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Comphresive Literature Review: MPPT Techniques for Photovoltaic System

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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 those 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 the PV system and reduces the costs by decreasing the number of solar panels needed to get the desired power. This paper provides a comparison of 32 different techniques used in tracking the maximum power based on a literature survey. This paper is intended to be a reference for PV systems users.**

***Index Terms*— Maximum power point tracking system (MPPT), Photovoltaic (PV), System efficiency.**

I. INTRODUCTION

An important type of renewable energy is the solar energy that produces electrical energy directly using PV modules supported by the MPPT algorithm to maximize the output power. The main objective of obtaining MPP in PV systems are to regulate the actual operating voltage of PV panels to the voltage at MPP, by adjusting the output power of the inverter and dc converter[17]. Three categories to review MPPT algorithms as follows: perturb and observation P&O and incremental conductance IC and constant voltage method[22]. A review of MPPT techniques for Fractional open-circuit voltage(FOCV), Fractional short circuit current(FSCC), Sliding mode control(SMC), Robust unified control Algorithm (RUCA)[5]. A review of MPPT techniques for use in with and without shading conditions[10]. A review of MPPT techniques are Direct MPPT(P & O, IC, Fuzzy Logic, Artificial Neutral Network) and Indirect MPPT, Online MPPT(P & O, IC, Ripple correlation control, Advance adaptive)and Offline MPPT (Artificial Neutral Network, Genetic Algorithm)[23]. A review of Hill Climbing & Modified Hill Climbing presents a brief comparison between different techniques to help the users to choose an MPPT technique for a particular application [4]. The comparison between the MPPT methods includes cost, analog or digital implementation, sensor dependence, convergence speed, complexity, and effectiveness.

The second section illustrates the statement of the problem. A comparison between different MPPT techniques is given in the third section. In the 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.

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II. STATEMENT OF THE PROBLEM

In a medium- and large-scale systems, sun-tracking or MPPT or both are used to obtain maximum power. 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 the PV system depends on several factors including the 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 is displayed in Figure. 1. These characteristic curves present the parameters that describe the operation of the PV cell such as the open-circuit voltage VOC, short circuit current ISC, and the cell voltage, current, and power at the maximum power point, VMPP, IMPP, and PMPP, respectively. In addition, the fill factor FF and efficiency η are considered. FF measures the quality of the PV array. It is the the ratio of the actual MPP (PMAX) to the product of VOC and ISC as in (1) [21,2, 13].

$$P_{MAX}=V_{MPP}*I_{MPP} \quad (1)$$
$$FF=P_{MAX}/P_T=I_{MP}V_{MP}/I_{SC}V_{OC} \quad (2)$$

While the efficiency, η, of a solar cell is defined as the the ratio of the output electric power over the input solar radiation power under standard illumination conditions at the maximum power [13,2].Equivalent electrical circuit of cell shown in Figure 1.

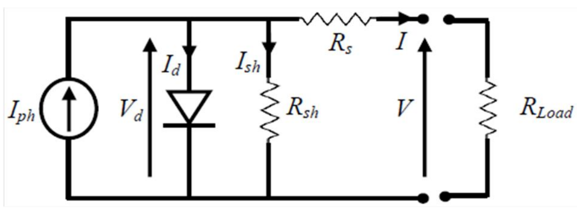

Figure.1.Equivalent electrical circuit of a cell

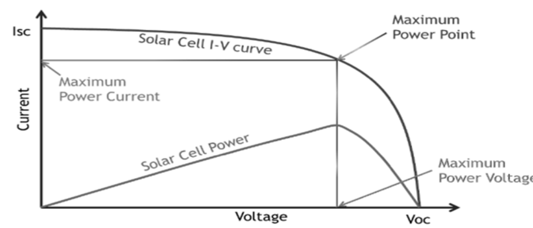

Figure 2. The relation between the characteristic I(v) of a cell and a load resistor[18]

The characteristic equation for the current and voltage of a the solar cell is given as follows [18].

$$I = I_{ph} - I_{sat}.[\exp(\frac{q.(V+R_s.I)}{nkT})-1]-\frac{V+R_s.I}{R_{sh}} \quad (3)$$

A. Comparison between MPPT techniques

This principle seems easy to carry; however, there are several limitations due to local maximums and oscillations around the maximum point during the search for this point. Due to such limitations which can be summarized that the voltage power characteristic of a photovoltaic (PV) array is nonlinear and time-varying because of the changes caused by the atmospheric and load conditions. The MPPT principles is to control the duty cycle for the pulse width modulation block that controls the power converter to deliver maximum power to the load as shown in Figure 3.

The MPPT techniques vary in many aspects, which might help the users to decide the system that suits their unique applications. These parameters include implementation, sensor, convergence speed, multiple local maximum, cost, application, and dependency on array parameter. Implementation is simply the type of circuit: analog or digital [1].Two different control variables such as voltage, current or solar irradiance, temperature etc. are often chosen to achieve the MPPT applications. According to the variables which need to be sensed, MPPT techniques can be classified into two types, such as one-variable techniques and two-variable techniques. It is easier and cheap to implement voltage sensor whereas current sensor is bulky and expensive and hence implementation of current sensor is inconvenient in PV power systems[12]. Due to a partial shading on PV, panels can affect the normal operation of the MPPT. If the selected algorithm is too sensitive, virtually MPPT that occurred by shading may be tracked. As a result of this, significant power losses may arise. Determination of the cost of an MPPT algorithm is not easy before implementation. Accurate cost compassion depends on system features such as analog or digital, software and programming requirements, and number of sensors. Generally analog algorithms are cheaper than digital ones[17].

Other MPPT techniques the Technique is based on Equalization of the Output operating points in correspondence to the forced Displacement of Input (TEODI) operating pointing of PV system is proposed. This method uses load current as the input and there is no power fluctuations present in operating point as this technique is not based on perturbation steps. However the implementation of this method during partial shading condition is difficult[11].
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[2].
Comparison between measured power and the instantaneous maximum power reference value. For the shape of the P-I curve, two alternative fields can be determined.
In the first field, the algorithm search the current of the MPP, by decreasing the measured current and imposing the operating current, while in the second field, the procedure is employed by imposing the actual current. This method is rapid but its implementation is complex [3]. An adaptive perceptive particle swarm optimization (APPSO)-based MPPT algorithm exhibit significant algorithmic complexity, which increases the implementation cost of the GMPPT control system[3].
In some applications especially commercialization, cost is the main factor to be considered. The cost of MPPT depends on the number of sensors implemented in the system, the complexity of the design as well as the choice of an analog or digital system. The number and type of sensors implemented influence the system cost because in most cases, current sensors are much more pricy than voltage sensors. Also affect the implementation cost while the choice of algorithm used determines the system capital cost. Besides that, analog circuits are lower in cost than digital circuits which require computer programming[6].
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[12].
Table I summarizes the most important characteristics of MPPT algorithm that is used to compare between different techniques.

TABLE I. PARAMETERS USED TO COMPARE MPPT ALGORITHMS

PV array dependent/ independentCCC	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

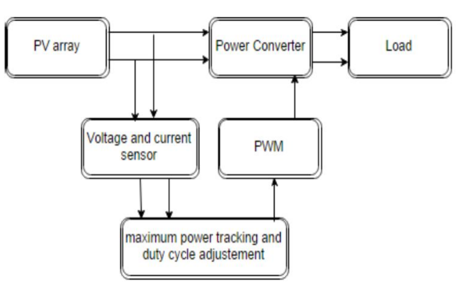

Figure 3: The MPPT Principle[13]

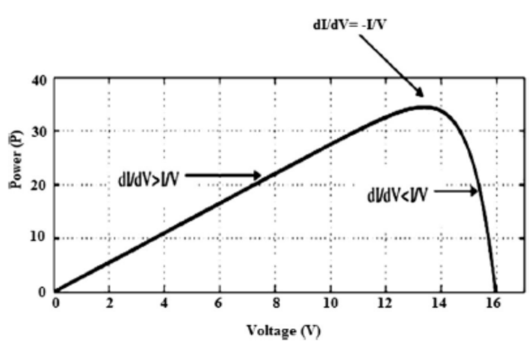

Figure 4: Slope of PV array power curve [2]

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[15].Table 1 summarizes the most important characteristics of MPPT algorithm that is used to compare between different techniques.

B. 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 32 different algorithms. The differences between all MPPT algorithms are listed in Table 2. Table 2 is an extended work to what have been presented in Further, algorithms are collected from other resources.

C. Results

The comparison between 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 [17,13] This method fails under rapidly changed atmospheric conditions and has a slow response speed oscillation around the MPP [1,13].

Incremental conductance algorithm:The incremental conductance is an adaptive method based on the fact that the sum of the instantaneous conductance (I/V) and the incremental conductance is zero at MPP. Figure2 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 Figure 2. An adaptive incremental conductance method is introduced in to reach to the maximum power in various operating conditions. 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 [2].However, it originally uses a fixed step to reach the maximum point which makes it be slow. Therefore, new modified IC method applies variable steps. Moreover, the new technique often integrates the conventional IC method with other methods to improve its performance and make it faster. The proposed method applies the fractional-order incremental conductance to capture a dynamic mathematical model of the system. Simulation results show the performance of the PV panel in varying conditions. An adaptive robust MPPT is developed in for the PV system. The proposed method utilizes a sliding surface to design a robust controller for the system. Then, the incremental conductance method is utilized to obtain the maximum power of the PV panel. The robust stability is shown by the Lyapunov theorem. Simulation results indicate an improvement in the tracking power compared to the conventional IC method in varying conditions[23].

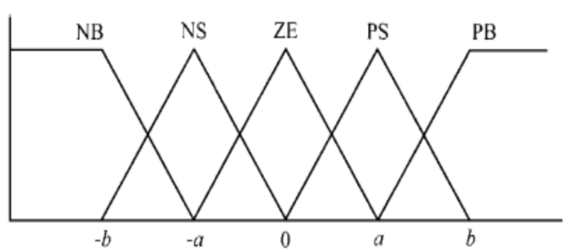

Figure 5:Membership Function [25]

TABLE II. 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	P&O[13,17]	No	Yes	Both	No	Vary	Low	*V* and *I*
2	Modified P&O[13,17]	Yes	Yes	Both	High	Average	Average	*V* and *I*
3	Hill Climbing P&O Normal[13]	Yes	No	Both	Average	High	Very low	*V* and *I*
4	Hill Climbing P&O Modified[13]	Yes	No	Both	Average	Very fast	Low	*V* and *I*
5	Incremental conductance Normal[13]	No	Yes	Digital	High	Very fast	Average	*V* and *I*
6	Incremental conductance Modified[13]	No	Yes	Digital	Average	Fast	Average	*V* and *I*
7	Fractional Voc[13]	Yes	No	Both	Yes	Medium	Low	*V*
8	Fractional Voc Intelligent[2]	Yes	No	Both	Low	Medium	Low	*V*
9	Fractional Isc[2]	Yes	No	Both	Medium	Medium	Medium	*I*
10	Fuzzy logic control Intelligent[2,15]	Yes	Yes	Digital	High	Fast	Medium	*V* and *I*
11	Neural network [2]	Yes	Yes	Digital	High	Fast	High	Varies
12	Artificial Neutral Network[15]	No	Yes	Both	No	High	Medium	*V* and *I*
13	Ripple Corelation Control Technique[6,12]	No	Yes	Analog	No	Fast	Low	*V* and *I*
14	Particle Swarm Optimization[6]	No	Yes	Digital	No	Fast	Simple	Varies
15	Differential evolution[6]	No	Yes	Digital	No	Fast	Low	*V* and *I*
16	Genetic Algorithm[12]	No	Yes	Digital	Yes	Fast	High	V,T and Ir
17	Paracitic Capacitance Technique[6,12]	No	Yes	Analog	No	Fast	Low	*V* and *I*
18	Artificial Intelligent[17]	Yes	Yes	Both	No	Fast	High	Varies
19	Online MPP Search Algorithm[6]	No	Yes	Digital	No	Fast	High	*V* and *I*
20	dP/dV or dP/dI feedback control[12]	No	Yes	Digital	No	Fast	Medium	*V* and *I*
21	One Cycle Control[12]	Yes	No	Both	Yes	Fast	Medium	*I*
22	Look Up Table technique[12]	Yes	Yes	Digital	Yes	Fast	Medium	*V,I,T* and *Ir*
23	Forced Oscillation Technique[12]	Yes	Yes	Analog	No	N/A	Low	*V*
24	Estimated perturb Perturb[12]	No	Yes	Digital	No	High	Medium	*V* and *I*
25	Current weep Technique[12]	Yes	Yes	Digital	Yes	Slow	High	*V* and *I*
26	Load I or V maximization[12]	No	No	Analog	No	Fast	Low	*V* and *I*
27	DC Link Capacitor Droop Control Technique[12]	No	No	Both	No	Medium	Low	*V*
28	Gauss Newton Technique[12]	No	Yes	Digital	No	Fast	Low	*V* and *I*
29	Steepest Descent Technique[12]	No	Yes	Digital	No	Fast	Medium	*V* and *I*
30	Sliding Mode Based MPPT[12]	No	Yes	Digital	No	Fast	Medium	*V* and *I*
31	Analytic based[12]	Yes	No	Both	Yes	Medium	High	*V* and *I*
32	Simulated Annealing[12]	No	Yes	--	No	Varies	Low/ Moderate	--

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 Figure 4. 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 Figure 4, 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 (ΔE), 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 ΔE(k) expresses the moving direction of this point [16,25,2].

III. CONCLUSION

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

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