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Simulation and Performance Evaluation of P&O MPPT Algorithm for Off-Grid and Grid-Connected Solar PV Applications

Madavena Kumara Swamy
kumaraswamy2k21@gmail.com
Malla Reddy College of Engineering and Technology
Secunderabad, Telangana

Mangali Madhukar
mangalimadhu09@gmail.com
Malla Reddy College of Engineering and Technology
Secunderabad, Telengana

***Abstract*—This paper presents the simulation & performance evaluation of MPPT charge controller for standalone lead acid systems and photovoltaic grid connected system using P&O MPPT technique. The human activities contribute to global temperature rise, leading countries to reduce fossil fuel use. The world faces depleting non-renewable energy sources and rising costs, causing economic instability. Governments are exploring alternative energy source, the solar power can be one of the fastest growing and most promising. The solar power can be used as On-grid applications and Off-grid applications. The Off-grid applications are standalone systems. For standalone system a buck converter is used for charge control with the P&O MPPT algorithm tracking the PV panel's maximum power. The charge controller employs a 3-stage charging strategy. The overall charge controller efficiency reaches 98%, matching the commercial MPPT controllers. The On-grid applications means the PV power is directly integrated to the grid using power electronic converters and step-up transformer. This study evaluates the MPPT algorithm performance.**

***Keywords*—PV panel, MPPT algorithm, buck converter, boost converter, inverter, step-up transformer.**

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1. INTRODUCTION

The growing concern over global temperature rise, driven by human activities, has led to increased efforts by countries worldwide to reduce their dependence on fossil fuels. The depletion of non-renewable energy sources and the rising costs of traditional energy have created significant economic instability, prompting governments to explore alternative energy sources[1]. Among these alternatives, solar power has emerged as one of the most promising and rapidly growing renewable energy sources[2]. It offers a viable solution to the global energy crisis, with applications in both grid-connected (on-grid) and standalone (off-grid) systems[3]. In particular, standalone systems, often referred to as off-grid applications, play a crucial role in areas without access to a stable power grid. These systems typically rely on solar photovoltaic (PV) technology to generate electricity, which is then used to charge batteries for storing energy. To optimize the energy extraction from the PV panels, Maximum Power Point Tracking (MPPT) algorithms, like the Perturb and Observe (P&O) method, are employed[4-8]. These algorithms ensure that the solar panels operate at their maximum power output under varying environmental conditions.

The primary function of a grid-connected photovoltaic (PV) system is to extract the maximum amount of solar energy and feed it into the grid while maintaining a unity power factor[9], despite varying environmental conditions such as temperature and solar radiation. These systems are designed to enhance the performance of the electrical grid by reducing power losses, improving voltage profiles, and lowering the maintenance and operational costs of the utility grid. A typical grid-connected PV system consists of several key components: the PV solar cells, power converters, and the grid interface control system. The grid interface control system ensures the efficient transfer of power between the renewable energy source (solar energy) and the utility grid. It also manages the power factor of the PV inverter connection to the grid, ensuring that power quality remains high. Overall, grid-connected PV systems contribute to the stability and efficiency of the electrical grid while promoting the use of renewable energy[10-17].

This paper presents the design and simulation of an MPPT charge controller for standalone lead-acid battery systems and photovoltaic grid-connected systems, utilizing the P&O MPPT technique. The standalone systems are controlled using a buck converter[18], while a three-stage charging strategy is implemented to efficiently charge the battery. The MPPT controller is evaluated for its performance, and the results show that the charge controller achieves an efficiency of up to 98%, aligning with the specifications of commercial MPPT controllers. Additionally, the paper highlights the integration of

PV systems in on-grid applications, where the PV power is directly connected to the grid using power electronic converters and a step-up transformer. This study aims to provide a comprehensive evaluation of the P&O MPPT algorithm's effectiveness in both standalone and grid-connected solar PV systems[19-21].

2. MATHEMATICAL MODELING OF PV SYSTEM

Solar cells are made from semiconductor materials that generate electricity through the photovoltaic (PV) effect. This effect occurs when visible radiation (sunlight) strikes the P-N junction within the solar cell, causing the generation of a potential difference and, subsequently, an electric current. To enhance their power output, individual solar cells are connected together to form a solar module. A solar module typically consists of multiple solar cells, packaged together for long-lasting performance and high reliability in various applications. For larger-scale energy generation, multiple modules are connected to form a solar array, which can produce a substantial amount of electricity. The efficiency of these systems depends on the quality and design of the solar cells, modules, and arrays. Solar arrays are widely used for renewable energy generation in both residential and commercial applications, harnessing sunlight to produce clean, sustainable power[22-26].

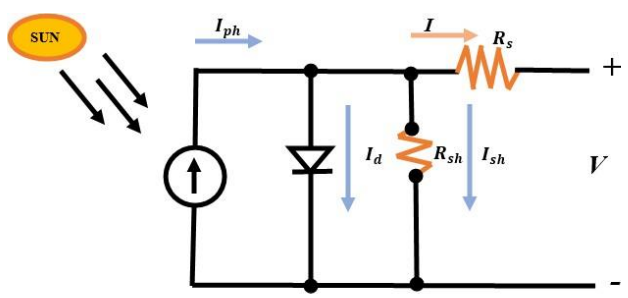

Fig.1 Equivalent circuit of a PV cell

An ideal photovoltaic cell can be represented by a light-generated current source Iph connected in parallel with a single diode, as shown in the equivalent circuit of Fig.1. The output current, I is denoted by equation(1).

$$I = I_{ph} - I_d = I_{ph} - I_o\,(e^{\frac{gV}{KT}} - 1) \quad \text{..... equation(1)}$$

The solar cell (or circuit) contains series (Rs) and parallel (or shunt, Rsh) resistances. This made I-V characteristic of solar cells different from the ideal photovoltaic model in equation(1) and gave rise to a characteristic of the form shown in equation(2).

$$I = I_{ph} - I_d = I_{ph} - I_o\,(e^{\frac{gV}{KT}} - 1) - I_{sh} \quad \text{....equation(2)}$$

Where

$$I_{ph} = [I_{sc} + K_i(T_r - T_o) * (\frac{S}{1000})] \quad \text{...................... equation(3)}$$

Equation (2) depends on the solar cell irradiance and cell's working temperature.

$$I_{rs} = \frac{I_{sc}}{[exp\,(\frac{qV_{oc}}{N_s AKT_o}) - 1]} \quad \text{.........equation(4)}$$

Equation(3) is the reverse saturate current at the reference temperature.

$$I_o = I_{rs}\,(\frac{T_o}{T_r})^3\; exp\,[\frac{q * E_{go}}{AK}(\frac{1}{T_r} - \frac{1}{T_o})] \quad \text{.......equation(5)}$$

Equation(4) is the diode saturated current, and it depends on the temperature.

$$I_{pv} = N_p * I_{ph} - N_p * I_o\,[exp\,(\frac{qV_{pv}}{N_s AKT}) - 1] \quad \text{........equation(6)}$$

$$P = I_{pv} * V_{pv} \quad \text{.....equation(7)}$$

Where

I_{pv}: Photocurrent (Ampere)

I_{sc}: Short-circuit current (Ampere)

K_i: Cell "s short-circuit current temperature coefficient (Ampere /Kelvin)

T_o: Cell operating temperature (Kelvin)

T_r: Cell" is reference temperature in degree (Kelvin)

S: Solar irradiance (Watt/meter square)

I_{rs}: reverse saturation current of the diode

q: Electron charge (1.602 × 10-19Coulomb)

V_{oc}: Open circuit voltage (Volt)

N_p: Cells interconnected in parallel (1)

N_s: Cells interconnected in series (36)

A: Ideality factor

k: Boltzmann's constant (1.38 × 10-23 Joule/Kelvin)

T: the temperature of p-n junction

I_{pv}: Output current of a PV module (A)

I_o: PV module saturated current (A)

V_{pv}: Output voltage of a PV module (A)

E_{go}: band gap for silicon

3. IMPLEMENTATION OF MPPT TECHNIQUES

A. *For Standalone System*

The P&O (Perturb and Observe) Maximum Power Point Tracking (MPPT) algorithm is widely used in small and medium-sized commercial solar photovoltaic (PV) charge controllers and grid-connected inverters due to its effectiveness and simplicity. The primary goal of this algorithm is to track the maximum power output of the PV array and adjust the duty cycle accordingly to optimize power transfer to the battery charge controller or inverter.

The P&O algorithm works through a trial-and-error process to find the maximum power point. It continuously monitors the changes in power output as it perturbs the PV panel's operating voltage by adjusting the duty cycle of the converter's switching device. These adjustments change the effective input resistance of the buck converter, which in turn affects the PV system's power generation. The algorithm then observes the resulting power output and checks whether it has moved closer to the maximum power point.

If the power output increases, the algorithm continues to adjust the voltage in the same direction; if the power output decreases, the direction of the voltage adjustment is reversed. This process of perturbing and observing continues indefinitely, allowing the system to dynamically track and adjust to the optimal power point, even under changing environmental conditions like sunlight and temperature. The Fig.2 represents the flowchart of P&O algorithm for standalone system.

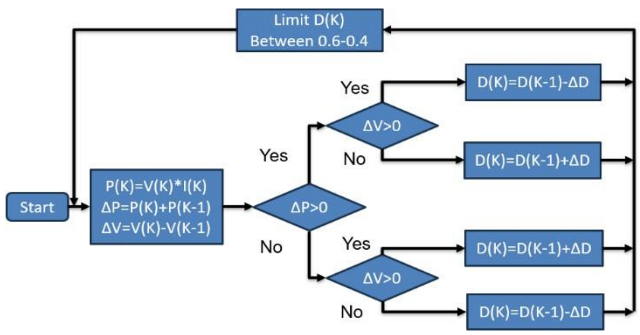

Fig.2 Flowchart of P&O algorithm for standalone system

This iterative method ensures that the solar system operates at its most efficient power output, providing maximum energy harvest from the PV array at all times. The simplicity and effectiveness of the P&O MPPT algorithm make it a popular choice in solar power applications.

The implementation of the MPPT Perturb & Observe (P&O) algorithm in Simulink is done entirely using blocks without any scripting code. Each block is labeled according to its function in the algorithm flowchart. The system takes voltage and current readings from the PV array, and the previous sample (K-1) is handled by a unit delay block. The three if-else conditions of the P&O algorithm are managed by a condition switch block. A ΔD block allows adjustment of the duty cycle's perturbation step size, while an adder with a memory block (D(K-1)) performs the duty cycle increment and decrement. The duty cycle is then limited within the range of 0.4 to 0.6 by a D(K) limit block. The output duty cycle is connected to the battery charge controller, and the PV power output is used for computing conversion efficiency. This design ensures a straightforward, block-based implementation of the MPPT algorithm in Simulink.

B. For Grid Connected System

The algorithm works by analyzing the relationship between the PV module's output power and its voltage, continuously adjusting the operating point to find the maximum power point (MPP). The below Fig.3 represents about the flowchart of P&O algorithm for grid connected system.

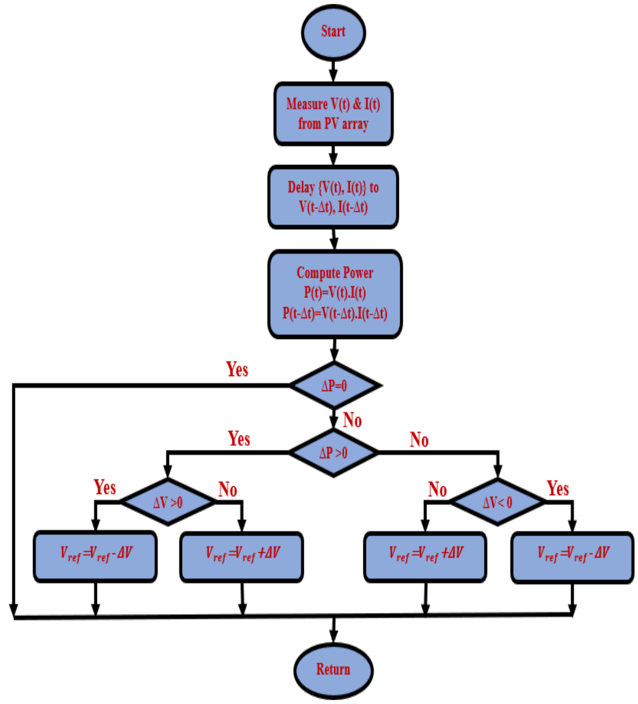

Fig.3 Flowchart of P&O algorithm for grid connected system

The P&O algorithm starts by measuring the voltage and current from the PV array, which are then multiplied to calculate the actual power output of the PV module. The algorithm then checks whether the power change (ΔP) is zero, indicating that the system is already operating at the MPP. If ΔP is not zero, the algorithm proceeds by comparing the power change (ΔP) with the voltage change (ΔV).

When ΔP > 0 (indicating an increase in power), the algorithm checks the sign of ΔV:

- If **ΔV** > **0**, it means the operating point is to the left of the MPP (under-voltage), and the algorithm increases the voltage to move towards the MPP.
- If **ΔV < 0**, the operating point is to the right of the MPP (over-voltage), and the algorithm decreases the voltage to move towards the MPP.

This process of perturbing the voltage and observing the power output is continuously repeated, gradually guiding the system to the MPP. However, there is a trade-off between the step size of the voltage perturbation and the sampling rate of the algorithm. A small step size leads to more accurate tracking but slower convergence, while a larger step size provides faster tracking at the cost of potential overshooting or instability. Despite these trade-offs, the P&O algorithm remains a highly effective and popular method for MPPT in PV systems.

4. RESULTS

The two models are simulated in the matlab and simulink platform, and the results obtained of the standalone system and the grid connected system by using two different P&O

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algorithms are shown in below figures.

A. Standalone System

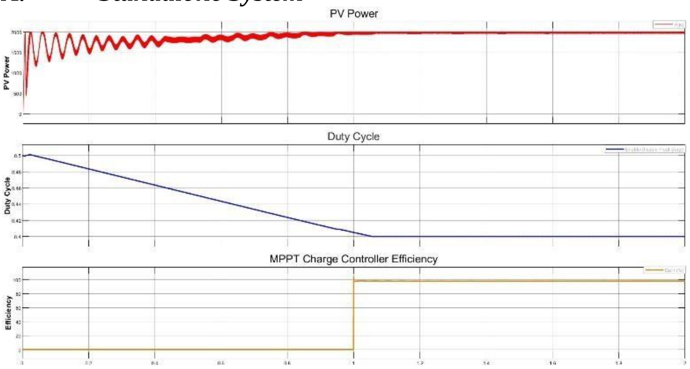

Fig.4 Results of standalone system

The red line represents the PV power, the blue line represents the duty cycle to operate the buck converter switch, and the gold line represents about the MPPT charge controller efficiency. The performance of the MPPT algorithm was evaluated by varying solar irradiance from 100 W/m² to 1000 W/m² in 100 W/m² steps, with a 2-second interval. A sudden drop from 1000 W/m² to 100 W/m² at 20 seconds simulated a passing cloud. The PV array, based on a commercial module, was configured with two parallel strings of four panels each, producing a total of 2 kW. The MPPT perturbation step was set to 1e-6. The system showed fast and accurate tracking of the maximum power point, with tracking times under 0.5 seconds and a tracking efficiency of 99.9% at 300 W/m², delivering 579W. When the battery voltage reached 55.4 V at 15 seconds, the charge controller switched to a constant voltage mode, with the duty cycle toggling between MPPT and zero. At 42 seconds, when the state of charge (SoC) reached 100%, the controller switched to the float stage, reducing the battery voltage to 52.8V.

B. Grid Connected System

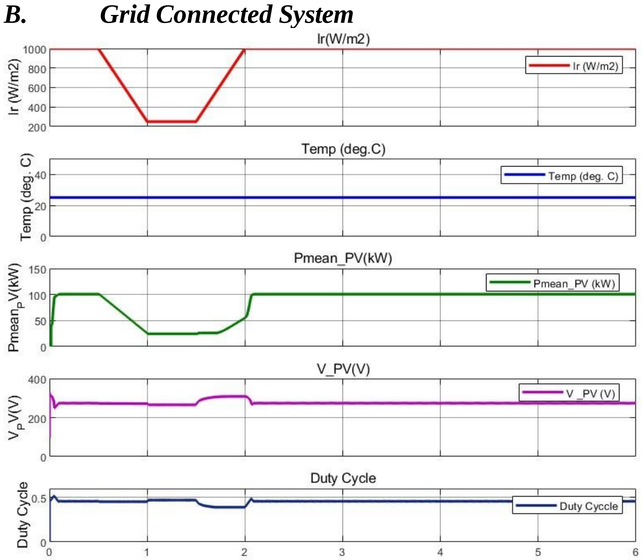

Fig.5 Outputs of PV Array

In the Fig.5 red color line represents about the Irradiation(Ir). The Ir is 1000W/$m2$. At initial from 0 – 0.5 sec the Ir is constant, from 0.5 – 1 sec the Ir is decreased to lowest value and continued upto 1.5 sec due to the partial shading conditions. Then after the Ir in slowly increased upto 2 sec and then it is constant. The blue color line represents about the Temperature. The temp is 25 degree C. It is maintained constant. The green color line represents about the output power of the PV panel. The max output power is 100kw. From 0 – 0.5 sec the power is constant, then from 0.5-1 sec the power is decreased due to partial shading conditions. From 1-1.5sec the power is lower only then 1.5 2sec it is increased and maintained constant. The pink color line graph represents about the voltage(V) of the PV panel. The V is generated upto the 230v from initial to 1.5 sec. Then from 1.5-2.1sec the V is gets some distractions. Then 2.1 it is maintained constant. The dark blue color graph represents about the duty cycle for boost converter switching operation.

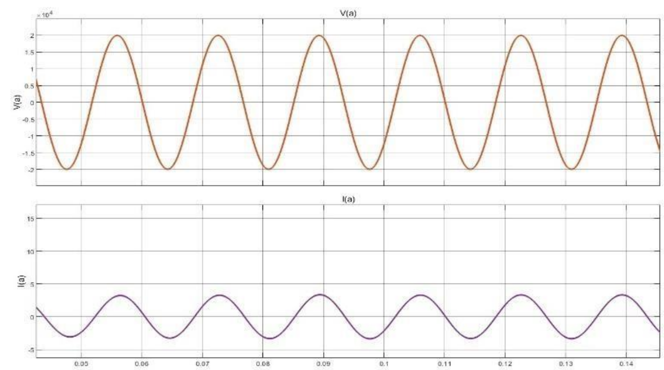

Fig.6 A-phase voltage and current (grid side)

Here this Fig.6 represents about the phase voltage & current (A-phase). The voltage is in AC form and the voltage is 20kw and the current is upto 5A.

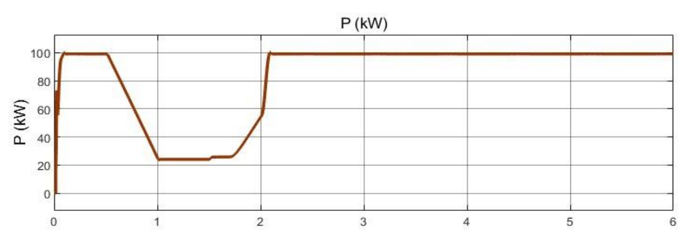

Fig.7 Gride side Power

The Fig.7 represents about the Grid power which is integrated. From 0-0.5sec the power is max i.e.,100kw from 0.5-1sec it is decreased and it continued till 1.5sec then it is increased and it will settle at 2sec. This change is due to partial shading conditions.

5. CONCLUSION

This paper presents the comparison of a Solar PV MPPT battery charge controller and grid connected PV system in

Simulink. The charge controller incorporating the Perturb and Observe (P&O) MPPT algorithm, a buck converter, and a three-stage charging strategy to efficiently charge a 12V lead-acid battery from a 2 kW PV array. The system achieves an impressive average efficiency of 98.3%, comparable to high-end commercial MPPT charge controllers. The model is fully reproducible and adaptable for different commercial applications with similar topologies, providing an effective solution for solar battery charging.

In comparison, a grid-connected PV system using the P&O MPPT algorithm offers a reliable solution for harnessing solar energy. It continuously adjusts the system's operating point to extract maximum power, ensuring optimal performance even as environmental conditions fluctuate. Surplus energy can be fed back into the grid, contributing to renewable energy generation and reducing dependence on conventional power sources. Additionally, the system can draw power from the grid when solar generation is insufficient, ensuring a stable energy supply.

Both approaches highlight the effectiveness of the P&O MPPT algorithm in optimizing solar energy utilization, with the battery charge controller focusing on efficient charging and the grid-connected system enhancing sustainability through grid integration.

REFERENCES

[1] T. Hoff and D. S. Shugar, "The value of grid-support photovoltaics in reducing distribution system losses," in IEEE Transactions on Energy Conversion, vol. 10, no. 3, pp. 569-576, Sep 2015

[2] B. N. Mohapatra, A. Dash, B. P. Jarika, Power Saving Solar Street Lights, International Journal of Emerging Technologies in Engineering Research, 5, 105-109 (2017).

[3] Trishan Esram, Patrick L. Chapman, Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques, IEEE Transactions on Energy Conversion, 22, 439-449 (2007).

[4] Mohamed A. Eltawil, Zhengming Zhao, MPPT Techniques for Photovoltaic Applications, Renewable and Sustainable Energy Reviews, 25, 793-813 (2013).

[5] Ankur Bhattacharjee, Design and Comparative Study of Three Photovoltaic Battery Charge Control Algorithms in MATLAB/Simulink Environment, International Journal of Advanced Computer Research, 2, 129-135 (2012).

[6] Mohamed A. Enany, Mohamed A. Farahat, Ahmed Nasr, Modelign and Evaluation of Main Maximum Power Point Tracking Algorithms for Photovoltaics Systems, Renewable and Sustainable Energy Reviews, 58, 1578-1586 (2016).

[7] Nabil Karami, Nazih Moubayed, Rachid Outbib, General Review and Classification of Different MPPT Techniques, Renewable and Sustainable Energy Reviews, 68, 1-18 (2017).

[8] B. Sree Manju, R. Ramaprabha, B.L. Mathur, Modelling and Control of Standalone Solar Photovoltaic Charging System, International Conference on Emerging Trends in Electrical and Computer Technology (2011).

[9] L. Hossain, E. Olias, J. Quintero, M. Haddadi, "Digital power factor control and reactive power regulation for grid-connected photovoltaic inverter, Renewable Energy", Volume 34,Issue 1, January 2015, Pages 315-321, ISSN 0960-1481.

[10] S Krauter, R Rüther, ―Considerations for the calculation of greenhouse gas reduction by photovoltaic solar energy, Renewable Energy‖, Volume 29, Issue 3, March 2014,Pages 345-355, ISSN 0960-1481.

[11] U. Borup, F. Blaabjerg and P. N. Enjeti, "Sharing of nonlinear load in parallel- connected three- phase converters," in IEEE Transactions on Industry Applications, vol. 37, no. 6, pp. 1817-1823, Nov/Dec 2011.

[12] Manohar, K & Shobha Rani, P 2012, ―MPPT and Simulation for a Grid-Connected Photovoltaic System and Fault Analysis‖, The International Journal of Engineering and Science, vol. 1, no. 2,pp. 158-166.

[13] Huajun Yu, Junmin Pan, An Xiang, "A multi-function grid-connected PV system with reactive power compensation for the grid, Solar Energy‖, Volume 79, Issue 1, July 2015, Pages 101-106,ISSN 0038-092X.

[14] Yang B, Li W, Zhao Y, He X (2010) Design and analysis of a grid-connected photovoltaic power system. IEEE Trans Power Electron 25(4):992–1000.

[15] Pires V, Husev O, Vinnikov D, Martins JF (2015) A control strategy for a grid-connected PV system with unbalanced loads compensation. In: IEEE 9th international conference on compatibility and power electronics (CPE). pp 154–159.

[16] Ahmed AS, Berzoy A, Mohammed O (2017) Design and hard ware implementation of FL-MPPT control of PV systems based on GA and small-signal analysis. IEEE Trans Sustain Energy 8(1):279–290.

[17] Nandurkar SR et al (2014) Modeling simulation & design of photovoltaic array with MPPT control techniques. Int J Appl Power Eng (IJAPE) 3(1):41–50.

[18] Illan Glasner, Joseph Appelbaum, Advantage of Boost vs Buck Topology for Maximum Power Point Tracker in Photovoltaic Systems, IEEE Proceedings of 19th Convention of Electrical and Electronics Engineers in Israel, (1996).

[19] N Elgendy M, Zahawi B, Atkinson D (2012) Assessment of perturb and observe MPPT algorithm implementation techniques for PV pumping applications. IEEE Trans Sustain Energy 3(1):21–33

[20] Ozcelik MA, Yilmaz AS (2016) Effect of improving perturb and observe MPPT algorithm on AC grid connected PV systems. IU JEEE 16(2):3025–3032

[21] Elgendy M, Zahawi B, Atkinson D (2012) Assessment of perturb and observe MPPT algorithm implementation techniques for PV pumping applications. IEEE Trans Sustain Energy 3(1):21–33

[22] Ghani Faisal, Rosengarten Gary, Duke Mike, Carson JK. The numerical calculation of single-diode solar-cell modelling parameters. Renew Energy 2014;72:105–12.

[23] Tripathi Abhishek Kumar, Ray Shashwati, Aruna Mangalpady, Prasad Sandeep. Evaluation of solar PV panel performance under humid atmosphere. Mater Today Proc 2021;45:5916–20

[24] Jakhrani Abdul Qayoom, Samo Saleem Raza, Kamboh Shakeel Ahmed, Labadin Jane, Rigit Andrew Ragai Henry. An improved mathematical model for computing power output of solar photovoltaic modules. Int J Photoenergy 2014;2014.

[25] Edouard Mboumboue, Njomo Donatien. Mathematical modeling and digital simulation of PV solar panel using Matlab software. Int J Emerg Technol Adv Eng 2013;3(9):24–32.

[26]] Chan Daniel SH, Phang Jacob CH. Analytical methods for the extraction of solar-cell single-and double-diode model parameters from IV characteristics. IEEE Trans Electron Devices 1987;34(2):286–93.