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Comparative Study for Maximum Power Point Tracking Algorithms in Photovoltaic Systems

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ABSTRACT

Renewable energy resources play a vital role in replacement of fossil fuel resources and solar energy is one of these resources which considered environment friendly and increased use it in the past years. The main problem when the solar panels used is fluctuate of operating point with change of solar irradiance intensity and surface temperature of solar panel. When the load is coupled directly with solar panel then the power delivered is not access to the maximum power in the most cases and so that maximum power point tracking controller is necessary to be the system is efficient which make matching operation between load and input impedance for voltage converter circuit and with this operation the operating point be at maximum power. In this research simulation of maximum power point tracking system has been conducted by using MATLAB-2016a program, and multiple algorithms used are: perturb and observe algorithm, incremental conductance algorithm, sliding mode controller and random search algorithm for load matching with input impedance for voltage converter circuit (Buck converter). Synchronous buck converter circuit has been designed and built it, then practically system implemented. Microcontroller arduino UNO used to implement of tracking algorithm. Perturb and observe algorithm used in the practically system implementation. The results showed that sliding mode controller faster than the conventional algorithms larger more than twice with respect to access for maximum power and faster than random search algorithm about 6msec, then random search algorithm faster than conventional algorithms about larger than 1.5 time also when irradiance intensity is change the response is faster with respect to access for new maximum power point. SMC has better Performance from conventional algorithms and random search algorithm stronger than conventional algorithms and performance it very close to performance of sliding mode controller. The response of practically implementation was very speed and strong.

INTRODUCTION

Now a day's renewable energy based power generation plays a vital role in power sector. Most of the energy is obtained from the wind and solar when compare to all other renewable resources like Tidal, Biomass...etc. Among all renewable energy resources, solar is one of the most available and abundance resource. Solar panels are used to convert the light energy into an electrical energy (C.Mohan Raj *et al.*, 2015). The main area of research in PV system is to reduce the cost and increase the efficiency of the overall system. The PV module has the weather dependent. PV system has nonlinear internal characteristics. Irradiation and temperature in the solar PV system will affect the voltage and power characteristics with unique Maximum Power Point (MPP). Therefore, it is necessary to develop maximum power point tracking (MPPT) controllers to

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extract the maximum power from the PV array. DC to DC converter is interfaced with the PV panel and the load (Anuradha. T *et al.*, 2016 & Esther Glory. S *et al.*, 2013).

Therefore, it is of great significance to research on the algorithms of maximum power point tracking technology of Photovoltaic System (PVS) in order to improve efficiencies in photoelectric transfer. At present, several kinds of MPPT controlling algorithms have been discussed in many references. For instance, there perturb and observe (P&O) method, incremental-conductance (INC) method, sliding mode controller, dividing rectangle search algorithms such as random search algorithm, and fuzzy control (FC) algorithm and so on (Wang Fei 2015). Much studies presented in this field such Anas EL Filali, EL Mehdi Laadissi and Malika Zazi implemented simulation by using MATLAB for MPPT on boost converter employing P& O and fuzzy logic controller and the shows that Fuzzy logic presents better performance with fast time response (Anas EL Filali *et al.*, 2016). M. Kadir KARAGÖZ and Hüseyin DEMİREL proposes a dual algorithm search method that consist of modified Bat Algorithm and Perturb & Observe algorithm. The results shown the of modified Bat Algorithm is faster than P&O, performance of the of modified Bat Algorithm is superior to P&O (M. Kadir KARAGÖZ and Hüseyin DEMİREL, 2017).

This paper proposes new method to track MPP is random search algorithm and compare its performance with conventional algorithms such as P&O and INC algorithms, then compare performance of sliding mode controller with both conventional algorithms and random search algorithms on DC/DC buck converter using MATLAB/Simulink. Practical implementation of MPPT system has been conducted. P&O algorithm to track MPP and synchronous buck converter used in practically implementation. The basic block diagram of MPPT system is shown in Fig.1.

Fig. 1: Block diagram of MPPT System

2. Solar Panel Analysis:

Fig.2 shows the equivalent circuit of solar cell.

Fig. 2: the equivalent circuit of solar cell

The PV panel is the combination of many PV cells connected in series and parallel fashion to provide the desired output voltage and current. This PV generator exhibits nonlinear insolation dependent v - i characteristics. The solar cell has extremely low output voltage (about 0.5-0.7V), so solar cells have to be connected in series and parallel combination according to the requirements of voltage and power ratings and in practical applications.

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

The term I_{ph} is the photocurrent depends on the operating temperature and the solar irradiation S .

$$I_{ph} = \frac{S}{1000} [I_{scr} + \beta(T - T_{ref})] \quad (2)$$

I_d is the diode internal diffusion current

$$I_d = I_o \left[\exp \left(\frac{q(V_{pv} + I_{pv}R_s)}{A.K.T} \right) - 1 \right] \quad (3)$$

q is the charge of electron ($=1.61 \times 10^{-19}C$), A is the diode ideality factor, K ($=1.38 \times 10^{-23}J/K$) is Boltzmann's constant and T is the PV cell's operating temperature in Kelvin (K). The I_o in the equation represents diode saturation current, which is always be present and produces when there is no light. I_o is thermally generated, and changing the temperature affected on the generated current because of its temperature dependency as follows by equation (4).

$$I_o = I_{rs} \left(\frac{T}{T_{ref}} \right)^3 \exp \left[\frac{qE_g}{A.K} \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right] \quad (4)$$

I_{rs} is the cell reverse saturation current in ampere (A) at T_{ref} and solar irradiation S . E_g is the band-gap energy of semiconductor. Finally, the equivalent of an ideal relationship between the output current and voltage can be written as in Eq.5.

$$I = I_{ph} - I_o \left[\exp \left(\frac{q(V_{pv} + I_{pv}R_s)}{A.K.T} \right) - 1 \right] - \frac{V_{pv} + I_{pv}R_s}{R_{sh}} \quad (5)$$

Usually, the value of R_s is small & the value of R_{sh} is very large, so under ideal conditions, these quantities are negligible (Anmol Ratna Saxena and Shyam Manohar Gupta, 2014).

2.1 Solar Panel Characteristics:

The power generation of solar panel depends on the solar irradiance and the operating temperature (Joydipet *al*, 2014). Table 1 show specifications of the solar module used for simulation experiments at irradiance $1000W/m^2$ and temperature $25^\circ C$.

Table 1: Specification of Solar Module

Pmax	Voc	Vmp	Isc	Imp
104.8 w	39.6V	31.63	3.6A	3.312A

2.1.1 Effect of Solar Irradiation on Solar Panel Operation:

The effect in the change of solar insolation level is illustrated from the output characteristics of PV module fig. 3 and 4 shows the typical I-V and P-V characteristics for different solar insolation keeping the ambient temperature constant at $25^\circ C$. As the insulations increases the output current increases significantly which results in the increase of output power (Dhananjay and Anmol, 2014a).

Fig. 3: I-V curve at variable irradiance and temperature $25^\circ C$

Fig. 4: P-V curve at variable irradiance level and temperature $25^\circ C$

2.1.2 Effect of Temperature on Solar Panel Operation:

Solar cells vary under temperature changes. The change in temperature will affect the power output from the cells. The voltage is highly dependent on the temperature and an increase in temperature will decrease the voltage. Figures 5 and 6 show the effect of temperature on characteristic of PV module at constant radiation. With decreasing temperature, PV current decreases slightly but PV voltage increases clearly. As figure 6 indicates, output power of photovoltaic module increases with decreasing temperature (V.Jafari. *et al*, 2011).

Fig. 5: I-V curve at variable temperature and constant irradiance 1000W/m^2 .

Fig. 6: P-V curve at variable temperature and constant irradiance 1000W/m^2

3. DC/DC Buck Converter:

The dc-dc buck converter converts a higher dc input voltage to lower dc output voltage. The basic dc-dc buck converter topology is shown in Fig. a. It consists of a controlled switch S_w , an uncontrolled switch diode (D), an inductor L, an capacitance C and a load resistance R (Dhananjay and Anmol, 2014b). Table 2 show the parameters values used of the converter in simulation experiments.

Fig. 7: DC/DC Buck Converter

Table 2: Parameters of simulation Buck Converter

Cin	Cout	L	Switching Frequency	R
2000 μF	133 μF	30mH	4kHz	10 Ω

4. MPPT Algorithms:

The efficiency of a solar cell is very low. In order to increase the efficiency, methods are to be undertaken to match the source and load properly. One such method is the Maximum Power Point Tracking (MPPT). This is a technique used to obtain the maximum possible power from a varying source. In photovoltaic systems the I-V curve is non-linear, thereby making it difficult to be used to power a certain load. This is done by utilizing a DC/DC converter whose duty cycle is varied by using MPPT algorithm. A Buck converter is used on the load side and a solar panel is used to power this converter. There are many methods used for maximum power point tracking are listed below (Shiba and Pankaj, 2014):

4.1 Perturb and Observe (P&O) Algorithm:

In this algorithm a slight perturbation is introduced to the system. Due to this perturbation the power of the module changes. If the power increases due to the perturbation, then the perturbation is continued in that direction. After the peak power is reached the power at the next instant decreases and hence after that the perturbation reverses (L.V. and Ramesh. Vaddi, 2014) and as shown in fig. 8. Flowchart shown in fig. 9.

Fig. 8: Perturb and Observe Wave Form

Fig. 9: Flowchart of PO algorithm

4.2 Incremental Conductance (INC) Algorithm:

Fig.10 shows the incremental conductance method.

Fig. 10: incremental conductance method.

The incremental conductance can determine that the MPPT has reached the MPP and stop perturbing the operating point. If this condition is not met, the direction in which the MPPT operating point must be perturbed can be calculated using the relationship between dI/dV and $-I/V$. This relationship is derived from the fact that dP/dV is negative when the MPPT is to the right of the MPP and positive when it is to the left of the MPP (L.V. and Ramesh. Vaddi, 2014). Fig. 11 show flowchart of incremental conductance algorithm.

Fig. 11: flowchart of incremental conductance algorithm.

4.3 Sliding Mode Controller (SMC):

Fig.12 show block diagram of sliding mode controller to track MPP. The MPPT algorithm unit provides the sliding mode inner controller with an adaptive reference, which results in an adaptive switching surface. This in a way resembles sliding mode based inverters the inner feedback (sliding mode) regulates a linear combination of the PVG voltage and current to attain its operation along a line in close vicinity to the MPP loci (see Fig. 13). This is accomplished in a very rapid manner, at least an order of magnitude faster than the MPPT reaction. This allows using a small step increment in the MPPT algorithm (resulting in a high tracking efficiency in steady state) since most of the tracking is carried out by the inner loop, and the MPPT requires very few iterations (Yoash Levron and Doron Shmilovitz, 2013).

Fig. 12: Block diagram of MPPT By Using Sliding Mode Controller.

Fig. 13: PVG characteristics under different insulations, and the optimal switching surface (blue) $s(v,i)=0$.

4.3.1 Control Design of Sliding Mode Controller:

For MPP tracking, we define the switching surface by a linear combination of the PVG voltage and current. The system is illustrated in Fig. 11. Assuming a large output capacitor (or battery load) the converter output voltage may be assumed to be semi-constant. Thus, the PVG voltage and current constitute all the converter's state variables, resulting in the switching surface given by (6).

$$S(v, i) = a \cdot i - b \cdot v + ref = 0 \quad (a, b \geq 0) \quad (6)$$

$S < 0$: ON state, $S > 0$: OFF state

Where i and v are the inductor's current and input voltage, and a, b and ref define the switching surface. a and b set the slope in the PVG i - v plane, and are chosen as non-negative, and ref sets the offset. When $S < 0$ (on state), the low transistor is on, and the inductor charges. The current increases, and $S(v, i)$ increases. When $S > 0$ (off state), the low transistor is off, and the stored energy flows to the load. The current i decreases, and $S(v, i)$ decreases. As a result, $S(v, i)$ is kept a "switching band" around $S=0$. This controller constricts the system's operation to the sliding switching surface. The operating point of the PV module results from the intersection of the switching surface, $S=0$ with the PV curve (Fig. 13). To extract maximum power, the switching surface is adjusted by the MPPT algorithm, to intersect with the exact MPP at any given time. This algorithm samples the input power, and adjusts the switching surface by updating the constant ref , which is fed to the comparator (Yoash Levron and Doron Shmilovitz, 2013). a and b choose by trial and error and in this research a chooses a value 0.612, b chooses 0.085 and ref is generated and adjusted using incremental conductance algorithm.

4.4 Random Search Algorithm (RSA):

RSM is a direct search, gradient-free method which was first proposed by Anderson and is attributed to Rastrigin who developed RSM with basic mathematical analysis. RSM can be conveniently used either in maximization/ minimization problems because many compilers associated with digital controllers and computer libraries have random generators. This method works by moving/generating a sequence of improved approximation towards a better solution.

Consider a function, $f(X_1, X_2, \dots, X_n)$ with n variables, which is to be maximized using RSM. The sequential procedure of this method is given by the following steps (Kinattingal *et al*, 2014).

1. Set iteration number, k as 1. Designate a random number to each variable X_i^k between the $X_{i,min}$ and $X_{i,max}$. For n -dimensional problem, the function value $f^k(X_1^k, X_2^k, \dots, X_n^k) = f(X^k)$.

2. Generate a set of n random numbers $r_1, r_2, \dots, r_n$ each lying within the interval $[-1, 1]$ and formulate the unit vector u as

$$u = \frac{1}{(r_1^2 + r_2^2 + \dots + r_n^2)^{1/2}} \begin{pmatrix} r_1 \\ r_2 \\ \vdots \\ r_n \end{pmatrix} \quad (7)$$

3. For the next iteration, compute new vector X^{k+1} and the corresponding function values as given in (8) and (9) where λ is the initial step length.

$$X^{k+1} = X^k + \lambda u \quad (8)$$

$$f^{k+1} = f(X^{k+1}) \quad (9)$$

4. Compare the values of f^{k+1} and f^k if $f^{k+1} < f^k$ set the new values as given in (10) and (11) and then go to step 2; else go to step 5.

$$X^{k+1} = X^k \quad (10)$$

$$f^{k+1} = f^k \quad (11)$$

5. If $k \leq N$, set the new iteration as $k = k + 1$ and compute new reduced step length $\lambda = \lambda \times m$. If new step length is greater than ε , go to step 2; else go to step 6. Here, m is a constant value within the interval $[0, 1]$, ε is minimum allowable step length and N is the maximum iteration number.

6. Stop the procedure by taking $X^{optimal} \cong X^{k+1}$.

4.4.1 Application of RSM for MPP of PV systems:

The steps of RSM towards MPPT are described below:

1. Initialize step length λ , minimum allowable step length ε and m .
2. In this step, the digital controller generates a random duty cycle d^k within the interval $[d_{min}, d_{max}]$ to the dc-dc converter and senses V_{pv} and I_{pv} of the solar array after allowing a reasonable settling time and then computes power output of PV system, P_{pv}^k .
3. As it is a single-variable objective function, generate a random number r_1 in the interval $[-1, 1]$. $u = r_1$.
4. Compute new duty cycle: $d^{k+1} = d^k + \lambda u$ and measure corresponding output power of PV system, P_{pv}^{k+1} .
5. Compare the values of P_{pv}^{k+1} and P_{pv}^k . If $P_{pv}^{k+1} < P_{pv}^k$ set the new values as $d^{k+1} = d^k$ and $P_{pv}^{k+1} = P_{pv}^k$ and go to step 3; else go to step 6.
6. For $\lambda \leq \varepsilon$, terminate the program and go to step 7; else set $\lambda = \lambda \times m$ and go to step 3.
7. Output the optimal duty ratio $d^{optimal} = d^{k+1}$ corresponding to Globally MPP.
8. The microcontroller continuously monitors PV output power and whenever there is a deviation beyond 0.4% of the rated power of the PV array, then the microcontroller reinitiates the RSM (Kinattingal *et al*, 2014).

And the flowchart of random search algorithm shown in fig. 14. in this research $\lambda=0.086$, $m=0.92$ and $\varepsilon=0.00001$.

Fig. 14: Flowchart of random search algorithm

5. Simulation and Results:

Fig. 15: T System in MATLAB Program MPP

MATLAB/Simulink is used to simulate MPPT system and the fig. 15 is shown MPPT system in MATLAB/Simulink program and the fig. 16 shown the supplied irradiance on solar panel and the temperature on solar panel was 25 °C in the simulation. The following figures are response of algorithms.

Fig. 16: The supplied irradiance on solar panel

Fig. 17-a: solar panel power at using perturb and observe algorithm to track MPP

Fig.17-b: solar panel current at using perturb and observe algorithm to track MPP

Fig. 17-c: solar panel voltage at using perturb and observe algorithm to track MPP

Fig. 18-a: solar panel power at using incremental conductance algorithm to track MPP

Fig. 18-b: solar panel current at using incremental conductance algorithm to track MPP

Fig. 18-c: solar panel voltage at using incremental conductance algorithm to track MPP

Fig.19-a: solar panel power at using sliding mode controller to track MPP

Fig. 19-b: solar panel current at using sliding mode controller to track MPP

Fig. 19-c: solar panel voltage at using sliding mode controller to track MPP

Fig. 20-a: solar panel power at using random search algorithm to track MPP

Fig. 20-b: solar panel current at using random search algorithm to track MPP

Fig. 20-c: solar panel voltage at using random search algorithm to track MPP

The simulation results are tabulated in table 3.

Table 3 simulation results.

RSA	SMC	IC	P&O	The Method	
				The parameters	
24.1	24.77	75.1	75.01	Rise Time (msec)	
37.95	39.75	85.77	85.7	Settling Time (msec)	
59.55	53.5	94.5	95.29	Stable time at MPP (msec)	
8.8	4.2	35.9	32.5	Access time (msec) to reach MPP	Irradiance change (1000-800)W/m ²
35.48	0.18	1.49	0.78	Undershoot during access time only (%)	
1.4	0.9	43	31.6	Access time(msec) to reach MPP	Irradiance change (800-600)W/m ²
0.53	0.19	2.27	0.55	Undershoot during access time only (%)	

6. Practical Implementation:

In practical implementation of MPPT system, the specifications of solar panel that used is shown in table 4 at irradiance 1000w/m² and temperature 25°C.

Table 4: specifications of solar panel.

Pmax	Voc	Isc	Vmp	Imp
20W	20.88V	1.29	17.28	1.16

Current of solar panel is reading by ACS712 hall effect current sensor and used voltage sensor to read voltage of solar panel. Microcontroller Arduino UNO is used to program of MPPT algorithm and in practical implementation P&O algorithm is used. DC/DC synchronous buck converter is used instead of conventional buck converter and which difference from the conventional the diode is replace with transistor. MOSFET driver IR2104 is used to drive transistors in buck converter because of the output signal from Arduino do not enough to turn on the transistors and more information about it see datasheet, and the specifications of synchronous buck converter is shown in table 6.

Table 6: practical specifications of DC/DC synchronous buck converter.

Transistors	Cin	inductor	Cout	Switching Frequency	Load
IRF3205 NPN	2000 μ F	300 μ H	503 μ F	31.35kHz	10 Ω , 28 watt

The fig. 21 show the practical system.

Fig. 21: practical MPPT system. **Fig. 22:** Practical Circuit of MPPT system

$R1=R3=2.2k\Omega$, $R2=R4=1k\Omega$, $C1=C2=C3=C4=0.1\mu F$, $Cin1=10\mu F$, $R5=R6=220\Omega$.

The voltage dividers $R1$, $R2$ and $R3$, $R4$ is used to divide the voltage across source and load respectively because of the Arduino not read voltage more than 5V. $C1$, $C2$, $C3$ and $C4$ to prevent the spikes. $Cin1$ to smooth. $R5$ and $R6$ to protect IC IR2104 MOSFET driver. +5V in voltage sensors not connected. The perturb and observe algorithm is implemented in the practical system and the practical response of P&O algorithm to track MPP is shown in fig. 23.

Fig. 23: the practical response of MPPT

In fig.23 solar power in watt, solar voltage in volt, solar current and load current in ampere. The data is registered on serial monitor from arduino, then import data by MATLAB and plotted using MATLAB program, the difference between response of simulation and practical implementation because the parameters of DC/DC converter is different and switching frequency also was high in practical comparative with simulation. The practical response was very fast to track MPPT and strong.

Conclusion:

The simulation results shows that performance of maximum power point tracking algorithms was good. Performance of perturb and observe algorithm and incremental conductance algorithm was close to each other. At beginning of system simulation at irradiance $1000W/m^2$ sliding mode controller response faster than perturb and observe algorithm and incremental conductance algorithm about twice and faster than random search algorithm about 6 msec, then random search algorithm response was faster than perturb and observe algorithm and incremental conductance algorithm about 1.6 time. At change the irradiance from $1000W/m^2$ to $800W/m^2$ at time 0.3sec undershoot happened in the response of conventional algorithms with value 0.78% for perturb and observe algorithm and 1.49% for incremental conductance algorithm for 33msec approximately, then stabilized at maximum power. Undershoot in the sliding mode controller response was 0.18% for 4.4msec, then stabilized at maximum power and undershoot of random search algorithm was 35.48% for time 8.8msec, then stabilized at maximum power. At change the irradiance from $800W/m^2$ to $600W/m^2$ at time 0.6sec undershoot happened in the response of conventional algorithms with value 0.55% for perturb and observe algorithm for time 31.6msec and 2.27% for incremental conductance algorithm for time 43msec approximately, then stabilized at maximum power. Undershoot in the sliding mode controller response was 0.19% for 0.9msec, then stabilized at maximum power and undershoot of random search algorithm was 0.53% for time 1.4msec, then stabilized at maximum power. In general sliding mode controller faster and stronger than both conventional algorithms and random search algorithm, then random search algorithm faster and stronger than conventional algorithms and performance of random search algorithm very close to performance of sliding mode controller. Perturb and observe algorithm response of practical implementation was good and very fast.

In the future possible to implement random search algorithm and sliding mode controller to track MPP practically using Arduino or other microcontrollers such as raspberry pi; FPGA and DSP board or simulation and implementation other algorithms such as Dividing RECT angle (DIRECT) search algorithm or pattern search algorithm to track MPP in photovoltaic systems.

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