engineering proceedings

Proceeding Paper

A Novel MPPT-Based Solar Irradiance Estimator: Integration of a Hybrid Incremental Conductance Integral Backstepping Algorithm for PV Systems with Experimental Validation †

Ambe Harrison [1,*], Njimboh Henry Alombah [2], Salah Kamel [3], Hossam Kotb [4], Sherif S. M. Ghoneim [5] and Ilyass El Myasse [6]

1 Department of Electrical and Electronics Engineering, College of Technology (COT), University of Buea, Buea P.O. Box 63, Cameroon
2 Department of Electrical and Electronics Engineering, College of Technology, University of Bamenda, Bambili P.O. Box 39, Cameroon; henry.alombah@gmail.com
3 Department of Electrical Engineering, Faculty of Engineering, Aswan University, Aswan 81542, Egypt; skamel@aswu.edu.eg
4 Department of Electrical Power and Machines, Faculty of Engineering, Alexandria University, Alexandria 21544, Egypt; hossam.kotb@alexu.edu.eg
5 Electrical Engineering Department, College of Engineering, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia; s.ghoneim@tu.edu.sa
6 EEIS Laboratory, ENSET Mohammedia, Hassan II University of Casablanca, Casablanca 28830, Morocco; ilyaselmyasse@gmail.com
* Correspondence: ambe.harrison@ubuea.cm; Tel.: +237-682387064 or +237-658016181

† Presented at the 4th International Electronic Conference on Applied Sciences, 27 October–10 November 2023; Available online: https://asec2023.sciforum.net/.

Abstract: This paper outlines the development of a high-performance maximum power point tracking (MPPT)-based solar irradiance estimator for photovoltaic (PV) systems. The suggested estimator is constructed around a simple current–voltage-based algebraic equation that hinges on the operation of the PV system at its maximum power point (MPP). In the realm of MPP operation, the overall system is driven by a nonlinear MPPT controller. To achieve this function, we integrated a hybrid incremental conductance integral backstepping (H-INC-IBS) controller to effectively regulate the PV system. This controller was specially chosen for its powerful potency in maximizing the dynamics of the PV system, leading to heightened robustness against changing environmental conditions. The simulation results are provided to showcase the suitability of the proposed estimator. Furthermore, the estimator was verified under experimental conditions, highlighting its soundness and practicality. Through evaluations and comparisons with the conventional irradiance estimator, this paper aimed to emphasize the superiority of the proposed solar irradiance estimator in providing more accurate estimations of solar irradiance for PV systems operating under MPPT supervision.

Keywords: PV; MPPT; solar irradiance estimator; hybrid incremental conductance integral backstepping (H-INC-IBS)

check for updates

Citation: Harrison, A.; Alombah, N.H.; Kamel, S.; Kotb, H.; Ghoneim, S.S.M.; El Myasse, I. A Novel MPPT-Based Solar Irradiance Estimator: Integration of a Hybrid Incremental Conductance Integral Backstepping Algorithm for PV Systems with Experimental Validation. *Eng. Proc.* **2023**, *56*, 262. https://doi.org/10.3390/ASEC2023-15966

Academic Editor: Nunzio Cennamo

Published: 10 November 2023

1. Introduction

In recent years, nonconventional energy sources, such as solar energy, have gained popularity due to growing energy demands and environmental constraints. Through the use of photovoltaic (PV) cells, solar energy can easily be transformed into electrical energy. PV sources offer several advantages, including low maintenance costs, no moving or rotating parts, and pollution-free energy conversion. Despite such unique features, they are still very expensive, and more innovative techniques are required to increase their efficiency and reduce their final cost [1]. For example, maximum power point tracking (MPPT) in PV systems has been identified as an important consideration for improving the operational efficiency of PV systems [2–5]. Operationally, solar irradiance is one of the most important and functional parameters of every PV system. Monitoring the performance of such systems requires information related to the state of solar irradiance. Monitoring solar irradiance is not only important for PV systems, as the supervised parameter intersects largely with many interdisciplinary fields, including agriculture and environmental science [6]. When it comes to measurement, the Pyranometer is considered one of the most commonly used instruments for directly measuring solar irradiance [7]. Pyranometers are not cost-effective, have several sensors, and must be positioned in the direction of their corresponding panels [8]. Rather than employing expensive direct measurement methods for solar irradiance, numerous studies are resorting to estimating this intricate parameter.

The method presented in [9] makes use of the short-circuit current of the PV module, which can be measured using a readily available current sensor. This is one of the simplest and most cost-effective methods for estimating irradiance; however, it only provides moderate accuracy. Furthermore, it requires periodic short-circuiting of the PV module terminals, which, from an energy productivity point of view, represents a poor approach. A similar work presented in [10] avoids the classical use of a solar irradiance sensor (Pyranometer) to estimate irradiance. By using a low-cost microcontroller, information on both the short-circuit current (Isc) and the open-circuit voltage (Voc) is supervised. With these measurements, the method computes the electrical equation of the PV module using a fixed-point iteration technique. The major limitation of the latter approach lies with the fact that the load must be periodically disconnected from the PV panel to measure the open-circuit voltage and short circuited to obtain the short-circuit current. When conducting direct measurements, seeking both the Isc and the Voc of the solar panel proves intricate. Hence, the accuracy involved would be conditioned by the degree of asynchronization tolerated in measuring these parameters. In a PV-connected system, it is crucial to estimate the irradiance without altering the system operating point. For instance, a PV system composed of a solar panel and a maximum power point tracking (MPPT) controller is supposed to operate at a unique point, the maximum power point (MPP). Abruptly distorting this point with a short or open circuit can deteriorate the performance of the MPPT controller, which can further negatively affect the whole PV system from an energy point of view. This is the principal reason why the Isc and Voc methods in [9,10], are not highly recommended for PV-connected systems. The method presented in [11] makes use of the interpolated link between irradiance and voltage across a 50 Ω resistor to mathematically calculate the former. The accuracy achieved by this method is moderate due to the approximate expression between solar irradiance and output voltage across the resistor. Furthermore, the major flaw in this method lies in its dependence on fitted data.

The method presented in [12] exploits the nonlinear electrical current–voltage (I–V) equations of the PV cell and some suitable reparameterization to compute solar irradiance with a guaranteed level of stability. However, this method is PV-model-based and demands the use of some internal parameters of the PV module, which are not often readily available. Although irradiance can be successfully computed with attractive stability, the accuracy of this method is conditioned by the measurement of the PV array temperature, which is often not easy to acquire. An improved version of the estimator in [12] is presented in [13]. This work derives a nonlinear equation from which solar irradiance can be directly computed, provided that accurate measurements of PV array temperature, current, and voltage are available. Compared to the previously reported estimator of solar irradiance, the latter work is superior due to the following reasons: it does not require changing the PV operating point for sensing the Isc and Voc, as in [9,10], and it does not demand an iterative algorithm, as in [10]. The method is void of approximate expressions or fitted data, as in [11], and does not require the integration of data, as in [12]. However, the accuracy of the method is conditioned by the measurement of temperature. In practice, PV systems are conditioned by continually changing environmental conditions. These varying conditions induce systematic variations in the maximum power point. To improve the performance of PV systems, MPPT controllers are usually improvised between the PV system and the load [14].

In the realm of MPPT, numerous algorithms and controllers have been proposed in the literature. A computational-intelligence-based MPPT method was developed in [15]. This method combines a modified invasive weed optimization algorithm, belonging to the class of evolutionary algorithms, and the P&O algorithm in a hybrid scheme. The hybrid technique is a pertinent improvement of the P&O algorithm as it enhances the search performance for the maximum power output of the PV systems. However, its principal limitation is the slow convergence of the tracking process attributed to the lengthy optimization algorithm time. Furthermore, the algorithm does not tackle the problem of oscillations around the MPP exhibited in the conventional P&O method. In a grid-connected regime, a hybrid optimization MPPT algorithm was proposed in [16], which combines fuzzy logic control and particle swarm optimization (PSO) applied to a buck-boost zeta DC-DC converter. The MPPT method is applied to a grid-injected PV system. However, the applicability of the algorithm for estimating solar irradiance was not investigated by the authors. A hybrid MPPPT algorithm was proposed in [17], which combines a simplified firefly and a neighborhood attraction firefly for maximum power point tracking. Using a high-gain step-up SEPIC converter, the authors showed that the new algorithm is efficient for MPPT operation and high step-up voltage applications, such as electric vehicle charging systems. However, the algorithm was not applied to the estimation of solar irradiance in PV systems. To address the problems of poor MPPT performance of MPPT algorithms under variable solar insolation, [18] synthesized a novel learning algorithm based on the TS-fuzzy Radial Basis Neural Network. Although the algorithm offers rapid PV power tracking under fluctuating solar irradiance, its complexity moderates its practical feasibility. Moreover, the suitability of the proposed MPPT method was not investigated for solar irradiance in PV systems.

Although numerous maximum power point tracking algorithms have been recently developed, it is evident that only a few have shown the possibility of exploiting the PV system at the maximum power point (MPP) to estimate solar irradiance. This is an effective approach because certain impositions and sensors, such as temperature sensors, are not required. Moreover, such a method is PV-model free, hence it can provide better levels of accuracy. The most prominent work in this vein is the MPPT-based estimator that was recently proposed in [6]. The latter study presented a simplified MPPT-based equation to compute solar irradiance on the PV module. Considering that the estimator depends on the MPP, its performance is dictated by MPPT operation. Originally, the authors proposed conventional MPPT algorithms, such as P&O, to drive the PV system at the MPP. Recent progress in MPPT research has shown that conventional algorithms present problems, such as oscillations at the maximum power point and a tradeoff between dynamic response and steady-state oscillations [3,5,7]. These problems are inherent in conventional MPPT algorithms and will consequently impact the performance of the MPPT-based estimator. Therefore, to improve the performance of the estimator, it is crucial to regulate the PV system using MPPT controllers that ensure overall high performance of the solar estimator. MPPT algorithms have not received sufficient attention on the subject of solar irradiance estimation. The present state of the literature shows that only conventional MPPT algorithms have successfully been applied to the estimation of solar irradiance in PV systems. On the other hand, these conventional algorithms are limited and do not allow for maximizing the potential of the MPPT system to estimate solar irradiance.

In this paper, we seek to improve the performance of the conventional MPPT-based estimator by regulating the PV system with a recently proposed nonlinear MPPT controller. The MPPT controller is based on the hybrid incremental conductance integral backstepping (H-INC-IBS) algorithm [14]. Because of its nonlinear features, this controller is a very robust choice for MPPT applications. In this way, the proposed estimator acquires the robust characteristics of the H-INC-IBS algorithm.

A comparative study of the proposed estimator and previously published works is presented in Table 1, confirming that the MPPT-based estimation of irradiance has been limited to the use conventional algorithms. Due to the shortcomings of the conventional scheme, estimated solar irradiance fluctuates significantly at a steady state and is unreliable in the event of fast-changing operating conditions. In order to demonstrate the unique features of the proposed estimator, it was compared against the estimator based on the conventional MPPT algorithm. The simulation and experimental results showed substantial improvements in estimator performance when the proposed nonlinear MPPT controller was used to drive the PV system. The rest of this paper is composed as follows: The design of the proposed system is presented in Section 2. In Section 3, the major results are discussed and our conclusions are presented in Section 4.

Table 1. Comparative study between the proposed estimator and previously published works.

Ref.	Year	Method of Solar Irradiance Estimation	MPPT Algorithm	Key Remarks
[9]	2013	Short-circuit current method	N/A	- Requires periodic short-circuiting of the PV terminals - Not suitable for connected PV systems
[10]	2012	Short-circuit/open-circuit voltage method	N/A	- Requires periodic short-circuiting and open-circuiting of the PV terminals - Not suitable for connected PV systems
[11]	2011	Interpolation method	N/A	Requires fitted data
[12]	2014	PV-model-based	N/A	Requires some internal parameters of the PV model, which are not often fully available
[13]	2016	Analytical method	N/A	Analytical equation relies on internal parameters of the PV model
[19]	2021	N/A	Hybrid P&O-based Modified Invasive Weed optimization algorithm	MPPT not evaluated for irradiance estimation
[16]	2019	N/A	Hybrid PSO fuzzy logic controller	MPPT not evaluated for irradiance estimation
[17]	2022	N/A	Firefly optimization MPPT algorithm	MPPT not evaluated for irradiance estimation
[18]	2022	N/A	TS fuzzy Radial Basis Neural Network	MPPT not evaluated for irradiance estimation
[6]	2018	MPPT-Based	Conventional algorithm	- Oscillations at steady state due to limitations of the conventional algorithm - Low dynamic response under fast-changing irradiance conditions
[Proposed]	2023	MPPT-Based	H-INC-IBS	- Negligible oscillations at steady state - Suitable for fast-changing conditions due to the robustness of H-INC-IBS - Better accuracy than [6]

2. Design of the Proposed System

The PV system under study is presented in Figure 1. It consists of a solar PV panel, a dc–dc boost converter coupled with load, an MPPT system (H-INC-IBS MPPT), and an estimator of solar irradiance. The solar PV panel is driven by the H-INC-IBS MPPT controller. The estimator receives measurements of current and voltage from readily available current and voltage sensors and makes use of the system's operation at the MPP to compute solar irradiance. In reality, concerning MPPT, the boost converter shown in Figure 2 is used to implement the regulatory algorithm.

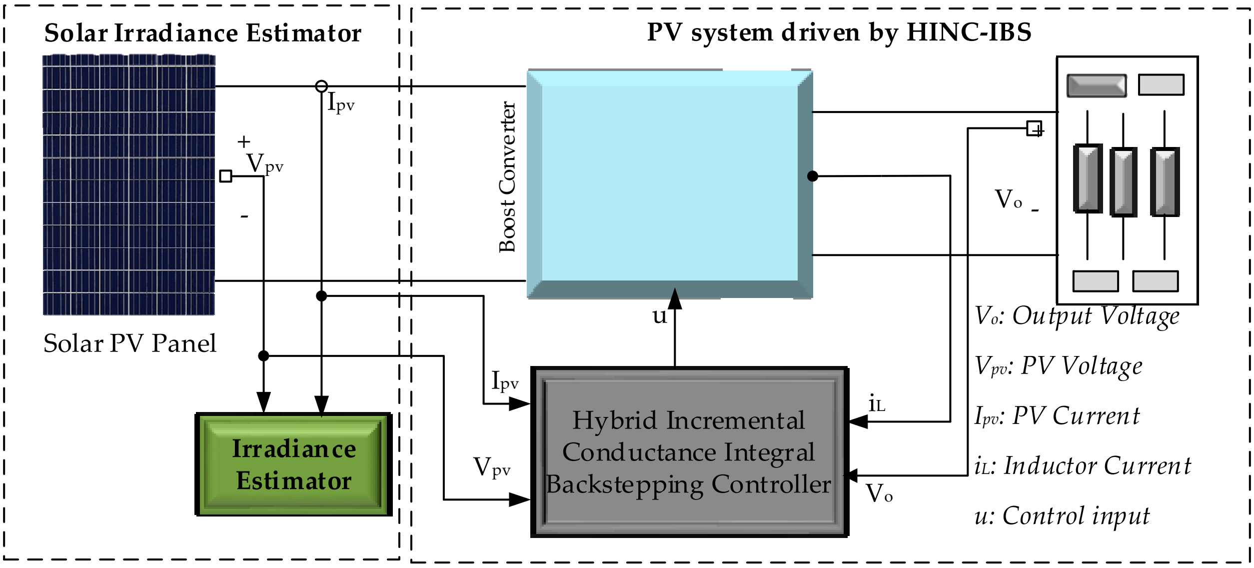

Figure 1. Block Diagram of the proposed system.

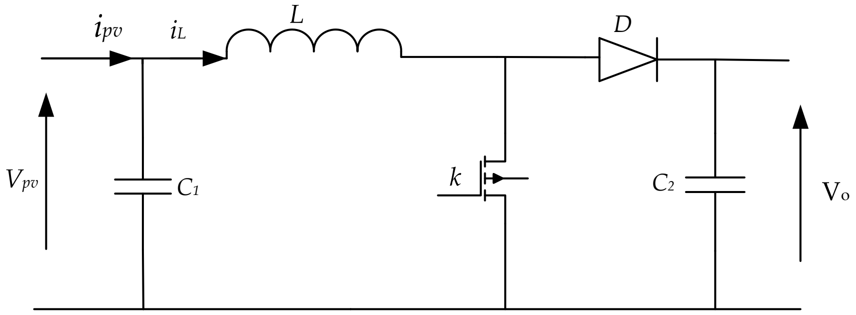

Figure 2. Electrical diagram of DC-DC Boost converter.

The converter is made up of a coupling capacitor (C_1), inductance (L), a switch (K), a diode (D), and an output capacitor (C_2). This converter, among other power electronics converter topologies, was chosen for its simplicity and higher efficiency in MPPT PV applications [20]. The following average dynamic model regulates operation of the converter in a continuous conduction mode [21]:

$$\begin{cases} \dot{x_1} = i_{PV} - \frac{x_2}{C_1} \\ \dot{x_2} = \frac{x_1}{L} - \frac{x_3}{L}(1-u) \\ \dot{x_3} = \frac{x_2}{C_2}(1-u) - \frac{x_3}{C_2 R} \end{cases} \tag{1}$$

where $[x_1\ x_2\ x_3]^T = \left[V_{pv}\ i_L\ V_o\ \right]^T = x$ are the state variables of the converter and u is the control input. A nonlinear controller can be designed to exploit this full dynamic and realize the control objective. We required the PV voltage to operate at a certain MPP reference V_{ref}. Since this variable is the first state of the system, it can be written as $x_{1ref} = V_{ref}$. The controller was then constructed based on the integral backstepping controller algorithm, designed with reference to the Lyapunov theory. To ensure that the system operated at the MPP, the following control framework was adopted [14]:

$$u = 1 - \frac{L}{x_3}\left(K_2 e_2 + \frac{x_1}{L} + K_1^2 C_1 e_1 + K_1 e_2 + kK_1 C_1 p - \dot{i}_{PV} + C_1 \ddot{x}_{1ref} - C_1 k e_1 - \frac{e_1}{C_1}\right) \tag{2}$$

where, $e_1 = x_1 - x_{1ref}$, $\varphi = C_1\left(K_1 e_1 + \frac{i_{PV}}{C_1} - \dot{x}_{1ref} + kp\right)$, $e_2 = x_2 - \varphi$ and $p = \int_o^t (e_1)\, dt$.

In this design, the reference system was supplied by an incremental conductance algorithm [14]. Thus, the synergic combination of the control law in Equation (2) with the INC results in H-INC-IBS, which represents the nonlinear MPPT controller adopted in this paper. Therefore, provided that the system operates at the MPP, an estimator of solar irradiance can be designed to exploit these conditions. In this work, we present a model-free MPPT estimator of solar irradiance for PV systems operating at the MPP. The major benefit of this estimator is that it does not induce a change in the operating point of the PV system. The main estimator equation can be written as [6]:

$$\hat{G} = G_{ref}\left(\frac{I_{sc-ref} + \left(I_{pv} - I_{mpp}\right)}{I_{sc-ref} + \left(\frac{K_i}{K_v}\right)\left(R_s \Delta I + \left(V_{pv} - V_{mpp}\right)\right)}\right) \tag{3}$$

where, G_{ref} is the irradiance at standard test conditions (STCs) (1000 W/m^2) and I_{sc-ref} is the panel short-circuit current at STC. The temperature coefficient of the short-circuit current (K_i) and the open-circuit voltage (K_v) are readily available from the panel specifications. The estimator depends on the series resistance of the PV (R_s), which is unaffected by environmental conditions. Also, the terms I_{mpp} and V_{mpp} represent the MPP current and voltage, respectively. Therefore, with a suitable current and voltage sensor for sensing the PV current (I_{pv}) and voltage (V_{pv}), the solar estimate of solar irradiance ($\hat{G}$) can be obtained when the PV system is operated at the MPP.

3. Results and Discussion

The proposed system was primality implemented in MATLAB/Simulink and was verified via simulations and experiments. To position the performance of the estimator, it was compared against the conventional estimator proposed in [6]. For this, a 60 W solar panel was adopted throughout the comparison [22]. The boost converter parameters were as follows: $L = 0.3$ mH and $C_1 = C_2 = 37$ µF, at the switching frequency of 250 kHz. The parameters of the controller were given as: $[k,\ K_1, K_2] =$ [47.1853, 13750, 10000]. The response of the estimators to fast-changing irradiance and temperature is presented in Figure 3. It can be seen that both estimators show notable performance in tracking the fast-changing irradiance. However, the proposed method exhibits faster tracking performance, reduced steady-state ripples, and achieves better estimation accuracy. To verify the obtained simulation outcomes, an experimental set-up was mounted to record solar irradiance and temperature on the PV modules. The acquired data was used for further assessment of the estimator, as revealed in Figure 4. It is evident that the proposed estimator aligned more closely with the experimental irradiance compared to the conventional method, confirming it superiority. The mean error of both estimators with reference to the actual experimental solar irradiance was computed, revealing a value of 3.4967% for the conventional method compared to 2.1911% for the proposed method. Such a result further confirms the superior accuracy of the suggested estimator.

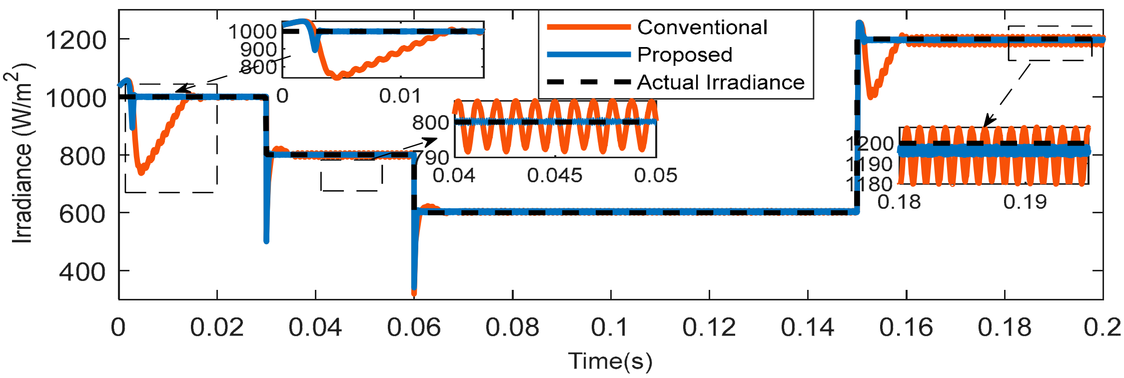

Figure 3. Simulation results of the estimators under fast-changing irradiance and temperatures.

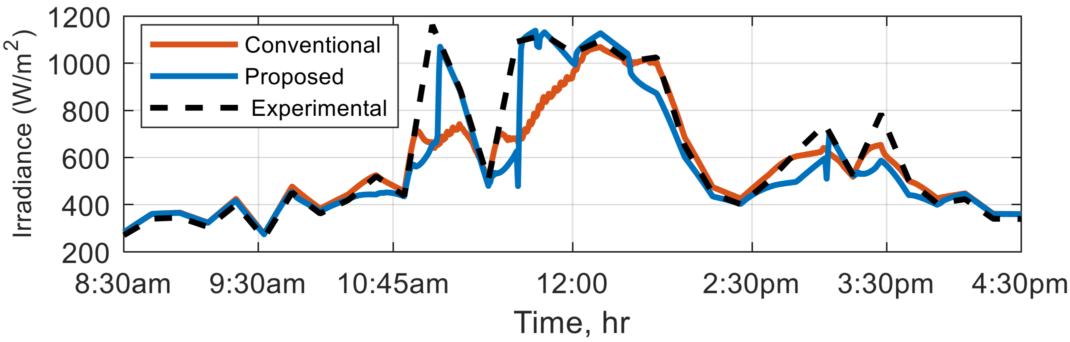

Figure 4. Experimental results of the estimators under real climatic conditions.

This paper therefore unwinds a new opportunity for integrating existing MPPT algorithms [23] and leveraging their performance for improved irradiance estimation in PV energy systems.

4. Conclusions

In this paper, an estimator of solar irradiance for PV systems operating at the maximum power point was proposed. We verified that it is possible to exploit the PV system operating at the maximum power point to compute solar irradiance using a simple algebraic equation. The estimator equation requires actual measurements of PV current and voltage, which can be easily sought using commercially available sensors. The operation of the PV system at the MPP was supervised using a H-INC-IBS controller. It was further confirmed that the estimator exhibits superior performance compared to a similar one driven by the conventional algorithm. The accuracy of the proposed estimator, measured by the mean error, was 2.1911% compared to 3.4967% for the estimator based on the conventional MPPT algorithm. The effectiveness of the proposed estimator was further validated using experiments under real environmental conditions.

Author Contributions: A.H.: conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing—original draft preparation, writing—review and editing; N.H.A.: software, validation, formal analysis, writing—review and editing; S.K., H.K., S.S.M.G. and I.E.M.: formal analysis, project administration, validation, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be made available by the corresponding author upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Fouad, R.H.; Ashhab, M.S.; Mukattash, A.; Idwan, S. Simulation and Energy Management of an Experimental Solar System through Adaptive Neural Networks. *IET Sci. Meas. Technol.* **2012**, *6*, 427. [CrossRef]
2. Harrison, A.; Nfah, E.M.; de Dieu Nguimfack Ndongmo, J.; Alombah, N.H. An Enhanced P&O MPPT Algorithm for PV Systems with Fast Dynamic and Steady-State Response under Real Irradiance and Temperature Conditions. *Int. J. Photoenergy* **2022**, *2022*, 6009632. [CrossRef]
3. Harrison, A.; de Dieu Nguimfack Ndongmo, J.; Alombah, N.H. Robust Nonlinear Control and Maximum Power Point Tracking in PV Solar Energy System under Real Environmental Conditions. In Proceedings of the ASEC 2022, 3rd International Electronic Conference on Applied Sciences, Online, 1–15 December 2022; MDPI: Basel, Switzerland, 2022; p. 49.
4. Li, L.-L.; Lin, G.-Q.; Tseng, M.-L.; Tan, K.; Lim, M.K. A Maximum Power Point Tracking Method for PV System with Improved Gravitational Search Algorithm. *Appl. Soft Comput.* **2018**, *65*, 333–348. [CrossRef]
5. Harrison, A.; Alombah, N.H. A New High-Performance Photovoltaic Emulator Suitable for Simulating and Validating Maximum Power Point Tracking Controllers. *Int. J. Photoenergy* **2023**, *2023*, 4225831. [CrossRef]

6. Moshksar, E.; Ghanbari, T. Real-time Estimation of Solar Irradiance and Module Temperature from Maximum Power Point Condition. *IET Sci. Meas. Technol.* **2018**, *12*, 807–815. [CrossRef]
7. Harrison, A.; Alombah, N.H.; de Dieu Nguimfack Ndongmo, J. Solar Irradiance Estimation and Optimum Power Region Localization in PV Energy Systems under Partial Shaded Condition. *Heliyon* **2023**, *9*, e18434. [CrossRef] [PubMed]
8. Cristaldi, L.; Faifer, M.; Rossi, M.; Ponci, F. A Simple Photovoltaic Panel Model: Characterization Procedure and Evaluation of the Role of Environmental Measurements. *IEEE Trans. Instrum. Meas.* **2012**, *61*, 2632–2641. [CrossRef]
9. Tan, R.H.G.; Tai, P.L.J.; Mok, V.H. Solar Irradiance Estimation Based on Photovoltaic Module Short Circuit Current Measurement. In Proceedings of the 2013 IEEE International Conference on Smart Instrumentation, Measurement and Applications (ICSIMA), Kuala Lumpur, Malaysia, 25–27 November 2013; IEEE: Toulouse, France, 2013; pp. 1–4.
10. Cruz-Colon, J.; Martinez-Mitjans, L.; Ortiz-Rivera, E.I. Design of a Low Cost Irradiance Meter Using a Photovoltaic Panel. In Proceedings of the 2012 38th IEEE Photovoltaic Specialists Conference, Austin, TX, USA, 3–8 June 2012; IEEE: Toulouse, France, 2012; pp. 002911–002912.
11. Husain, N.S.; Zainal, N.A.; Mahinder Singh, B.S.; Mohamed, N.M.; Mohd Nor, N. Integrated PV Based Solar Insolation Measurement and Performance Monitoring System. In Proceedings of the 2011 IEEE Colloquium on Humanities, Science and Engineering, Penang, Malaysia, 5–6 December 2011; IEEE: Toulouse, France, 2011; pp. 710–715.
12. Carrasco, M.; Mancilla-David, F.; Ortega, R. An Estimator of Solar Irradiance in Photovoltaic Arrays With Guaranteed Stability Properties. *IEEE Trans. Ind. Electron.* **2014**, *61*, 3359–3366. [CrossRef]
13. Laudani, A.; Fulginei, F.R.; Salvini, A.; Carrasco, M.; Mancilla-David, F. A Fast and Effective Procedure for Sensing Solar Irradiance in Photovoltaic Arrays. In Proceedings of the 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), Florence, Italy, 7–10 June 2016; IEEE: Toulouse, France, 2016; pp. 1–4.
14. Harrison, A.; Alombah, N.H.; de Dieu Nguimfack Ndongmo, J. A New Hybrid MPPT Based on Incremental Conductance-Integral Backstepping Controller Applied to a PV System under Fast-Changing Operating Conditions. *Int. J. Photoenergy* **2023**, *2023*, 9931481. [CrossRef]
15. Senapati, M.K.; Pradhan, C.; Calay, R.K. A Computational Intelligence Based Maximum Power Point Tracking for Photovoltaic Power Generation System with Small-signal Analysis. *Optim. Control Appl. Methods* **2023**, *44*, 617–636. [CrossRef]
16. Priyadarshi, N.; Padmanaban, S.; Kiran Maroti, P.; Sharma, A. An Extensive Practical Investigation of FPSO-Based MPPT for Grid Integrated PV System Under Variable Operating Conditions with Anti-Islanding Protection. *IEEE Syst. J.* **2019**, *13*, 1861–1871. [CrossRef]
17. Priyadarshi, N.; Bhaskar, M.S.; Sanjeevikumar, P.; Azam, F.; Khan, B. High-power DC-DC Converter with Proposed HSFNA MPPT for Photovoltaic Based Ultra-fast Charging System of Electric Vehicles. *IET Renew. Power Gener.* 2022; *Early View*. [CrossRef]
18. Priyadarshi, N.; Sanjeevikumar, P.; Bhaskar, M.; Azam, F.; Taha, I.B.M.; Hussien, M.G. An Adaptive TS-fuzzy Model Based RBF Neural Network Learning for Grid Integrated Photovoltaic Applications. *IET Renew. Power Gener.* **2022**, *16*, 3149–3160. [CrossRef]
19. Pradhan, C.; Senapati, M.K.; Malla, S.G.; Nayak, P.K.; Gjengedal, T. Coordinated Power Management and Control of Standalone PV-Hybrid System with Modified IWO-Based MPPT. *IEEE Syst. J.* **2021**, *15*, 3585–3596. [CrossRef]
20. Glasner, I.; Appelbaum, J. Advantage of Boost vs. Buck Topology for Maximum Power Point Tracker in Photovoltaic Systems. In Proceedings of the 19th Convention of Electrical and Electronics Engineers in Israel, Jerusalem, Israel, 5–6 November 1996; IEEE: Toulouse, France, 1996; pp. 355–358.
21. Harrison, A.; Dieu Nguimfack-Ndongmo, J.d.; Alombah, N.H.; Aloyem Kazé, C.V.; Kuate-Fochie, R.; Asoh, D.A.; Nfah, E.M. Robust Nonlinear MPPT Controller for PV Energy Systems Using PSO-Based Integral Backstepping and Artificial Neural Network Techniques. *Int. J. Dyn. Control* **2023**. [CrossRef]
22. Harrison, A.; Henry, N. A New Piecewise Segmentation Based Solar Photovoltaic Emulator Using Artificial Neural Networks and a Nonlinear Backstepping Controller. *Appl. Sol. Energy* **2023**, *59*, 283–304. [CrossRef]
23. de Dieu Nguimfack-Ndongmo, J.; Harrison, A.; Alombah, N.H.; Kuate-Fochie, R.; Ajesam Asoh, D.; Kenné, G. Adaptive Terminal Synergetic-Backstepping Technique Based Machine Learning Regression Algorithm for MPPT Control of PV Systems under Real Climatic Conditions. *ISA Trans.* 2023; *in press*. [CrossRef]