Maximum Power Point Tracking for Photovoltaic Array Using Parabolic Interpolation

Md. Ziaur Rahman Khan, Md. Zadid Khan, Mohammad Nasim Imtiaz Khan, Shammya Shananda Saha, Dewan Fahim Noor, and Md. Rifat Kaisar Rachi

Abstract—**Parabolic interpolation based maximum power point tracking (MPPT) technique has been used in this paper to track the maximum power point (MPP) of a photovoltaic system. The proposed technique requires only one current sensor to track the MPP, which means that systems incorporating this technique will need less hardware support and will be cost effective. The proposed technique has been applied on the simulation and experimental data of a charge controller circuit and it has been found that the proposed technique requires around 50% less iteration to track the MPP than the tradition P&O method.**

Index Terms—**Maximum power point tracking (mppt), parabolic interpolation, perturb & observe (p&o), photovoltaic panel, single-ended primary inductance converter (SEPIC).**

I. Introduction

With the fast depletion of conventional energy sources, domination of world's energy production seems to be shifting towards the alternate energy sources. Resources like gas, coal being on the wane for their usage over the centuries along with their negative impact on the environment have led the human race to the pursuit of renewable energy sources. As sun is the prime source of energy, the ultimate solution of energy problem rests specially with the proper utilization of the solar energy. This is especially true for countries like Bangladesh, which has no record of snow fall and a suitable global position to receive large amount of annual sunlight. Moreover, access to electricity in Bangladesh is one of the lowest in the world. Less than 20% of the total population is connected to the national grid and consumption of power is only about 110 kWh per capita per annum. Shortage of power supply, at times very acute and unreliable, has constrained economic growth. The lost output is, according to some estimates, as high as one percent of the Gross Domestic Product (GDP) [1]. So providing the basic electrical supply to many people is a big concern for the Government of Bangladesh. Solar Energy Program in the country has the mission of fulfilling basic electricity requirements in the rural areas and hence, supplementing the government's vision of electrifying the whole country by the year 2021. Under this program both grant and refinancing are channeled to Solar Home Systems (SHS) installed in rural areas where grid electricity is absent or unlikely to reach in the near future. Already 2 million Solar Home Systems have been installed in the country and there is a target of financing installation of 4 million SHSs by 2015 [2]. Efficient system design is very crucial for optimizing the cost of such systems.

The remarkable technological advancement has improved the efficiency of photovoltaic cell to approximately 12%. But drawing the maximum power from the cell has become a major area of interest. Due to Non-linear I-V characteristics, it is harder to extract maximum available power from solar cell for a continuous change of intensity of solar light and ambient temperature. If the solar panel can be operated at the MPP, the load can be supplied with the maximum extractable power at different weather conditions. Then it will be possible to charge the energy storage element like battery more quickly and efficiently than traditional approach where MPPT is not used. Moreover, when the battery is fully charged, it will be possible to supply solar energy to the power grid assembling a grid tie inverter with the solar charge controller. This paves the way of a probable future energy solution.

There are various methods to implement MPPT. In [3] the detailed comparison of different MPPT methods is discussed. Among these, P&O is by far the most popular method because of its simplicity. Traditionally P&O method is implemented with a hill climbing algorithm. The problem with this method is that it requires much iteration to reach the MPP.

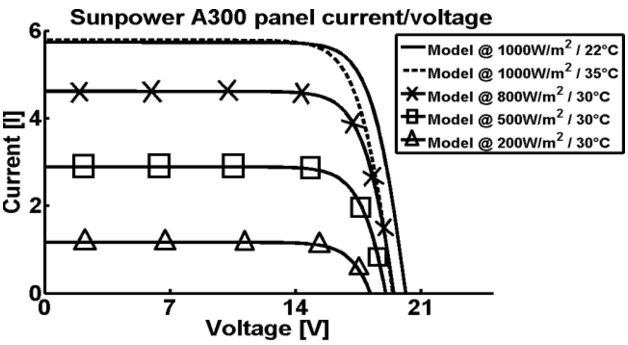

Fig. 1. I-V characteristic of sunpower A-300 solar panel.

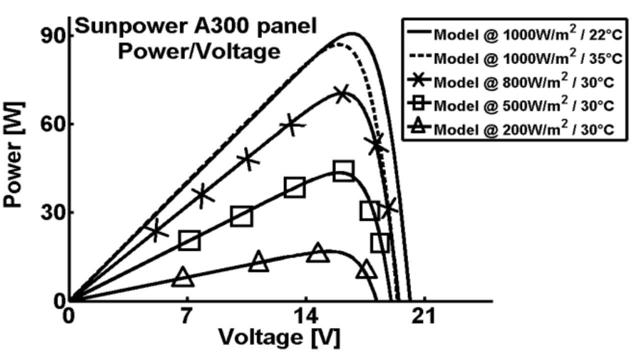

Fig. 2. P-V characteristic of sunpower A-300 solar panel.

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The authors are with the Department Electrical & Electronic Engineering, Bangladesh University of Engineering & Technology, Dhaka-1000, Bangladesh (e-mail: zrkhan@eee.buet.ac.bd).

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In [4], [5] fast algorithms are used to reach the MPP which requires less iteration but uses input power to track the MPP. Measuring input power requires high side current sensing which is expensive and complex. The strategy used in this paper is to sense the output current, I_O, (battery charging current) of a charge controller to track the MPP. It has been shown in [6] that the power generated by the solar panel can be estimated from output current. Therefore, MPP can be estimated from the output current alone without measuring the actual input power. The output current is sensed using only a resistor, a passive filter and an amplifier. The implemented circuit also consists of only one microcontroller chip, one coupled inductor, two capacitors, one MOSFET and one diode. Some additional components are required for protection. The overall cost of this circuit should be affordable for commercial competence.

The technique, described here, first predicts the maximum point of I_O vs Duty Cycle curve by parabolic interpolation. Parabolic interpolation is a technique used to find the minimum or maximum point of a curve by fitting a parabola (polynomial of degree two) to the curve at three unique points. It is shown that parabolic interpolation gives a good prediction of the maximum point of I_O vs Duty Cycle curve. Once the prediction has been made the exact maximum point is tracked by traditional hill climbing algorithm. The proposed algorithm requires less iteration to track the MPP than the traditional P&O method.

II. MPPT for Solar Cell

The I-V characteristic of solar panel is nonlinear and varies with irradiance and temperature. The I-V and P-V characteristics of Sunpower A-300 solar panel (36 cells) for different temperature and irradiance are given in Fig. 1 and Fig. 2. The curves are produced based on the codes given in [7].

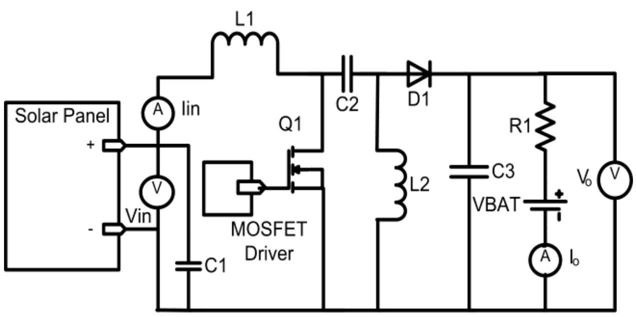

Fig. 3. Circuit diagram of DC-DC converter.

TABLE I: Values of Different Parameters for PSIM Simulation

Item	Value
Number of cell connected in series	32
Open-circuit voltage of each cell	0.665 V
Short-circuited Current of each cell	5.75 A
Inductor, L1	500 µH
Inductor, L2	500 µH
Capacitor, C1	100 µF
Capacitor, C2	1 µF
Capacitor, C3	1000 µF

There is a unique point on the P-V curve, called the MPP at which the entire solar panel operates with maximum efficiency and produces its maximum output power. The location of the MPP, which is not known, can be located either through calculation models or by search algorithms [8]. MPPT systems adjust the duty cycle of the DC-DC converter to consistently maintain the operating voltage of the panel at its maximum power point [9].

III. DC-DC Converter for MPPT

To track MPP over a wide range, the DC-DC converter needs to perform either Buck or Boost operation. There are several topologies of Buck-Boost converter. A detailed comparison of different DC-DC Buck-Boost converter is presented in [10]. Among these topologies, SEPIC has the advantage of non-inverting polarity, easy to drive switch and low input current pulsation for precise MPPT [10]. So in this work SEPIC topology has been chosen to design a MPPT based solar charge controller. The circuit diagram of the proposed SEPIC converter is shown in Fig. 3.

The simulation of the proposed circuit has been done on PSIM 9.0 software. This software has a built-in solar module (physical model) which can simulate the I-V characteristic of a solar panel. The parameters for the solar module have taken from the datasheet of Sunpower A-300 solar cell [11]. The key parameters of the solar module are given on Table 1. The rest of the parameters are set to default value. The Q1 MOSFET and the D1 diode are the built-in models of PSIM. To simulate battery charging condition in PSIM a dc voltage source of 12V is connected in series with a resistance of 0.1Ω.

IV. Parabolic Interpolation and the Proposed Algorithm

If the load is fixed or if the load variation does not happen often, the changes in the power generated by the solar panel can be estimated from the output parameters and specifically the output current [6]. Therefore, the input power of the solar panel can be approximated from the output current, I_O. To produce I_O vs Duty Cycle (Fig. 4), the proposed circuit has been simulated for different duty cycle in PSIM and then curve fitting technique is used on the simulated values of I_O. The geometric consideration concerning the shape of this curve can help to predict the duty cycle at which the solar panel operates at maximum power. As demonstrated in the Fig. 4, I_O vs Duty Cycle curve (as well as P-V curve) are a unimodal function. Successive parabolic interpolation technique is very popular for finding the minimum or maximum of a continuous unimodal function by successively fitting parabolas to the function at three unique points. It has the advantage of having a higher rate of convergence. The maximum point of a parabola can be estimated from three points on the curve, as described in [12].

Simulation result shows that parabolic interpolation makes a good prediction when two points are on the rising slope and the other one is on the falling slope or vice versa. An adaptive algorithm (shown in Fig. 5) ensures that not all three points are on the same side of the I_O vs Duty Cycle curve.

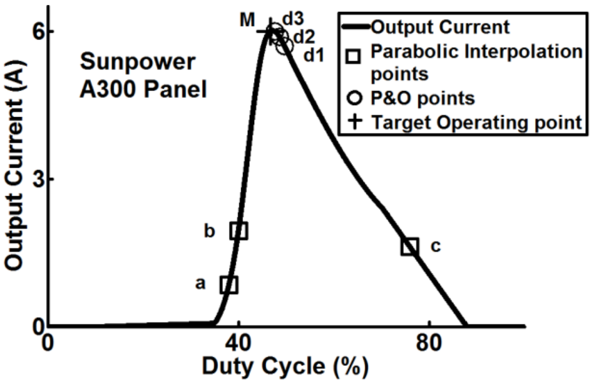

Fig. 4. Output current vs duty cycle (at 1000 Wm^{-2} irradiance and 22°C).

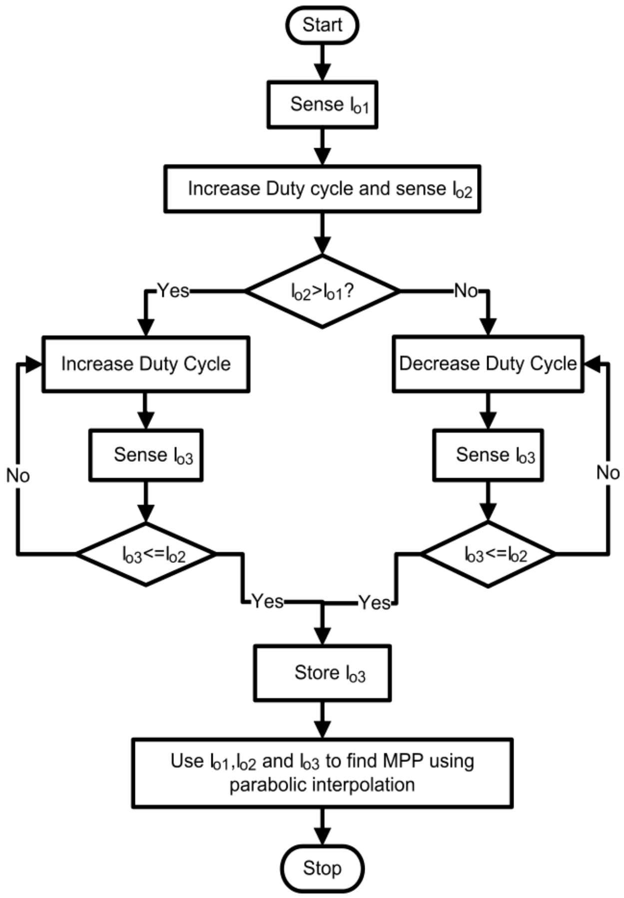

Fig. 5. Flowchart for Parabolic Interpolation.

One drawback of the P&O method is that continuous perturbation or oscillation occurs near the MPP [5]. So in the proposed algorithm, instead of tracking the MPP continuously, it is tracked only when output current changes. Simulation result shows that the I_O changes when the MPP shifts from the previous value due to temperature and irradiance change. For tracking purpose two threshold values ($Threshold_1$ and $Threshold_2$) are chosen, where $Threshold_2 > Threshold_1$. If the change in I_O is smaller than $Threshold_1$, it is assumed that there is no significant change of MPP position and there is no need to track MPP. Again, when the change in I_O is larger than $Threshold_1$ but smaller than $Threshold_2$, it is assumed that new MPP is slightly shifted with respect to the duty cycle and in this case the MPP can be efficiently tracked by hill climbing algorithm alone. If the change in I_O is larger than $Threshold_2$, the new MPP will be tracked first by predicting the new MPP using parabolic interpolation and then applying hill climbing algorithm to minimize iteration number.

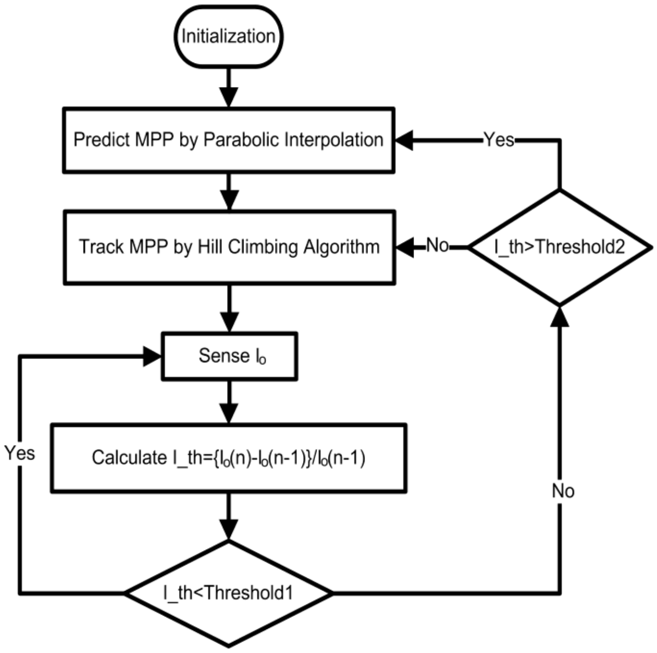

Fig. 6. Flowchart for the proposed algorithm.

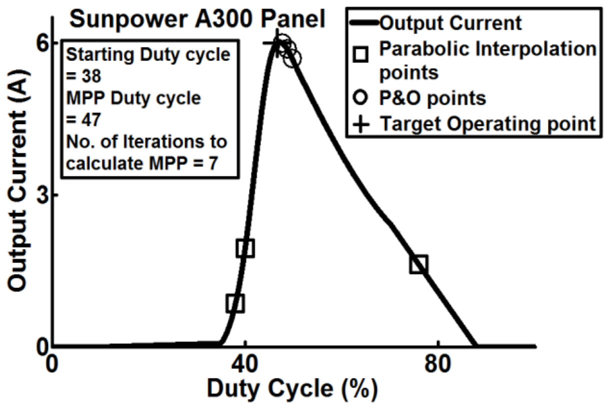

Fig. 7. Simulation of the proposed algorithm when starting point is 38%duty cycle (desired MPP approximately 47%).

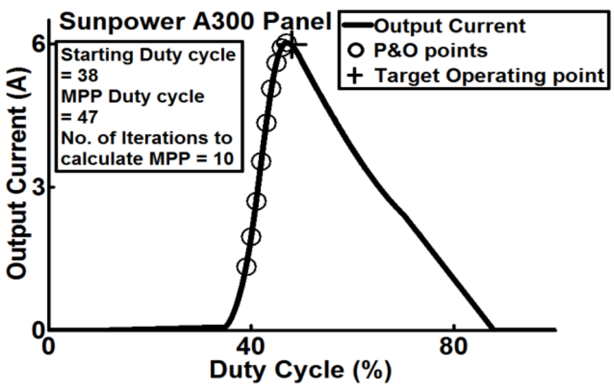

Fig. 8. Simulation of conventional P&O method when starting point is 38% duty cycle (desired MPP approximately 47%).

The predicted maximum point lies near the actual MPP. Therefore in the proposed algorithm of Fig. 6, once the prediction is done through the parabolic iteration the actual MPP is tracked by the traditional hill climbing algorithm. But because of the predicted maximum point, it will now take less iterations to reach the MPP by hill climbing algorithm.

The proposed algorithm first selects point a, b and c on I_O vs Duty Cycle curve of Fig. 4 and predicts the approximate MPP which is d1. Then traditional hill climbing algorithm is used (d1, d2, d3 and M) to track the exact MPP which is M in Fig. 4.

V. Simulation Results

Fig. 7, Fig. 8, Fig. 9, and Fig. 10 show the simulation results of the proposed algorithm and the traditional P&O method for two different atmospheric conditions.

A. Simulation Results for 1000 Wm^{-2} Irradiance and 22 ℃

In Fig. 7, it is assumed that at a certain point during operation, the duty cycle is 38% and the desired MPP duty cycle is approximately 47%. Therefore, a parabolic interpolation results in a duty cycle of 50%, which only takes 3 iterations. After that, the P&O method is applied according to the proposed algorithm, which results in a duty cycle of 47%, using 4 more iterations. So, in total 7 iterations are needed to reach MPP.

In Fig. 8, the result using the traditional P&O algorithm is shown. The starting duty cycle here is assumed to be 38% and the step size is assumed to be 1% duty cycle. In this case, 10 iterations are needed to reach MPP.

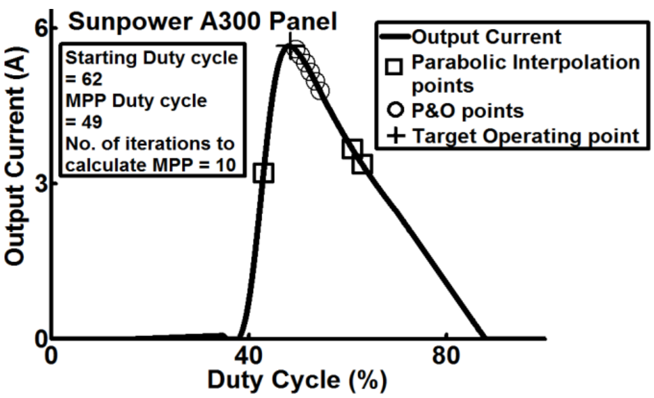

Fig. 9. Simulation of the proposed algorithm when starting point is 62% duty cycle (desired MPP approximately 49%).

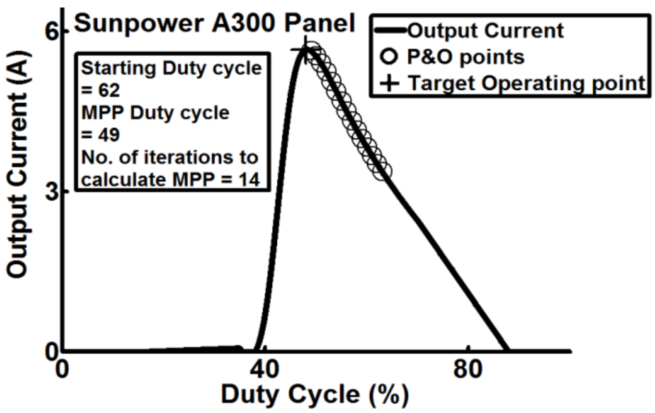

Fig. 10. Simulation of conventional P&O method when starting point is 62% duty cycle (desired MPP approximately 49%).

B. Simulation Results for 1000 Wm^{-2} Irradiance and 35 ℃

In Fig. 9, it is assumed that at a certain point during operation, the duty cycle is 62% and the desired MPP duty cycle is approximately 49%. So, a parabolic interpolation results in a duty cycle of 55%, which only takes 3 iterations. After that, the P&O method is applied according to the proposed algorithm, which results in a duty cycle of 49%, using 7 more iterations. So, in total 10 iterations are needed to reach MPP.

In Fig. 10, the results using the traditional P&O algorithm are shown. The starting duty cycle here is assumed to be 62% and the step size is assumed to be 1% duty cycle. In this case, 14 iterations are needed to reach MPP.

The simulation was carried out in similar manner for different atmospheric conditions and different starting conditions. All the results and their comparisons are included in Table II.

TABLE II: Comparison Regarding the Number of Iterations to Reach the MPP between Two Methods at Different Atmospheric and Starting Condition

Irradiance (Wm^{-2})	Temper-ature (°C)		Proposed Method	P&O Method	Improve-ment (%)
1000	35	Starting Duty Cycle	62	62	28.57
		MPP Duty Cycle	49	49	
		Iteration	10	14	
1000	30	Starting Duty Cycle	70	70	56.52
		MPP Duty Cycle	48	48	
		Iteration	10	23	
800	30	Starting Duty Cycle	36	36	61.54
		MPP Duty Cycle	48	48	
		Iteration	5	13	
500	30	Starting Duty Cycle	65	65	42.11
		MPP Duty Cycle	47	47	
		Iteration	11	19	
200	30	Starting Duty Cycle	37	37	40
		MPP Duty Cycle	46	46	
		Iteration	6	10	

As seen from the figures and comparison tables, the iteration number required by the proposed algorithm is comparatively less than the traditional P&O method. The last column of the table shows the overall improvement that is the reduction of total number of iteration with respect to the traditional P&O method. So, the convergence time should be smaller, which will enable faster and more efficient operation. In application, for rapidly varying environmental condition, the proposed algorithm can reach the desired operating point (MPP) more quickly.

One important conclusion which can be drawn from these results is that, for all types of atmospheric conditions i.e. summer, rainy season or winter - this system, if practically implemented, is expected to produce similar results to the ones above. The proposed technique will require 50% less iteration to track MPP than the traditional hill climbing algorithm.

VI. Experimental Results

In order to verify the effectiveness of our proposed method in real life we physically constructed the circuit shown in Fig.3.The power devices and the components of the SEPIC converter are as follows:

- Power Mosfet Q1 is IRF3205
- Diode D1 is RHRP840
- Capacitor C1, C2 and C3 is 100uF, 1uF and 1000uF
- Inductor L1 and L2 both are 500uH
- Mosfet driver is TC4427

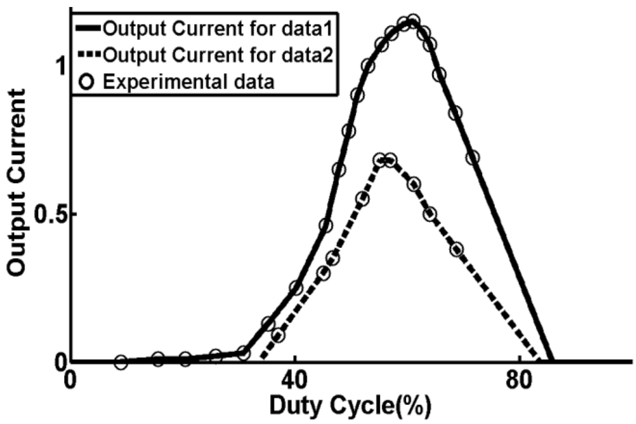

Fig. 11. Output current vs duty cycle (experimental results).

Capacitors C1 and C3 are electrolytic capacitors and C2 is a metalized polyester film capacitor. The inductors L1 and L2 are designed with the calculation provided in [x]. Required airgap were provided to avoid saturation up to rated current of 3A. It is to be noted that the resistance, R1 shown in Fig. 3 is used to simulate battery internal resistance and R1 is not included in the experimental setup.

The specification of the solar panel is listed below:

- Rated peak power : 65 Watt
- Rated Voltage : 17.5 Volt
- Rated Current : 3.65 Ampere
- Open Circuit Voltage : 21.5 Volt
- Short Circuit Current : 4.05 Ampere
- Power Specification at STC : 1000 W/ m2 irradiance
- Manufacturer: Rahim Afrooz Bangladesh

Rating of the battery used is listed below:

- Voltage: 12 V
- Capacity: 7.2 AH
- Manufacturer: BSB Power Company Limited

During the experiment, the Duty cycle of the switching signal was manually varied and corresponding output current, I_o was measured through multimeter. It is to be noted that during this experiment the temperature and irradiation condition remains unchanged. Another set of data has been collected during different temperature and irradiation condition. Linear interpolation technique was applied on the experimental data to produce the *Io* vs Duty Cycle curves in Matlab. The resulting curves are shown in Fig. 11.

The proposed algorithm and the traditional P&O hill climbing algorithm were applied on the experimental data and the results are summarized below.

In the proposed algorithm the parameters which have been used for the practical data are included in Table III.

TABLE III: Parameters for Practical Data

Name	Value
$Threshold_1$	1%
$Threshold_2$	25%
Step size of duty cycle	1%
1st increase for parabolic interpolation	1%
2nd increase or decrease for parabolic interpolation	20%

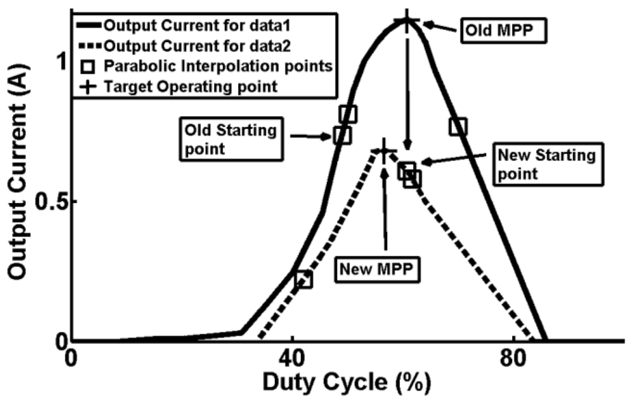

Fig. 12. Experimental results of the proposed algorithm for 2 different datasets simultaneously.

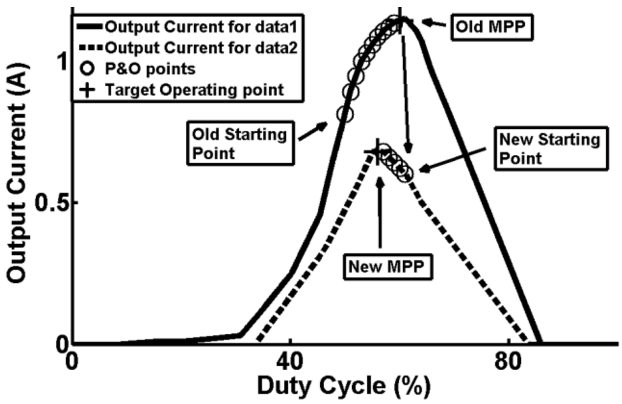

Fig. 13. Experimental results of the conventional P&O method for 2 different datasets simultaneously.

In Fig. 12, it is assumed that the starting duty cycle on data 1 curve is 49%. Now the algorithm will use another 2 points at 50% and 70% duty cycle to predict the MPP which is at duty cycle 61%. Now the P&O method will take over but the initial guess here is approximately correct, so the duty cycle remains 61%, I_{th} is measured. In this case the I_{th} falls below $Threshold_1$ and the algorithm recognize 61% duty cycle as the MPP and keeps on operating at 61% duty cycle until I_{th}

becomes greater than $Threshold_1$ or $Threshold_2$. In this way, continuous oscillation around MPP point (which is a problem of P&O method) is eliminated in the proposed approach. Here total 4 points are required to reach MPP.

Now let us assume that the weather condition changes and the new operating point is shown on the data 2 curve. In this case I_{th} becomes 45% which is greater than $Threshold_2$. So the algorithm will now use the parabolic interpolation technique to predict the new MPP. Here 61% duty cycle is the new starting point and the algorithm will use another 2 points at 62% and 42% duty cycle to predict the MPP which is at duty cycle 55%. Next the P&O method will take over, but again the initial guess is very accurate, so the duty cycle remains 55%, $I_{th}$is measured. In this case the I_{th} falls below $Threshold_1$ and the algorithm recognize 55% duty cycle as the MPP and keeps on operating at 55% duty cycle until I_{th}becomes greater than $Threshold_1$ or $Threshold_2$. Here another 4 points are required to reach MPP.

In Fig. 13, the results using the traditional P&O algorithm are shown. The starting duty cycle on data 1 curve is assumed to be 49% and the step size is assumed to be 1% duty cycle. In this case, 13 iterations are needed to reach MPP. Also the operating point will keep oscillating around the MPP.

TABLE IV: EXPERIMENTAL RESULTS FROM PRACTICAL DATASET 1

Method	Traditional Hill Climbing	Proposed Algorithm
Starting Duty Cycle	49%	49%
MPPT Duty Cycle	61%	61%
Total Iteration	4	13
Improvement	69.23%	

TABLE V: EXPERIMENTAL RESULTS FROM PRACTICAL DATASET 2

Method	Traditional Hill Climbing	Proposed Algorithm
Starting Duty Cycle	61%	61%
MPPT Duty Cycle	55%	55%
Total Iteration	4	7
Improvement	42.86%	

Now let us assume that the weather condition changes and the new starting point is shown on the data 2 curve, which is the same as the previous MPP point, i.e. 61% duty cycle. In this case, 7 iterations are needed to reach MPP.

The results from the practical data are summarized in Table IV and Table V.

So the proposed algorithm requires less iteration to track MPP than the traditional hill climbing algorithm. Also the continuous oscillation problem around MPP point is solved by the proposed approach.

VII. CONCLUSION

In this paper, a parabolic interpolation based MPPT technique has been proposed to track the maximum power point of a photovoltaic system. The proposed algorithm has been applied on the simulation and experimental data of a SEPIC topology based charge controller circuit and it has been found that the proposed algorithm can track the MPP with much less iteration than the traditional hill climbing algorithm. The proposed algorithm also introduces two threshold values. The lower threshold value prevents the continuous oscillation around MPP point during stable weather condition, whereas the higher threshold value determines whether the algorithm will use traditional hill climbing technique or the proposed technique to track MPP. When MPP shifts slightly from previous position, the proposed algorithm will use traditional hill climbing method to track the new MPP. On the other hand, when MPP shifts far from previous position due to sudden change in weather conditions, the proposed algorithm will track the MPP with less iteration. The team is going to implement this algorithm in the micro-controller based charge controller circuit and observe its transient performance in changing weather condition.

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M. Ziaur Rahman Khan received his B.Sc engineering and MSc. engineering from Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology and Ph.D. from University of Cambridge, UK in 2009. His research interests include characterization and modeling of SOI Devices with high-k dielectrics, numerical simulation of ultra-thin body SOI-MOSFETs, modeling power semiconductors, design and characterization of power electronic circuits, etc. He is currently a professor in the Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology.

Md. Zadid Khan was born in Rajshahi, Bangladesh, in 1991. He is now at his final year of undergraduate study under the Department of Electrical and Electronics Engineering (EEE) in Bangladesh University of Engineering and Technology (BUET). His research interest includes 3D quantum simulation of nanoscale devices, photovoltaic systems, ac/dc converters, numerical techniques etc.

Mohammad Nasimimtiaz Khan was born on September 25, 1990. he is pursuing his undergraduate degree under the Department of Electrical and Electronics Engineering (EEE) in Bangladesh University of Engineering and Technology. He became a member of ieee in 2012. His research field is properties Of graphene and its application on power devices.

Shammya Shananda Saha was born on 28 March, 1990 in Dhaka, Bangladesh. He is now at his final year of undergraduate study under the Department of Electrical and Electronics Engineering (EEE) in Bangladesh University of Engineering and Technology (BUET).His research interests include inductor-less DC-DC converter, smart grid and solar home system. He can be reached at shammya_eee@mail.com

Dewan Fahim Noor was born on December 6, 1991. He is pursuing his undergraduate degree under the Department of Electrical and Electronics Engineering (EEE) in Bangladesh University of Engineering and Technology. He became a member of IEEE in 2012. His research interest is sensitivity of Poly-HgI2 based X-ray image detectors.

Md. Rifat Kaisar Rachi was born in Rajshahi, Bangladesh, in 1993. He is now at his third year of undergraduate study under the Department of Electrical and Electronic Engineering (EEE) in Bangladesh University of Engineering and Technology (BUET). His research interest includes ac/dc & dc/dc converters, photovoltaic systems and power supply & control system for LED based lighting.