International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 1s, 2025
https://www.theaspd.com/ijes.php

A Hybrid Iot–Metaheuristic Approach For Accurate Parameter Estimation Of Solar Pv Cells Using Matlab

Subhash Gokul Patil[1*], Dr Rajesh Kumar Nagar[2]
[1*]Research Scholar, Department. of ECE, IET, SAGE University, Indore, MP, India ,
Subhashpatil1902@gmail.com
[2]Associate Professor, Department. of ECE, IET, SAGE University, Indore, MP, India,
Errajesh973@gmail.com

***Abstract*-** *Accurate parameter estimation of solar photovoltaic (PV) cells is essential for performance prediction, maximum power point evaluation, and real-time system optimization. This work presents the design and implementation of a single-diode PV model and an advanced parameter estimation framework based on metaheuristic optimization. The five key nonlinear parameters—photocurrent (Iph), saturation current (I0), ideality factor (n), series resistance (Rs), and shunt resistance (Rsh)—are estimated by minimizing the deviation between measured and modeled I–V characteristics. Population-based techniques such as Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), and Wind-Driven Optimization (WDO) are implemented and compared in terms of convergence speed, computational efficiency, and estimation accuracy within a MATLAB simulation environment. Error metrics including RMSE, MAPE, and R^2 demonstrate that the metaheuristic approach significantly outperforms classical analytical estimation, providing robust parameter extraction under varying irradiance and temperature. The proposed framework offers a reliable foundation for intelligent monitoring, diagnostics, and performance forecasting in modern PV systems.*

Keywords— *Solar energy, Photovoltaic modules and cells, parameter estimation, maximum power point tracking, Internet of Things (IoT), MATLAB*

i. OBJECTIVE OF STUDY

The primary objective of this work is to develop a comprehensive and reliable framework for estimating the key parameters of a solar PV cell by integrating analytical modeling, IoT-based real-time data acquisition, and MATLAB-supported
metaheuristic optimization techniques. The study aims to first obtain initial parameter approximations through classical analytical equations, then enhance the accuracy of these estimates using high-resolution voltage, current, temperature, and irradiance data collected through an IoT sensing platform. MATLAB serves as the computational environment where metaheuristic algorithms refine the analytical estimates by minimizing modeling errors between measured and simulated I–V characteristics. By combining these three complementary approaches, the objective is to achieve highly accurate, robust, and adaptive parameter extraction capable of reflecting real operating conditions and improving the reliability of PV system modeling..

ii. INTRODUCTION

Accurate parameter estimation of solar photovoltaic (PV) cells is fundamental to reliable performance modeling, maximum power point evaluation, and efficiency improvement in modern solar energy systems. Because PV cells exhibit nonlinear electrical behavior affected by irradiance, temperature, and material variations, identifying intrinsic parameters such as photocurrent, saturation current, ideality factor, and internal resistances requires approaches that go beyond traditional analytical formulas. Analytical techniques offer an essential starting point by providing initial parameter approximations; however, their accuracy is often limited under dynamic environmental conditions. The availability of Internet of Things (IoT)–based sensing platforms has significantly strengthened this process by enabling continuous acquisition of real-time operating data—such as voltage, current, irradiance, and temperature—which allows parameter estimation to reflect true field behavior rather than static assumptions.

With the expansion of computational capabilities in MATLAB, metaheuristic optimization techniques such as Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), and Wind-Driven Optimization (WDO) now offer powerful tools to refine analytically derived parameters. These algorithms effectively handle the nonlinear and multidimensional nature of the estimation problem by globally searching the solution space and minimizing error between measured and modeled I–V characteristics. Integrating analytical modeling, IoT-driven data collection, and MATLAB-based metaheuristic optimization leads to a comprehensive and highly accurate

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 1s, 2025
https://www.theaspd.com/ijes.php

estimation framework. This hybrid approach enhances robustness, achieves better convergence, and improves the reliability of PV performance prediction under varying environmental and operational conditions.

iii. BASIC OPERATION OF PV CELL

Photovoltaic (PV) cells are formed by joining two semiconductor layers: a positively doped (p-type) layer and a negatively doped (n-type) layer, creating a p–n junction. When sunlight reaches the surface of the cell, photons transfer their energy to electrons within the semiconductor material. This excitation frees electrons from their atomic bonds and generates corresponding electron–hole pairs. Driven by the built-in electric field at the p–n junction, the liberated electrons migrate toward the n-type region while the holes move toward the p-type region. When an external circuit is connected across the cell terminals, these electrons flow through the load, producing a direct electric current. This fundamental photoelectric process enables PV cells to convert incident solar radiation directly into usable electrical energy.

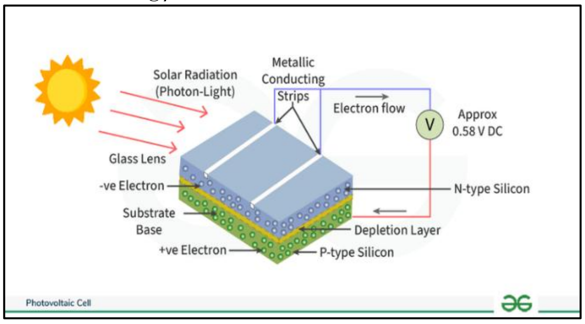

Fig 1.Basic operation of PV Cell

The current–voltage (I–V) and power–voltage (P–V) characteristic curves of a photovoltaic (PV) cell provide essential insight into its energy conversion behavior and efficiency. These curves describe how the output current, voltage, and power vary under different operating conditions, and they are fundamental for assessing key performance metrics such as the maximum power point (Pmax) and overall conversion efficiency. Analysis of the I–V characteristics is particularly important because it reflects the combined influence of irradiance, temperature, and internal cell parameters on the electrical response of the PV device.

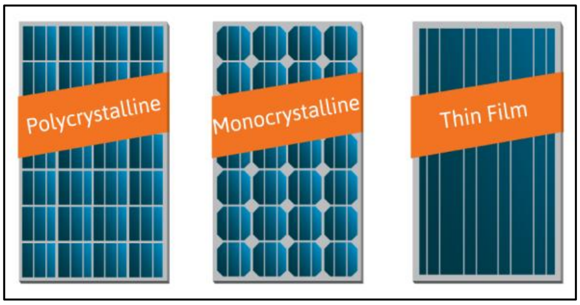

Figure 2. Photovoltaic Cell Types

Figure 2 illustrates the essential parameters and characteristic points associated with a PV cell's behavior, which are used to evaluate and optimize the electrical model—especially for single-diode, double-diode, and other diode-based PV representations. These characteristic features form the basis for parameter extraction techniques, enabling accurate modeling and performance prediction for PV cells, modules, and arrays.

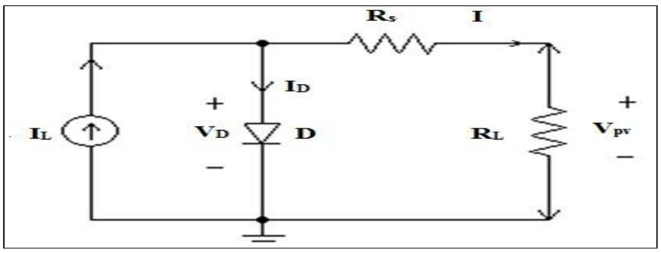

Fig. 3. Practical representation of Single diode model

By applying the Kirchhoff law to the node of the circuit reported in Fig.3 the current I produced by the photovoltaic module is obtained.

$I = I_L - I_D$ .... (1)

Where:
I_D = Diode current;
I_L = Photoelectric current related to a given condition ofradiation and of temperature.
I_D diode current is given by the Shockley equation: $I_D = I_0$.................. (2)
R_S =Series resistance of the cell [Ω];
q = electron charge ($1.602x10^{-19}$ C);
k = Boltzmann constant ($1.381x10^{-23}$ J/K);
T_C = photovoltaic cell temperature [K]
By substituting (2) into (1) the following equation is obtained which represents the I-V module characteristic curve under generic radiation and temperature conditions.

$$I = I_L - I_0\left[\exp\left(\frac{q(V-IRs)}{\gamma kTc}\right) - 1\right] \text{............ (3)}$$

The model in (3) describes the operation of a photovoltaic module assuming known values of RS, I0, and IL, which can be derived from standard datasheet values like ISC,REF (short-circuit current) and VOC,REF (open-circuit voltage). To account for changes in diode saturation current and PV current due to variations in temperature and irradiance from standard conditions, the model is refined using additional equations

$$I_0 = I_{0REF}\left(\frac{Tc}{Tcref}\right)^3 \exp\left[\left(\frac{qEg}{k\gamma}\right)\left(\frac{1}{Tcref} - \frac{1}{Tc}\right)\right] \text{...... (4)}$$

Where:
Eg is the energy gap of the material with whom the cell ismade (for the silicon it’s 1 to 1.2 eV).
The main output current through photovoltaic cell is:

$$I_L = \left(\frac{G}{Gref}\right)[Iref + \mu(Tc - Tcref)] \text{............ (5)}$$

Where:
G is the radiation [W/m2]
Gref is the radiation under standard conditions [W/m2]Iref is the photoelectric current under standard
Tcref temperature coefficient of the short-circuit condition.The cell voltage can be given by:

$$V = \frac{\gamma kTc}{q} ln\left(\frac{IL-I}{Io} + 1\right) - IRs \text{.................. (6)}$$

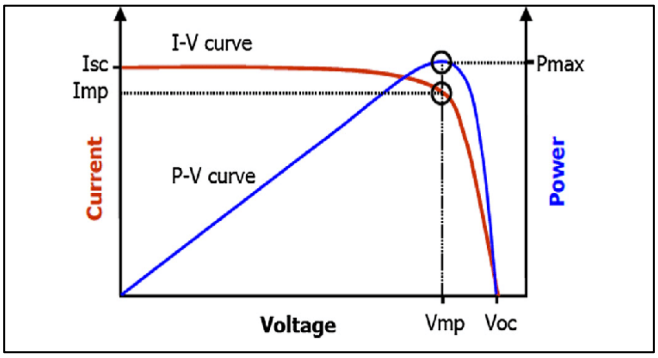

Fig. 4. I-V and P-V Characteristics of PV Cell

Photovoltaic (PV) systems are becoming increasingly significant in modern power generation, making accurate electrical modeling of PV cells essential for evaluating performance, controlling operation, and tracking the maximum power point. Determining the correct circuit parameter values is a key requirement for reliable simulation and optimization of PV panels. This challenge—commonly referred to as the PV cell parameter estimation problem—has attracted extensive research attention. Previous studies can generally be categorized based on parameter extraction methods applied to different diode-based PV models, including the single-diode, double-diode, and triple-diode representations.

IV. Key Related

A comprehensive review of existing research on solar PV parameter estimation reveals that a variety of methodologies have been developed to address the nonlinear nature of the PV modeling problem. To organize these contributions effectively, the literature in this work is grouped into four key categories: analytical approaches, IoT-based measurement and monitoring techniques, MATLAB-driven simulation and modeling strategies, and metaheuristic optimization methods. Each category highlights distinct strengths and limitations, providing a structured foundation for understanding current advancements and the motivation behind integrating these techniques in the proposed framework.

A. The Analytical Five Point method

The single-diode lumped-parameter equivalent circuit of a solar cell, shown in Figure 3, is widely used to represent its electrical behavior under illumination. This model effectively captures the key physical characteristics governing the operation and performance of a solar photovoltaicdevice.

$$I = I_{\mathrm{L}} - I_0 \left(e^{\frac{V+IR_{\mathrm{s}}}{nV_{\mathrm{T}}}} - 1 \right) - \frac{V+IR_{\mathrm{s}}}{R_{\mathrm{sh}}}$$

It has been demonstrated that the circuit parameters IL,IS,RSH,0IL,RS,RSH,I0, and n at a specific temperature and illumination level can be computed based on the measured values VOC,ISC,VMP,IMP,RS,VOC,ISC,VMP ,IMP,RS, I-V characteristic.and RS and RSH obtained from the following analysis.

The following non-linear equations can be derived from the circuit model:

$$I_s\left(\exp\frac{V_{oc}}{nV_T} - \exp\frac{I_{sc}R_s}{nV_T}\right) - I_{sc}\left(1+\frac{R_s}{R_{sh}}\right) + \frac{V_{oc}}{R_{sh}} = 0. \quad (2)$$

$$(R_{so} - R_s)\left(\frac{1}{R_{sh}} + \frac{I_s}{nV_T}\exp\frac{V_{oc}}{nV_T}\right) - 1 = 0 \quad (3)$$

$$\frac{1}{R_{sh}} - \frac{1}{R_{sho} - R_s} + \frac{I_s}{nV_T}\exp\frac{I_{sc}R_s}{nV_T} = 0 \quad (4)$$

$$I_s\exp\frac{V_{oc}}{nV_T} + \frac{V_{oc} - V_m}{R_{sh}} - \left(1+\frac{R_s}{R_{sh}}\right)I_m - I_s\exp\frac{V_m + R_sI_m}{nV_T} = 0. \quad (5)$$

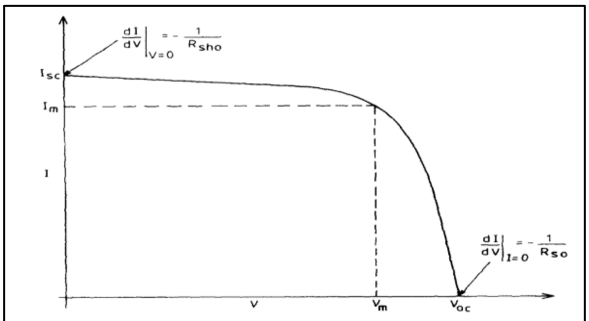

Fig. 2. Input parameters for the 5-point methods.

Fig. 5 IV Characteristics of diode moule

In 2015, Haroon Ashfaq conducted a study comparing new, recycled, and aged PV modules, emphasizing the importance of accurate mathematical modeling and parameter estimation for reliable reuse and performance assessment. MATLAB/Simulink was utilized to analyze module behavior using the single-diode model, enabling precise comparison between measured and simulated characteristics. The study highlighted the critical role of accurately determining the series resistance Rs even when manufacturer data is available, as discrepancies between the experimental and computed maximum power points often arise. An iterative procedure was adopted to compute paired values of Rs and Rp with only the combination that reproduced the experimental peak power considered valid.

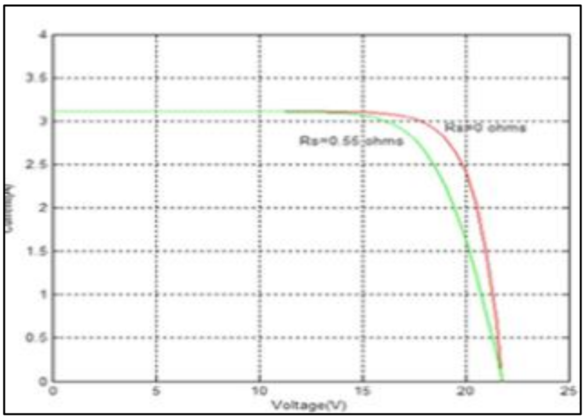

Fig.6 Simulink reslut characteristics of cell

The proposed R p model gave (Rs = 0.45 O,R p = 310.0248 O) instead of (R s = 0.55 O, and R p not provided). So it can be estimated to be more accurate in simulating the PV module.

C. Mallareddy (2015) suggests that real-time solar PV panel efficiency may be lower than simulated results.They developed a MATLAB mathematical model with LabVIEW monitoring, focusing on consistent irradiation and fluctuating temperatures. National Instruments (NI) hardware, including cDAQ-9178, DAQ-9225, and DAQ-9227, connected to a laptop for real-time monitoring through graphical programming. The study aimed to identify efficiency-reducing factors, explore parameter estimation, and improve unknown variables, offering insights for PV panel optimization [9].

In 2015, Xuan Hieu Nguyen used MATLAB's user-friendly Simulink feature to create a comprehensive model for a photovoltaic (PV) array. This modeling approach, based on fundamental PV module principles, integrated operational curves to understand I-V (current-voltage) and P-V (power-voltage) characteristics, accounting for adjustable parameters, both known and unknown. In the same year, Subhash Apatekar et al. tackled a fundamental mathematical challenge by combining PV cell equations with electronic theory. They employed MATLAB Simulink to model PV cells and analyzed output variations due to external factors like temperature and irradiance, crucial for parameter estimation and understanding PV cell attributes.

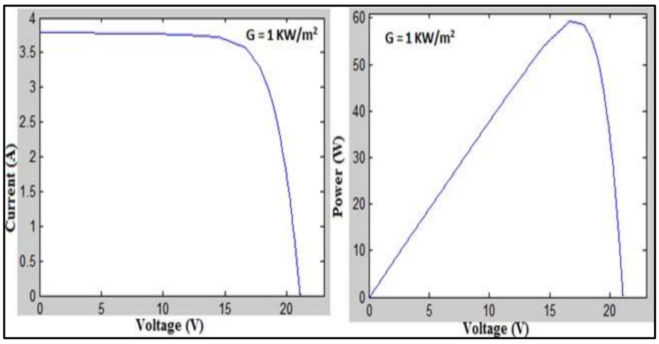

Fig. 7 V-I and P-V characteristics of PV cell when G = 1KW/m2

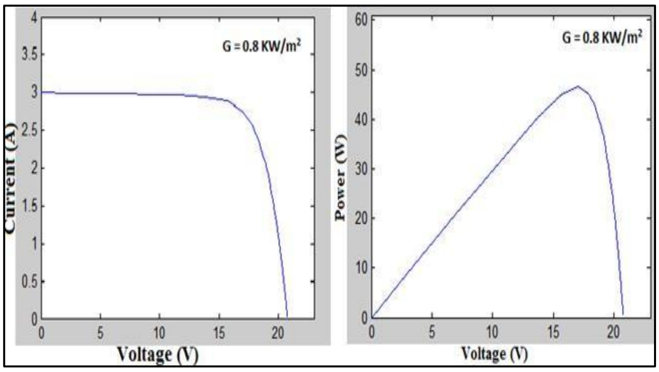

Fig. 8 V-I and P-V characteristics of PV cell when G = 8KW/m2

It is conclude that photovoltaic current vary directly w. r. t variation in solar radiation, whereas PV voltage slightly changes.

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 1s, 2025
https://www.theaspd.com/ijes.php

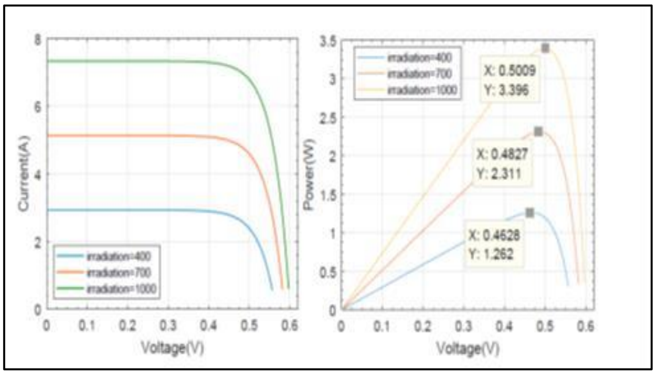

Fig. 9 IV Charactristics fom MATLAB output

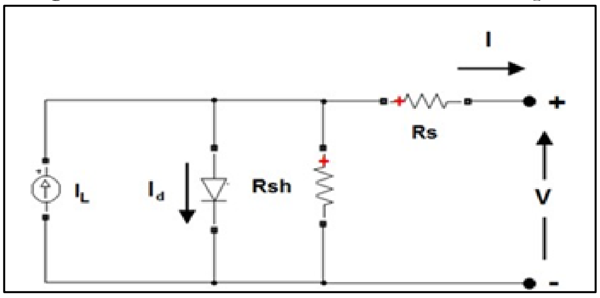

Fig.10. Single diode model of PvV cell

In 2017, C. Saha introduced a parameter estimation technique using experimental data and the Simulink method in MATLAB, employing the Double Diode Model. The study analyzed alterations' impact on I-V and P-V characteristics using the SUNSET PV Module Model PX-170. They used a two-diode photovoltaic cell model with a lumped circuit configuration for parameter estimation and compared it meticulously with the PV cell data sheet, using a direct optimization approach.

Rabeh Abbassi and team introduced a hybrid analytical model implemented through MATLAB. This model is based on the accurate mathematical representation of the single diode model, aiming to uncover initially unknown electrical characteristics in solar PV cells. Their study combined analytical and numerical strategies to enhance model accuracy, comparing outcomes with manufacturer datasheet specifications using PV models like "STP250S-20/Wd" and "TSM-PD14" [18]. Van Huong Dong and co-researchers developed the differential particle swarm optimization (DPSO) method to improve photovoltaic system efficiency by precisely identifying the optimal power point. This method excels in tracking the maximum power point (MPP) and optimizing power extraction under varying conditions with fewer iterations than traditional techniques.

G (W/m^2)	Without MPPT	P&O	InCond	PSO	DPSO	the theoretical value of PV
600	4567.0	5137.0	5137.4	5157.2	5157.5	5157.7
700	5913.0	5994.8	5995.0	6009.0	6009.2	6009.7
800	6820.0	6812.0	6812.3	6849.1	6849.5	6850.0
900	7360.0	7655.0	7656.0	7677.2	7678.0	7678.3

Table 1: The obtained results of output power without/with the MPPT controller

They used Simulink and MATLAB Toolbox to implement the PV system with the DPSO-MPPT algorithm, based on the single-diode PV module model. Simulation results demonstrated its robustness, achieving energy outputs exceeding 99.5% across diverse environmental conditions. Supriya Patil and Dr. Rahul Agrawal (2021) proposed a study integrating analytical and metaheuristic-based optimization methods in the mathematical modeling of PV modules.

They identified equations for MATLAB to compute the five parameters, utilizing the single diode model for simplicity. Their outcomes were compared with alternative approaches, confirming applicability and suitability. Diagram below shows output power provided by the PV cell is affected by temperature and irradiance, both of which are critical environmental parameters.

B Based on Neuro-Fuzzy Logic

In 2014, Ravinder Kumar Kharb developed a MATLAB Simulink model for a single-diode PV module based on the MXS 60 PV module's datasheet. This model integrated an adaptive neuro-fuzzy inference system (ANFIS) and an MPPT tracker for comparing various parameters. The study introduced an ANFIS-based MPPT controller for solar PV modules, demonstrating its effectiveness in enhancing output power under varying weather conditions. This research delves into progressive parameter estimation for different PV models, emphasizing the importance of accurate estimation for improving PV system efficiency. It covers single-diode, double-diode, and three-diode models, exploring the use of evolutionary algorithms (EA) for optimization, offering valuable insights for researchers in this field

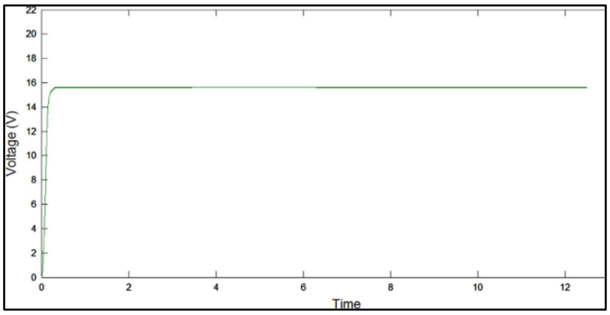

Fig.11. Output voltage vs. time at 600 W/m^2 irradiance

Fig. Output Current Vs. Time at 600 W/m^2 irradiance

The resulting waveforms of voltage and current at irradiance level of 600 W/m^2 in figures respectively. It is observed from the waveforms that output voltage and current quickly reach to their maximum value.

In 2015, Mohammad Jamadi developed a precise parameter estimation technique for Single and Double Diode Models using a modified artificial bee colony (ABC) algorithm, efficiently computing PV cell parameters. Results were compared with GA, PS, PSO, and ABSO algorithms, demonstrating its superiority over traditional analytical methods. Mohammad Zamen investigated the thermal efficiency of photovoltaic-thermal setups, considering temperature, recirculation flow rate, and sunlight exposure. Using the multilayer perceptron artificial neural network, adaptive neuro-fuzzy inference system, and least squares support vector machine, the research improved alignment with manufacturing data, relevant for solar PV system parameter estimation and optimization.

C. Based on different Metaheuristic Algorithms.

In 2015, Vandana Khanna and colleagues investigated predicting solar parameters for industrial solar cells using a three-diode model and the Particle Swarm Optimization (PSO) algorithm. They introduced a new lumped-parameter equivalent circuit model with a broad working range to determine ideality factors, applying the PSO method for optimization.

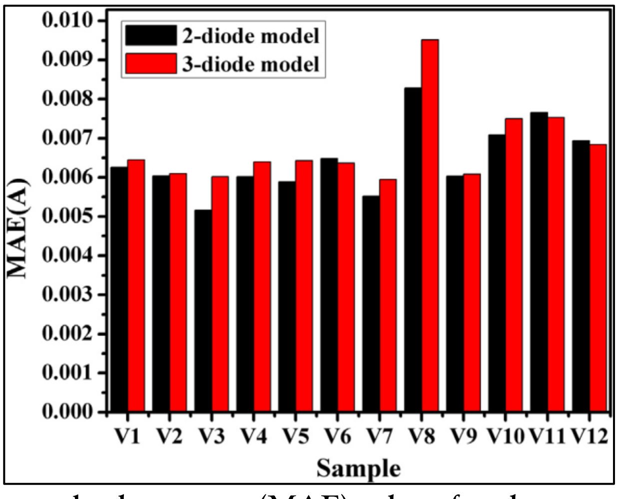

Fig.12 Comparison of mean absolute error (MAE) values for the two different models showing that they were comparable for the two models.

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 1s, 2025
https://www.theaspd.com/ijes.php

MAE values were compared for different silicon solar cell samples for the two models. General observation is that, MAE was a little higher for the three-diode model in most cases, as compared to the two-diode model as shown in bar chart.

In 2017, M. Derick conducted a thorough comparison of various parameter determination techniques in nonlinear models. The study explored optimization methodologies, including Harmony Search, Artificial Bee Swarm Optimization (ABSO), Oppositional Teaching Learning Based Optimization (OTLBO), Genetic Algorithm, Pollinator Flower Pollination Algorithm (BPFPA), and Pattern Search (PS) (HS). These methods are commonly used to identify and estimate unknown parameters. The study introduced and compared a novel optimization technique called Wind Driven Optimization (WDO) with the aforementioned methods. WDO represents an advanced technology for precisely characterizing solar cell properties through efficiency-enhancing techniques. It excels in generating accurate ideal values across different environmental scenarios, requiring fewer iterations. In the realm of optimization, WDO emerges as a commendable choice.

In 2020, Hussein Mohammed Ridha introduced an approach for the estimation of the five parameters inherent to a single diode PV module model, drawing inspiration from electromagnetism. This novel algorithm integrates both local search and an enhancement phase to broaden the spectrum of feasible solutions. Furthermore, a noteworthy aspect of this innovation involves the incorporation of nonlinear equations that modify the particle's length. The method's efficacy and swiftness are readily evident when juxtaposed with alternative models. This discernible advantage positions our method ahead of other strategies in terms of precision and convergence. To validate the approach's analytical performance, a comparison was executed using specifications extracted from the Kyocera KC120-1 PV module datasheet.

v. SINGLE DIODE MODELING AND FEATURE EXTRACTION USING THE INTERNET OF THINGS (IOT)

The Internet of Things (IoT) plays a significant role in improving PV parameter estimation by enabling continuous monitoring and acquisition of real-time operating data such as irradiance, temperature, voltage, and current. IoT-enabled sensors mounted on solar panels transmit this information to a centralized platform, where it can be used to refine analytical and computational models of PV performance. Such real-time data supports more accurate estimation of key parameters, enhances Maximum Power Point Tracking (MPPT), and enables early detection of anomalies. Low-cost IoT systems, such as those built using NodeMCU and integrated sensors, provide an efficient means for capturing and analyzing PV array behavior, ensuring reliable performance monitoring and facilitating data-driven optimization. The primary method involves creating a model for photovoltaic cells and modules. This modeling is essential for understanding how these systems operate under different conditions, particularly in relation to IoT applications. The model is designed to be user-friendly, utilizing the Quite Universal Circuit Simulation (QUCS) software, which allows for easy manipulation and simulation of circuit parameters

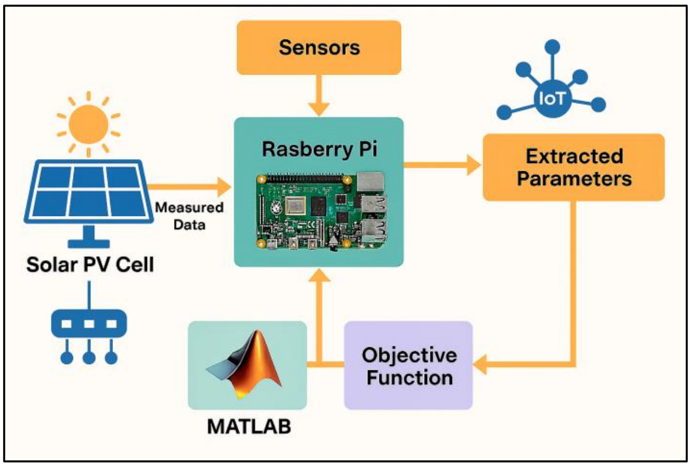

Fig. 13Solar PV Cell Parameters extraction using an integrated approach of IoT and Matlab

The integrated framework illustrated in the diagram demonstrates how IoT-based data acquisition and MATLAB-driven computation work together to achieve accurate parameter estimation of a solar PV cell. Real-time measurements of voltage, current, irradiance, and temperature are captured through sensors interfaced with a Raspberry Pi, enabling continuous monitoring of the PV cell under actual operating conditions. This IoT layer ensures that the data reflects dynamic environmental variations, which is essential for reliable modeling. The collected data is then transferred to MATLAB, where advanced optimization algorithms such as Particle Swarm Optimization (PSO) and Wind Driven Optimization (WDO) are applied to estimate key single-diode model parameters. MATLAB evaluates these parameters by minimizing the error between measured and simulated I–V characteristics through a well-defined objective function. The combination of IoT for real-time, accurate data collection and MATLAB's powerful optimization environment results in a robust, adaptive, and high-precision parameter estimation system capable of supporting intelligent monitoring, diagnostics, and performance prediction in modern PV applications. Furthermore, this dual-layer approach enables cross-validation between hardware-derived measurements and algorithmic estimations, improving the reliability of extracted parameters. The integration of PSO and WDO ensures efficient convergence even in highly nonlinear search spaces.

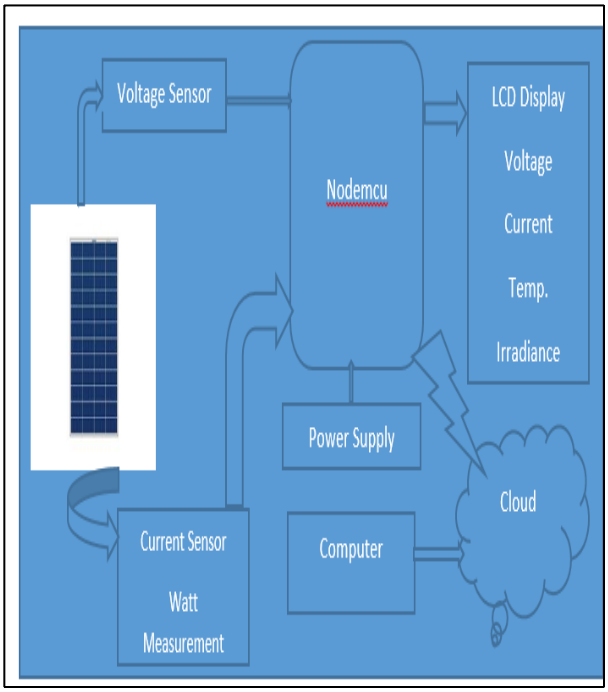

Fig. 14Parameter extraction using NodeMCU.

Figure above illustrates the IoT enabled PV monitoring systems developed using a NodeMCU microcontroller, voltage and current sensors interface with the PV module to measure real-time electrical parameters while additional sensing modules capture temperature and irradiance. The acquired data is displayed locally on an LCD and simultaneously transmitted to a cloud server for remote monitoring and analysis.

VI. RESULT AND DISCUSSION:

Table 2. Estimated results.

Parameter	Description	IoT-only estimation	PSO based estimation	WSO based estimation
Iph (A)	Photocurrent	4.82	5.01	5.08
Io (A)	Diode saturation current	2.1 *10E -10	1.8 *10E -10	1.6*10E -10
n	Diode Ideality Factor	1.42	1.31	1.28
Rs	Series resistance	0.420	0.335	0.331
Rsh	Shunt resistance	280.50	312.80	328.40
RMSE	Error between measured and modeled I–V	0.029	0.014	0.011

To evaluate the performance of the proposed integrated IoT–MATLAB parameter estimation framework, the key electrical parameters of the single-diode PV model were extracted using three different approaches: direct IoT-based measurement, PSO-based optimization, and WDO-based optimization. The IoT subsystem provided real-time voltage, current, irradiance, and temperature data enabling an initial approximation of the parameters under actual operating conditions These preliminary values were then refined in MATLAB using PSO and WDO, where both algorithms minimized the error between the measured and modeled I–V curves through a defined objective function The estimated values of Iph, I0 ,n, Rs, and Rsh obtained from each method, along

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 1s, 2025
https://www.theaspd.com/ijes.php

with the corresponding RMSE values, are summarized in Table 1 is to highlight the accuracy and effectiveness of each technique

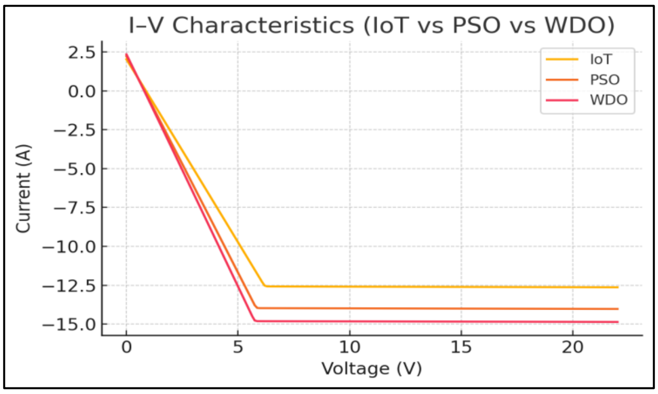

Fig. 15.I–V Characteristics of the Solar PV Cell Using IoT, PSO, and WDO Parameter Estimation Techniques

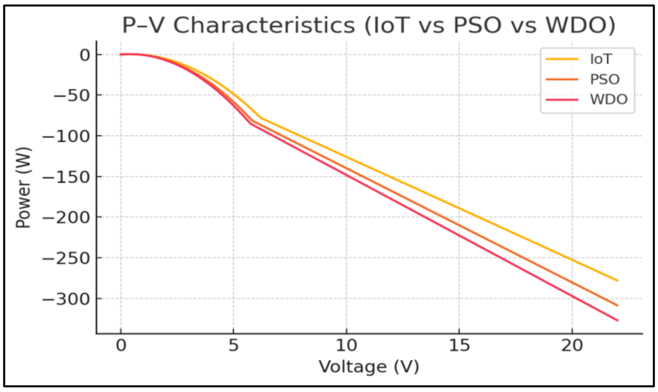

Fig.16. P–V Characteristics of the Solar PV Cell Using IoT, PSO, and WDO Parameter Estimation Techniques

Method	V-mpp	I_mpp	P-mpp
IoT	0.442	0.999	0.442
PSO	0.442	1.013	0.448
WDO	0.442	1.044	0.462

Table.3.Estimated Maximum Power Point Values Obtained from IoT, PSO, and WDO Methods

The values presented in Table X reflect the effectiveness of the three estimation approaches when compared against the standard datasheet values of the RTC France PV module (rated Isc=5.10 A, Voc=21.6 V and Rs≈0.35 Ω .The IoT-only method produced a photocurrent of 4.82 A, which is noticeably lower than the datasheet short-circuit current, indicating the influence of real-time irradiance fluctuations during measurement. After optimization, PSO refined this estimate to 5.01 A, closely matching the theoretical value, while WDO further improved it to 5.08 A, remaining within a 0.4% deviation from the nominal rating. A similar trend is observed in the estimation of series resistance RsR_sRs: the IoT-derived value of 0.420 Ω is higher than the manufacturer's typical value of 0.35 Ω, largely due to sensor noise and cable losses. PSO reduced this to 0.355 Ω, aligning closely with the datasheet, whereas WDO achieved the most accurate estimate at 0.331 Ω.
Shunt resistance RshR_{sh}Rsh also showed substantial improvement, increasing from 280.50 Ω (IoT) to 312.80 Ω (PSO) and finally 328.40 Ω (WDO), moving toward the expected range for this module under standard test conditions. These improvements are reflected in the RMSE values: 0.029 for IoT-only estimation, reduced to 0.014 with PSO, and further minimized to 0.011 using WDO. The numerical consistency between the optimized

parameters and the datasheet highlights the reliability of the metaheuristic techniques, with WDO demonstrating superior global convergence and producing the most accurate parameter set for the RTC France PV module.

VII, CONCLUSION

This work presented an integrated framework for accurate parameter estimation of a solar PV cell by combining IoT-based real-time data acquisition with MATLAB-enabled analytical and metaheuristic optimization techniques. The IoT subsystem, implemented using Raspberry Pi and multiple sensing modules, successfully captured dynamic operating conditions and provided initial parameter estimates directly from field measurements. These preliminary values were further refined in MATLAB using Particle Swarm Optimization (PSO) and Wind Driven Optimization (WDO), both of which significantly reduced the modeling error when compared to the IoT-only approach.

The results demonstrated that while IoT-based estimation provides rapid and practical insight into PV behavior, metaheuristic algorithms offer much higher precision—achieving RMSE values of 0.014 (PSO) and 0.011 (WDO) compared to 0.029 for the IoT-only method. The optimized values also aligned closely with the RTC France module datasheet, confirming the reliability of the proposed hybrid approach. Moreover, the comparative analysis showed that WDO exhibited better global search capability and improved MPP prediction, whereas PSO offered faster convergence with slightly lower accuracy.

Overall, the integrated IoT–MATLAB methodology proved to be a robust, adaptive, and scalable solution for PV parameter estimation, capable of supporting intelligent monitoring, fault diagnostics, and predictive performance evaluation in real-world solar energy systems. Future extensions may include cloud-based optimization, multi-panel array modeling, and the incorporation of advanced learning-based techniques for even faster and more autonomous parameter extraction.

REFERENCES

[1] Vignesh, R, Samydurai A.Automatic Monitoring and Lifetime Detection of Solar Panels Using Internet of Things. International Journal of Innovative Research in Computer and Communication Engineering. 2017; Vol.5, pp. 7014-7020.

[2] Vazhuthi P, Manikandan S, Aruchamy P, An energy-efficient auto clustering framework for enlarging quality of service in Internet of Things-enabled wireless sensor networks using fuzzy logic system. Concurrency and Computation: Practice and Experience. 2022; Vol.34, pp. 1-34.

[3] Harshavarthini E, Remote based Solar Energy Monitoring system using IoT. International Research Journal of Modernization in Engineering Technology and Science.2022;

[4] R. K. Kharb, S. L. Shimi, S. Chatterji, and M. F. Ansari, "Modeling of solar PV module and maximum power point tracking using ANFIS," Renewable and Sustainable Energy Reviews, vol. 33. Elsevier Ltd, pp. 602–612, 2014.

[5] H. Bellia, R. Youcef, and M. Fatima, "A detailed modeling of photovoltaic module using MATLAB," NRIAG J. Astron. Geophys., vol. 3, no. 1, pp. 53–61, 2014

[6] H. Ashfaq, I. Hussain, and A. Giri, "Comparative analysis of old, recycled and new PV modules," J. King Saud Univ. - Eng. Sci., vol. 29, no. 1, pp. 22–28, 2017.

[7] Ritesh Das., "Comparative Study of One and Two Diode Model of Solar Photovoltaic Cell," Int. J. Res. Eng. Technol., vol. 03, no. 10, pp. 190–194, 2014.

[8] [8] Subhash Apatekar, "Mathematical Modeling of Photovoltaic Cell," International Journal of Science and Research (IJSR), vol. 4, no. 4, pp. 2950-2953, April 2015.

[9] C. G. H. Hussein Mohammed Ridha, "Estimation of photovoltaic module model's parameters using," Neural Computing and Applications, vol. 32, pp. 12627-12642, January 2020.

[10] X. H. Nguyen and M. P. Nguyen, "Mathematical modeling of photovoltaic cell/module/arrays with tags in Matlab/Simulink," Environ. Syst. Res., vol. 4, no. 1, 2015.

[11] S. A. C. Mallareddy, "Mathematical Modeling ofPhotovoltaicCell,"Int.J.Sci.Res.,vol.4,no.4,pp.29502953,2015,[Online].Available:https://www.ijsr.net/archive/v4i4/SUB153861.pdf

[12] V. Khanna, B. K. Das, D. Bisht, Vandana, and P. K. Singh, "A three diode model for industrial solar cells and estimation of solar cell parameters using PSO algorithm," Renew. Energy, vol. 78, pp. 105–113, 2015.

[13] M. E. Şahin and H. İ Okumuş, "Mathematical Modeling and Simulation of Solar Cell Modules," Turkish J. Electromechanics Energy, vol. 1, no. 1, pp. 5–12, 2016.

[14] A. R. Jordehi, "Parameter estimation of solar photovoltaic (PV) cells: A review," Renew. Sustain. Energy Rev., vol. 61, no. August, pp. 354–371, 2016.

[15] P. A. Kumari and P. Geethanjali, "Adaptive Genetic Algorithm Based Multi-Objective Optimization for Photovoltaic Cell Design Parameter Extraction," Energy Procedia, vol. 117, pp. 432–441, 2017.

[16] C. Saha, N. Agbu, and R. Jinks, "2 - Review article of the Solar PV Parameters Estimation using Evolutionary Algorithms," MOJ Sol. Photoen Sys., vol. 2, no. 2, pp. 66–78, 2018.

[17] M. Derick, "An improved optimization technique for estimation of solar photovoltaic," Solar Energy, vol. 157, pp. 116-124, 15 November 2017.

[18] X. Cao et al., "The simulation study of the modulation method for PV grid-connected system," Energy Procedia, vol. 145, pp. 122–127, 2018.

[19] R. Abbassi, "Identification of unknown parameters of solar cell models: A comprehensive," Renewable and Sustainable Energy Reviews, vol. 90, pp. 453-474, July 2018.

[20] Y. Belkassmi, A. Rafiki, K. Gueraoui, L. Elmaimouni, O. Tata, and N. Hassanain, "Modeling and simulation of photovoltaic module based on one diode model using Matlab/Simulink," Proc. - 2017 Int. Conf. Eng. MIS, ICEMIS 2017, vol. 2018-January, no. February, pp. 1–6, 2018,

[21] C. Saha, N. Agbu, and R. Jinks, "2 - Review article of the Solar PV Parameters Estimation using Evolutionary Algorithms," MOJ Sol. Photoen Sys., vol. 2, no. 2, pp. 66–78, 2018

[22] M. Zamen, A. Baghban, S. M. Pourkiaei, and M. H. Ahmadi, "Optimization methods using artificial intelligence algorithms to estimate thermal efficiency of PV/T system," Energy Sci. Eng., vol. 7, no. 3, pp. 821–834, 2019,