from abroad. In Morocco, 88, 5% of essential energy is imported from abroad (Wikipedia). Renewable energy sources, especially photovoltaic power generation, have had great advantages in recent decades. That is why many researchers and scientists have carried out a lot of research to improve and promote this energy (WBG, 2017).

In addition, these energies provide a good opportunity to reduce the impact of global warming. Among them, the process of manufacturing photovoltaic systems has been improving over the last decade and photovoltaic systems have become an interesting solution. Specifically, photovoltaic systems include photovoltaic cell arrays, choppers (mainly DC/DC step-down converters or boosters), MPPT control systems and storage and/or network connectivity devices. Various efforts have been made to improve the efficiency of these systems. However, since solar energy is diffused (approximately 1 kW/m²) and the efficiency of photovoltaic cells is theoretically limited to 19%, it is necessary to strengthen energy transfer. This includes the design of photovoltaic systems and energy management through the search for Maximum Power Points (MPP). MPPT (Faranda and Leva, 2008; Hohm and Ropp, 2000) contains a large number of publications, which are not easy to understand their differences and evaluate their performance.

The main contribution of this paper is to present key research on MPPT technology: first, we introduce photovoltaic theory and emphasize the main parameters of the photovoltaic system to focus on the key elements of MPPT. This article describes some of the most common MPPT technologies and describes their advantages and disadvantages. However, the latest improvements in MPPT studies are not taken into account. Criteria such as efficiency, tracking time, stability, robustness and cost will be introduced to compare the MPPT method chosen. Finally, the simulations will be compared using the Matlab/Simulink® software.

System Configuration

The systems studied in this work include: Solar panels: Electricity generation by applying solar radiation to its surface. Boost DC-DC Converter: It is a power electronics block, its main objective and power adaptation between the photovoltaic panel and the load. MPPT Control System: Due to the information received from the solar panels (current and voltage), the system generates sufficient control to maximize the output power of the photovoltaic genera (Fig. 1).

PV Generator Model

The photovoltaic generator consists of multiple photovoltaic cells. Each solar cell is essentially a p-n node made of a thin semiconductor wafer. With exposure to sunlight, some photons and energy above the semiconductor band generate electron pairs (Ting-Chung and Shen, 2009). The properties of solar panels are given by the formulas (1) and (Fig. 2) (Kim *et al*., 2001):

$$\left[I = I_{sc} - I_0 \left\{ \exp\left[\frac{q\left(V + R_s I\right)}{nkT_k} \right] - 1 \right\} - \frac{V + R_s I}{R_{sh}} \right] \quad (1)$$

- I: Indicates the output current of the solar panel
- V: is the voltage of the solar panel
- R_{sh}: is the battery bypass resistor
- R_s: is the resistance of the battery series
- q: Represents the electronic load (1.60217x10-19 C)
- Isc: is the current generated by light
- I_0: is the reverse saturation current
- N: for non-dimensional coefficient
- K: for Boltzmann constant and T_k for temperatur
- (in° K)

As shown in Fig. 3, Equation (1) has been used to extract the output characteristics of solar cells.

The curve shows that the characteristic operating point of the generator is closely related to temperature changes, solar radiation and load. Each feature has a point with maximum power, photovoltaic generators work perfectly.

DC-DC Converter

The voltage of the PV DC-DC converter battery is always low, so to produce a generator capable of supplying the load, it is necessary to connect several batteries in parallel. Another thing, to raise the voltage to a sufficient level and adapt the input power to the output, you need to use a DC-DC Boost converter (Hohm and Ropp, 2000).

Figure 4 shows the pulse converter diagram.

The output current and voltage of the boost converter are expressed as Equation 2 and 3 (Liu *et al*., 2008; Bennacer *et al*., 2018):

$$Vs = \frac{Vpv}{1 - D} \quad (2)$$

Where:

D: Represent the duty cycle
V_{pv}, I_{pv}: PV generator voltage and current.
V_s, I_s: Boost converter voltage and current.

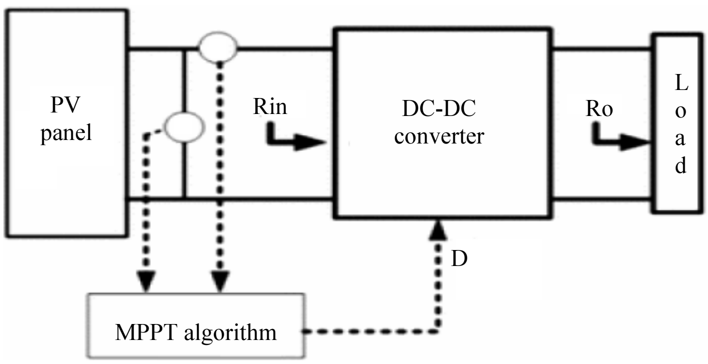


Fig. 1: PV system with MPPT

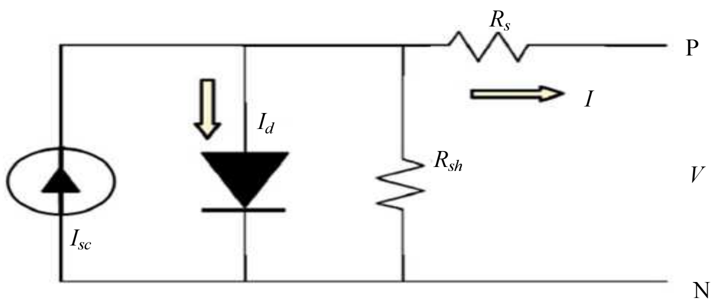


Fig. 2: Equivalent circuit of PV array

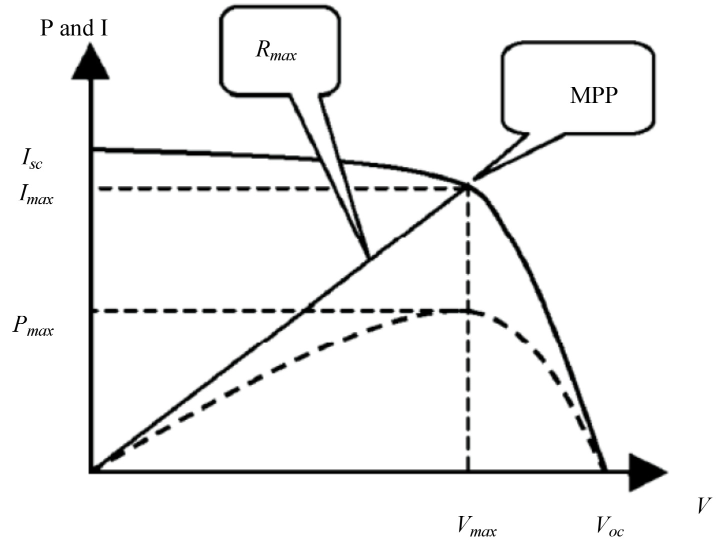


Fig. 3: Output characteristics of a solar cell

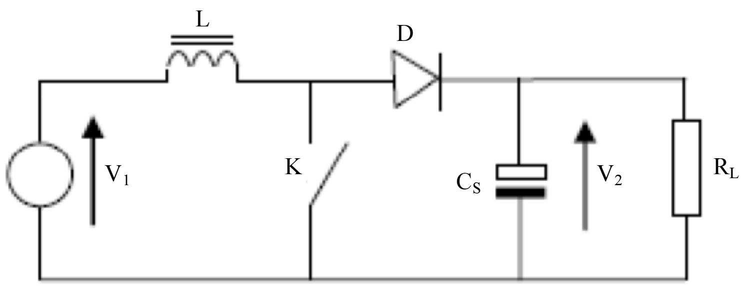


Fig. 4: Equivalent scheme of Boost converter

Presentation of Different MPPT Methods

In this section we will introduce the principle of operation of the MPPT algorithm that we will deal with, namely:

- Incremental Conductance (InC)
- Perturb and observe (P and O)
- Current sweep Technique (CS)
- Ripple correlation control (RCC)
- Fraction Open Circuit Voltage Technique (FOCV)
- Fractional Short Circuit current (FSCI)
- Fuzzy logic technique
- Neural Network technique

To find the operating point of the system, each algorithm has the task of achieving this condition: the power of the mutation system in relation to the voltage must go to zero (Wang *et al*., 2010).

Incremental Conductance

The incremental conductivity method uses the slope of the power characteristics of photovoltaic assemblies for *MPP* processing (Kim *et al*., 2001; Liu *et al*., 2008) Fig. 5. The method is based on the slope of the *PV* generator power curve is less than zero in *MPP* (Mekhilef and Kadir, 2010; Azadeh and Mekhilef, 2010), the output power is less than the *MPP* value is positive and the output power value is less than the *MPP* value is negative:

$$\frac{dP}{dV} = 0,\ at\ MPP$$
$$\frac{dP}{dV} > 0,\ left\ \ of\ MPP$$
$$\frac{dP}{dV} < 0,\ right\ \ of\ MPP$$

By using the power formula, P = V.I, its derivative becomes:

$$dP = V.dI + I.dV \tag{4}$$

When:

$$\frac{dp}{dv} = 0\ \ and\ \ \frac{d(VI)}{dV} = 0; \tag{5}$$

$$I + \frac{VdI}{dV} = 0; \qquad (6)$$

On comparing the Equation (5) and (6):

$$I + \frac{V\Delta I}{\Delta V} = 0; \frac{\Delta I}{\Delta V} = -\frac{I}{V} \qquad (7)$$

So that:

$$\frac{\Delta I}{\Delta V} = -\frac{I}{V}, \text{ at MPP;}$$
$$\frac{\Delta I}{\Delta V} > -\frac{I}{V}, \text{ left of MPP;}$$
$$\frac{\Delta I}{\Delta V} < -\frac{I}{V}, \text{ right of MPP;}$$

Therefore, after MPP, instantaneous conductivity (I/V) is compared with incremental conductivity (ΔI/ΔV). Vref-the reference voltage for the force of photovoltaic arrays to operate. In MPP, Vref = MPP once it reaches MPP, the PV array operation will remain at this point unless it occurs at "I". The algorithm continues MPP by applying decrement or increment to Vref. The size of the increment or decrement determines the rate at which MPP is tracked.

Benefits

Incremental methods allow better MPP tracking. Provides an effective solution in a rapidly changing environment. Disadvantages: This method requires complex control circuits.

Perturb and Observe (P and O)

P and O technique can be achieved by disturbing the reference voltage or current reference signal of solar panels (Wasynczuk, 1983; Hohm and Ropp, 2000; Vikrant, 2005; Abdelsalam *et al*., 2011). Scaling (Van Wyk and Enslin, 1983) modify the disruption of the duty cycle of the power converter, P and O modify the disturbance of the operating voltage of the DC link between the photovoltaic generator and the power converter (Fig. 6). Methods of disturbance and observation at different stages are as follows: 1. 2. Measure the current and voltage and calculate the power. If the power is constant, again start taking new measurements. If the power decreases or increases, the test voltage changes 4. The current changes depending on the direction of the voltage change. First, measure the voltage and PV current and calculate the corresponding power P1. The P2 corresponding to the DC-DC converter is calculated taking into account the small voltage disturbance (ΔV) or duty cycle disturbance (ΔD) in one direction. Then compare P2 with P1. If P2>P1, the disturbance is in the right direction, otherwise it must be reversed. In this way, maximum power points can be identified and the corresponding MPP is calculated. The disturbance changes in the following disturbances are explained in Table 1.

Interference is done this way. The working cycle of the power converter disrupts the current of the photovoltaic generator, thus disrupting the photovoltaic generation.

Disadvantages

The main disadvantage of P and O is occasional deviations from the maximum point of operation, such as cloud dispersion, in rapidly changing atmospheric conditions.

Provides the correct disturbance size for good performance in dynamic response and stable states. Changes quickly, the algorithm gets tracked errors.

Solution

To overcome this problem, you can use a modified adaptive update technique with a variable disturbance step size. When the power supply changes over a wide range (mainly due to environmental changes), the automatic rotation controller changes the size of the disturbance step to meet the rapid response requirements in the transient phase.

Fraction Open Circuit Voltage Technique (FOCV)

This is one of the common and simple ways (Schoeman and Van Wyk, 1982; Enslin *et al*., 1997), where V_{mpp} can be calculated from empirical relationships as follows:

$$V_{MPP} \approx K_1 V_{OC} \qquad (8)$$

The value of K_1 varies between 0.78 and 0.92. K_1 can be calculated by analyzing the photovoltaic system in the range of solar radiation and temperature. The photovoltaic system is turned on for one second at the end of the load to measure V_{oc}_. The power converter should be temporarily suspended due to power loss at each measurement. Figure 7 shows the basic flow chart of FOV technology. The main disadvantage of the current method is that since the determination of V_{MPP} is not continuous, it is not possible to follow *MPP* under irradiated slopes. The place to get to *MPP* is wrong, because the relationship is just an approximation. Measure Voc and then measure V_{MPP} using the formula above. Repeat this V_{oc} process repeats the sampling every few seconds and updates the V_{MPP} value.

Table 1: Perturbation change in power next perturbation

Perturbation	Change in power	Next perturbation
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

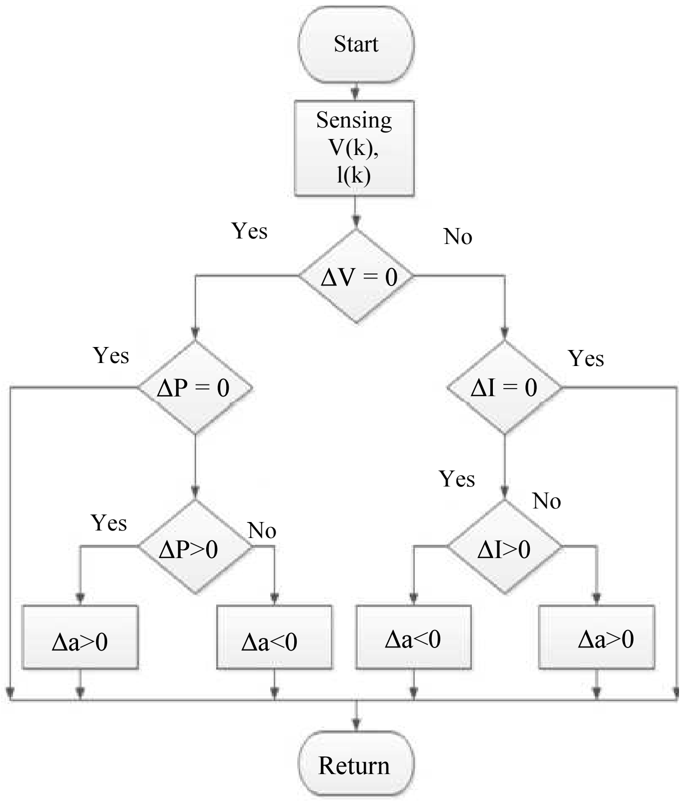


Fig. 5: Block Diagram InC technique

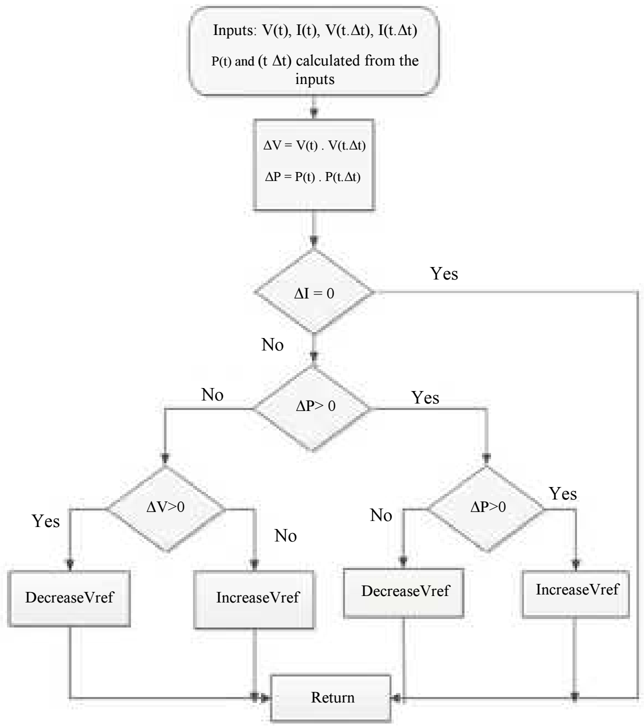


Fig. 6: Block diagram perturb and observe (P and O) technique

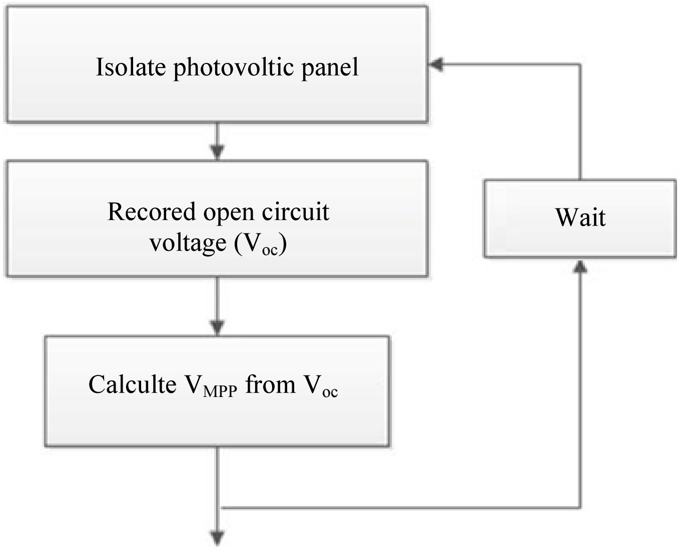


Fig. 7: Block diagram of the open circuit voltage method

Disadvantages: Temporarily lose energy when measuring V_{oc} in an open circuit. The value of K_1 is no longer valid in the presence of a partial shadow of the photovoltaic generator, which leads to complex implementation and increased energy loss.

Fractional Short Circuit current (FSCI)

In FSCI technology (Noguchi *et al.*, 2002; Yuvarajan and Xu, 2003), non-linear VI characteristics of the photovoltaic system were modeled using mathematical equations, taking into account various environmental conditions and degradation levels of the photovoltaic panels. Figure 8 shows the basic FSCI technology flowchart. Based on feature VI, the mathematical relationship between IMPP and ISC is constructed because IMPP is linearly based on Isc through relationships.

On the basis of characteristics VI, a mathematical relation between I_{MPP} and ISC is constructed, since I_{MPP} is linearly dependent on I_{sc} by a relation:

$$I_{MPP} \approx K_{SC} \times I_{SC} \tag{9}$$

Value of the K_{sc} fixed between 0.64 and 0.85

Difficult to Implement

- I_{sc} measurements during operation are problematic
- The cost of the system increases even more due to the increase. A switch must be added to the power converter circuit to periodically short-circuit the photovoltaic generator to measure I_{sc} using current sensors
- When searching for I_{sc}, the power consumption decreases and MPP never fits perfectly

Current Sweep Technique

Current scanning technology uses the waveform of the photovoltaic generator current to acquire and update the I-V characteristics of photovoltaic assemblies at constant intervals (Bodur and Ermis, 1994). The VMPP is then calculated from the characteristic curve with the same interval. The function selected for the current scan waveform is proportional to its derivative, as follows:

$$i(t) = K_1 \left[\frac{di(t)}{dt}\right] \tag{10}$$

At the maximum power point:

$$\frac{dp(t)}{dt} = \frac{d[V(t)i(t)]}{d(t)} = 0$$

$$i(t)\left[\frac{di(t)}{dt}\right] + V(t)\left[\frac{di(t)}{dt}\right] = 0;$$

$$\left[K_1 \frac{dV(t)}{dt} + V(t)\right]\frac{di(t)}{dt} = 0;$$

Solution of Equation (10):

$$i(t) = Ce\frac{t}{K_1} \tag{11}$$

$$i(t) = Ce^{\frac{t}{K_1}}\, i(t) = I_{max}\, e\frac{-t}{\tau}, \tau = -K_1; C = I_{max}.S$$
$$\left[\frac{dp(t)}{di(t)}\right] = V(t) + K_1\left[\frac{dv(t)}{dt}\right] = 0 \tag{12}$$

After calculating VMPP after the current scan, you can use the above equation to check if the MPP has been reached. The current scan takes about 50 milliseconds, which means the available power is lost. At fixed intervals, the reference points are often updated, so if the scale coefficients K_1 and C are selected correctly, the performance is obtained accurately.

Ripple Correlation Control (RCC)

When connected to a power converter, the switching effect of the power converter causes ripple and voltage and current fluctuations to the photovoltaic generator. This leads to the ripple of power of the photovoltaic generator. RCC uses ripple to perform MPPT (Midya *et al*., 1996). RCC correlates the temporal derivative of the photovoltaic power variable P with the temporal derivative of the photovoltaic current I or the voltage V and derives the temporal derivative of the photovoltaic power P from the zero-time variable photovoltaic assembly, thus executing *MPP*:

$$\begin{aligned} & i=\frac{di}{dt},\dot{V}=\frac{dv}{dt},\dot{P}=\frac{dp}{dt} \\ & \frac{dv}{dt}>0(or)\frac{di}{dt}>0 and \frac{dp}{dt}>0, then V<MPP(or) \\ & \frac{dv}{dt}>0(or)\frac{di}{dt}0 and \frac{dp}{dt}<0, then V>MPP, \\ & I>MPP \end{aligned} \quad (13)$$

When connected to a power converter, the switching effect of the power converter causes ripple and fluctuation of voltage and current to the photovoltaic generator. This leads to a corrugation of the power of the photovoltaic generator. RCC uses ripple to perform MPPT (Midya *et al*., 1996). RCC correlates the temporal derivative of PV power variable P over time with the temporal derivative of PV current I or voltage V that varies in time to derive the time derivative of PV power P from the zero time variable PV set, thus performing *MPP*:

$$d(t)=-K_3\int\dot{P}\dot{V}dt \quad (14)$$

$$d(t)=K_3\int\dot{P}\dot{I}dt \quad (15)$$

This service speed monitoring method ensures continuous monitoring of MPP processing, making RCC a real MPP monitor.

Advantages

- Real-time implementation can be achieved by simple and economical analog circuits
- It does not require any prior information on the properties of photovoltaic panels
- MPP monitors accurately and quickly, even at different levels of irradiance

Fuzzy logic based MPPT Technique

Fuzzy logic control is one of the intelligent technologies of MPPT (Salah and Ouali, 2011; Algazar *et al*., 2012). Fig. 9 and Fig. 10 shows the block diagram of the basic fuzzy control.

They offer excellent performance, fast, unsurpassed response and no constant state fluctuations to cope with rapid temperature and irradiance changes. MPPT based on fuzzy logic does not require an accurate photovoltaic model. Fuzzy logic has two inputs and one output. The two input variables are error (e) and the error change (Ce) in the Kth sampling is defined as follows:

$$e(k)=\frac{dp}{dv}(k)-\frac{dp}{dv}(k-1) \quad (16)$$

$$Ce(k)=e(k)-e(k-1) \quad (17)$$

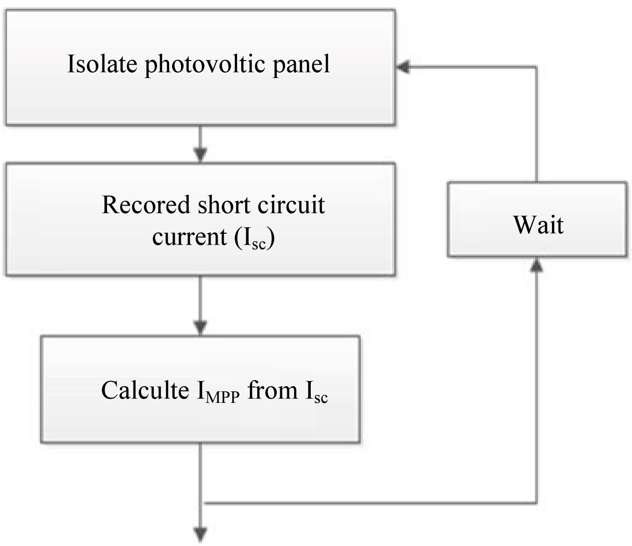


Fig. 8: Block Diagram of the short circuit current method

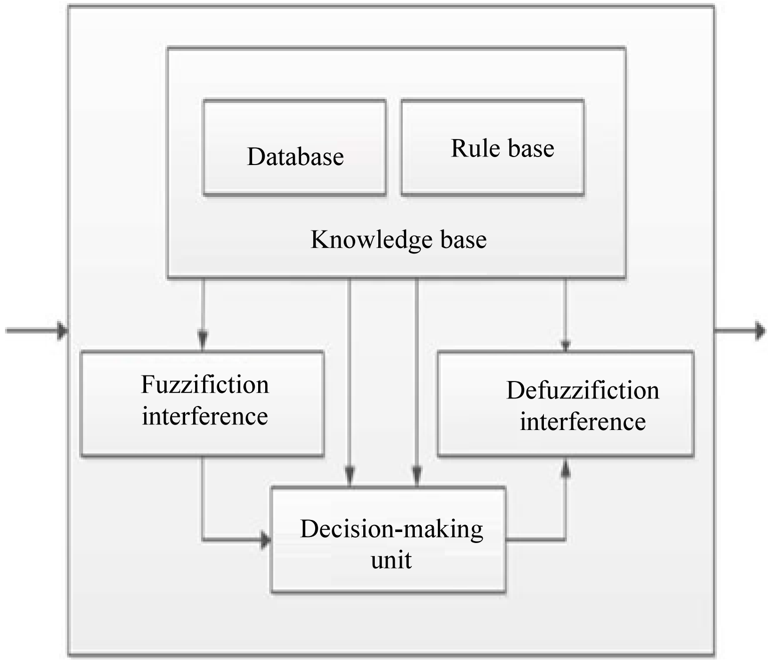
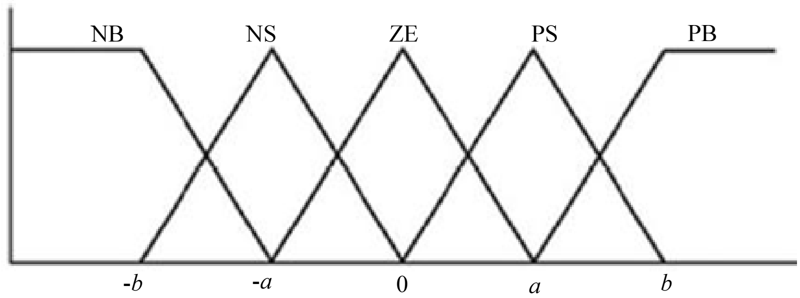


Fig. 9: Block diagram of fuzzy logic and membership functions diagram



Numerical variable
Fig. 10: Membership function for inputs and output of fuzzy logic controller

e(*k*)-position error of the operating point of the load at the *K*th instant.

e(*k*): error in the position of the load at the point of instant operation *K*. East (*k*)-the direction of movement of this point. The three steps of fuzzy logic control are: numeric fuzzy input variables become language variables based on membership functions. Rules: Make decisions based on the lookup table. Blurring: The output of the fuzzy logic controller is converted from a language variable to a numeric variable. The number of membership functions depends on the accuracy of the controller to be designed, but generally varies between levels 5 and 7. For example, in the chart, five levels are used.

Values a and b are based on the range values of numeric variables. When the inputs are *e*(*K*) and *Ce*(*K*), as defined (16) and (17), the output corresponds to the intermediate circuit voltage, *Ce*(*K*). For example, if the operating point is at the right end of the MPP, *e*(*K*) is NBs and *Ce*(*K*) is zero, the reference voltage must be reduced to reach MPP, so dV must be NP (negative). Move the work point to MPP. This provides an analog signal to control the MPP power converter. Table 2 shows the rules defined by seven levels of fuzzy logic controllers and member functions are written as follows: NB-negative large, NM-negative medium, NS-negative small, Ze-zero, PS-small positive, PM-positive mean, PB-taizor.

Neural Network

Neural network control functions as a black box model and does not require detailed information about the photovoltaic system. Neural networks usually have three layers: Input layer (i/p), hidden and o/p (Hiyama *et al*., 1995; Hiyama and Kitabayashi, 1997).

Table 2: Rules set for seven levels fuzzy logic controller

E (K)\Ce(K)	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	ZE	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Table 3: Comparison of MPPT techniques

MPPT	Application	Converter Used	Control Strategy	PV array dependent	Analog /Digital	Parameters Sensed	Periodic Timing	Convergence speed	Complexity	Training	Cost
P and O	Standal one	DC/DC	Sampling Method	NO	Both	V, I	NO	Varies	Low	NO	High
INC	Standal one	DC/DC	Sampling Method	NO	Digital	V, I	NO	Varies	Medium	NO	High
FOCV	Standal one	DC/DC	Indirect Method	Yes	Both	V or I	Yes	Medium	Simple	Yes	Low
FSIC	Standal one	DC/DC	Indirect Method	Yes	Both	V or I	Yes	Medium	Simple	Yes	Low
Current Sweep	Grid	DC/AC	Modulation Method	Yes	Digital	I	Yes	Slow	Complex	NO	High
RCC	Standalone	DC/DC	Modulation Method	NO	Analog	V or I	NO	Fast	Low	NO	High
Fuzzy Logic	Both	Both	Intelligent	Yes	Digital	V or I	Yes	Fast	high	Yes	High
Neural Network	Both	Both	Intelligent	Yes	Digital	V or I	Yes	Fast	high	Yes	High

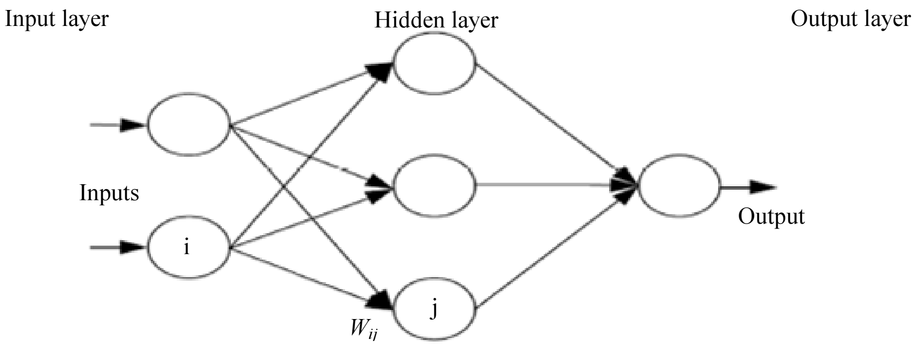


Fig. 11: Block diagram of Neural Network

The number of nodes in each layer varies by user Fig. 11. Input variables are photovoltaic generator parameters such as Voc, I_{sc}, radiation and temperature. The output is usually one or more reference signals, such as the duty cycle used to make the power converter operate in or near MPP. Links between nodes are weighted. To accurately identify MPP, Weights (Wii) must be carefully determined through the training process; the training database is obtained by testing a photovoltaic board within a month and the mode between input and output of the neural network is recorded. The properties of photovoltaic panels also change over time, which means that neural networks must be trained regularly to ensure accurate MPPT.

Results and Discussions

In this study, we use Matlab/Simulink as a means to model and simulate our systems. The objective is to simulate the photovoltaic generator using the MPPT command to compare the efficiency of all proposed algorithms. These results are presented in Table 3 for ease of understanding.

The results are formulated in Table 3 to facilitate understanding.

Conclusion

This article will analyze and explain in detail the different MPPT technologies. The pros and cons of these echnologies are discussed and the results are presented in Table 3 to facilitate understanding. This article also discusses the different factors that affect MPPT performance and panel types, which can be used as a quick guide to panel selection and MPPT technology for specific applications.

Author's Contributions

All authors also contributed to the preparation, preparation and implementation of the manuscript.

Ethics

This item is original. The author claims that this is not an ethical issue that may arise after the publication of this manuscript.

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