Performance of low-cost solar radiation logger

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ABSTRACT

In solar power systems, irradiance value data are among the most important parameters. Such data can be used in installing photovoltaic (PV) modules, such as determining the exact location, tilt angle, and required area, for optimal power efficiency. In this study, the comprehensive simulation and implementation of a solar radiation meter with a PV cell and temperature sensor are presented. The irradiance measurement value is based on the power reading generated by the small capacity of the PV cell at a specific load converted into a digital value in the microcontroller using the implicit Newton polynomial interpolation (NPI) equation as a low-cost alternative method. The effect of temperature is included in the conversion to obtain precise measurement results. Firstly, the structure and characteristics of the PV cell are discussed. Secondly, the parameters, measuring method, and conversion of the measurement reading data using the NPI equation are presented to assess the results. Finally, the simulation of the solar radiation meter using the PSIM and implementation of the hardware are conducted to validate the concepts and compare their results. The proposed hardware has an average error of 2.72% in the implementation of the measurement test.

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1. INTRODUCTION

The availability of renewable energy source (RES) data is fundamental before the implementation of renewable energy technology, especially in areas facing problems with electricity availability. For example, the application of solar power plants requires a solar radiation time series and meteorological variables as key elements for modeling the energy production of solar power plants. At present, using energy from renewable resources is a key factor in improving and adding benefits to society because it is sustainable [1], [2]. One such RES is solar energy, which is secure, clean, and available on earth throughout the year. Solar energy has great potential and vast application prospects that can be used to meet the majority of the total energy demand. The most promising, emerging solar energy technology is photovoltaic (PV) technology, which can transform solar radiation into electric energy through PV modules [3]–[6].

In conjunction with solar PV modules, as a new RES, the intensity of the sun is measured in watt per square meter (W/m^2), which is called irradiance [7]. The intensity of solar radiation is one of the most important parameters that must be determined before solar PV modules are installed to ensure their operation at the maximum power point (MPP) [8]–[10]. This task is complicated by the fact that this operating point changes significantly as a function of solar radiation and cell temperature, which can be illustrated by a typical current-voltage (I-V) curve of a PV array [11]–[14].

Numerous researchers developed various methods for measuring the intensity of solar radiation. Common sensors for measuring the intensity of solar radiation are pyranometers and irradiance meters [15], [16]. A pyranometer is utilized for measuring solar radiation on the flat surface of a 180-degree plane. Solar radiation passes through two glass domes and is absorbed by a black ceramic disk bound tightly to a thermopile sensor [17]. Most thermopile sensors can convert small thermopile voltage outputs into watts per square meter and generate or record the data. To obtain real-time radiation values based on the data quality desired, a pyranometer must be developed to display the data of the measurement results. A pyranometer generally uses cables to connect sensors to processing devices and data viewers. However, despite the addition of equipment, the use of a pyranometer is rare owing to high costs [18].

Low-cost methods for measuring solar radiation were developed, including using green light emitting diodes (LEDs) as sensors to conduct accurate field measurements of global, direct, and diffuse solar radiation [19], employing light-dependent resistor (LDR) sensors [20], and applying the mathematical model of extraterrestrial radiation absorbed by concentrating PV panels in specific locations [21]. Similar methods for measuring solar radiation using PV panels as sensors were also presented, in which measurement results are based on parameters of open circuit voltage, short circuit current, and solar panel temperature [22], [23].

This study presents a new low-cost alternative method for measuring solar radiation using small-capacity PV cells and temperature sensors to complete the collection of the research projects mentioned above. In this method, irradiance measurement resulted based on the PV output power at a certain load. In addition, the power value is converted using the Newton polynomial interpolation (NPI) equation to obtain the same value according to the calibration value. This method has been simulated using the PSIM software and implemented in the field to compare the results.

2. MATERIALS AND METHODS

The proposed measurement system uses low-cost materials such as a small capacity of PV cells, a temperature sensor, and a microcontroller as the processing unit to display the results. Changes in radiation intensity will result in changes in the power generated by the PV cells. To produce an accurate amount of irradiance (W/m^2), in the conversion system, the electric power from the PV cell (watts) must include the calculation of the correction value generated by the temperature sensor (°C this value is necessary because the power generated by the PV cells with the same radiation intensity can vary owing to the influence of temperature changes. The results of the power and temperature readings of the PV cells are then converted into digital values by an electronic device using a microcontroller following the equation programmed to be displayed on the liquid-crystal display (LCD) display.

2.1. Electrical characteristics of PV cells

PV cells are rated based on their production of wattage, voltage, and amperage under specific conditions. The industry standard against which all PV cells are rated and compared is the standard test conditions (STC). The STC is a defined set of approximate laboratory test conditions under which PV cells may be used. Although other standards offering better real-world approximations exist, the STC provides the most universal standard for characterizing PV cells in terms of two parameters, namely, irradiance and temperature [24].

Every solar PV cell has unique performance characteristics, which can be represented graphically in a chart. This graph is called the ‘I-V curve’ and refers to the module’s output relationship between the current (I) and voltage (V) under prevailing irradiance (1000 W/m^2) and temperature (25°C) conditions according to the STC standard [25], [26]. A typical I-V curve, including the maximum power of the solar PV cell at varying irradiance levels. To obtain maximum power corresponding to irradiance, the solar PV cells must be operated at the MPP, located around the curvature/knee of its I-V curve. The voltage generated by the PV cells is also influenced by temperature, where the higher the temperature, the lower the output voltage. As the characteristics of the current and voltage of the PV cells are not linear, the maximum power output from the PV cells decreases as the cell temperature increases [27].

2.2. NPI approach

The electrical characteristics of PV cells are nonlinear owing to the influence of the irradiance parameters and temperature [28]. Specifically, the non-ideal diode component of PV cells requires a convenient mathematical equation for modeling and simulation [29], [30]. One of the equations used for solving mathematical models resulting in a form with nonlinear characteristics is the Newton-Raphson equation. This equation was used by other researchers to model the I–V curves of PV cells using a single diode at STC, with high accuracy [31].

Interpolation is the process used for finding and calculating the value of a function with a curve formed from a set of points typically resulting from a known function, where the curve must be connected to all existing points with high accuracy. The most widely used interpolation function is the polynomial function because the value of polynomial functions is easy to operate. A polynomial can interpolate values when a polynomial can be used to calculate a value, such as *y*, which is related to *x* and not contained in an observation but lies between the *x* values in that observation. In this study, *y* represents irradiance, and *x* represents the PV power. The irradiance values are determined from the simulations, and the results are known functions with nonlinear curves with respect to the PV power. In other words, in this study, the role of the NPI equation is to display the linear irradiance values of the nonlinear PV power values.

A polynomial P_n (*x*), which has a degree less than or equal to *n* in its standard form, is a function that can be written as (1),

$$P_n(x) = a_0 + a_1x + \cdots + a_nx^n, a_n \neq 0 \quad (1)$$

where the coefficients $a_0, a_1, \ldots, a_n$ are real numbers. If the coefficients are not zero, then the polynomial has a degree of n. The shape of the Newton polynomial with a degree of n is presented in (2),

$$P_n(x) = a_0 + a_1(x - x_0) + a_2(x - x_1)(x - x_0) + \cdots + a_n(x - x_0)(x - x_1) \ldots (x - x_{n-1}) \quad (2)$$

where a_0 and a_1 are the coefficients of the Newton polynomial function. Recursively, the preceding analysis can be generalized to fit an n^{th}-order polynomial to n+1 data points. The n^{th}-order polynomial is presented in (3) [31],

$$P_n(x) = P_{n-1}(x) + a_n(x - x_0)(x - x_1) \ldots (x - x_{n-1}) \quad (3)$$

where the basis of $P_0(x) = f(x_0) = a_1$. The mean absolute percentage error indicator can be used to measure the accuracy of the estimation analysis, as presented in (4),

$$MAPE = \sum_{t=1}^{T} \frac{PE_t}{T} \quad (4)$$

where y_t is the actual data value at time *t*, f_t is the estimated data value at time *t* and *T* is the amount of data.

3. SIMULATION AND PROTOTYPE IMPLEMENTATION

3.1. Simulation

A simulation is performed to test whether the measurement method works well and is in accordance with the theoretical approach before the actual implementation. Simulations performed using the PSIM software produce ideal outputs. That is, the output is unaffected by irregularities such as noise (known as noise in electronics) and interference that typically occur in the actual electrical circuit (real), and the parameter values in each component are real and precise values. The simulation begins with the design of the PV cell model, referring to market product specifications, as follows: *Pm*=0.6 W (±10%), *Vm*=5.5 V, *Im*=0.9 A, *Voc*=6.5 V, and *Isc*=0.12 A, according to the STC standard (200–1,000 W/m^2, 25 °C). The PV cell model simulation and I-V characteristics, including the P curve, are shown in Figures 1 and 2, respectively.

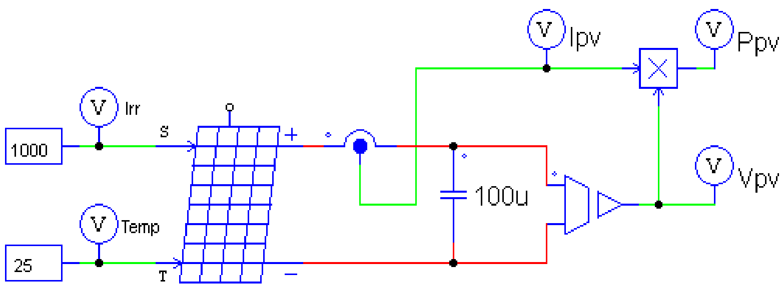


Figure 1. Simulation circuit of existing PV cell

The simulation circuit is depicted in Figure 3. The irradiance range used in the simulation test is 100–2,000 W/m^2, with an interval of 100, producing 20 measurement data calculated using the NPI approach, including the temperature correction factor value. The simulation tests for these options are performed at temperatures of 25 °C and 60 °C to analyze the effect of temperature. The temperature correction factor is determined by calculating the value of the percentage increase in the PV power every 1 °C, which is then added to the results of the irradiance calculation of the NPI equation. The complete process of this simulation is presented in the flowchart in Figure 4.

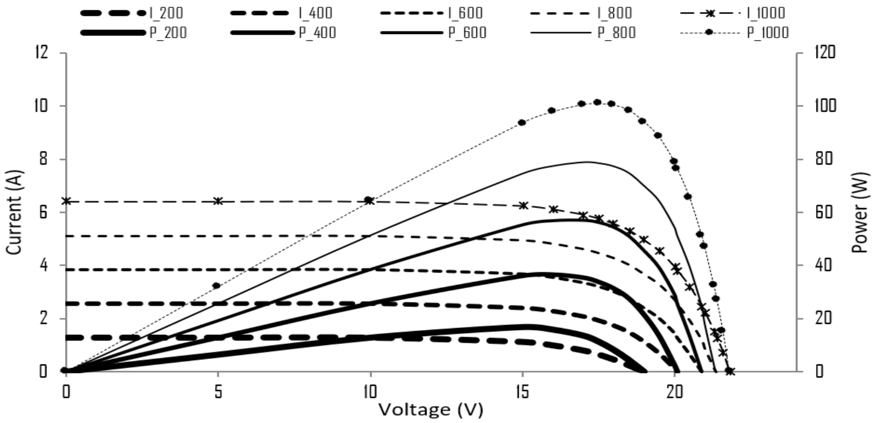


Figure 2. I-V characteristics of PV cell at STC testing

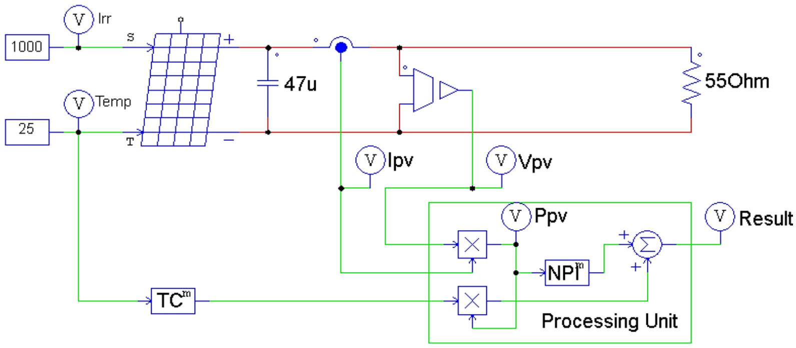


Figure 3. Simulation circuit of measurement system

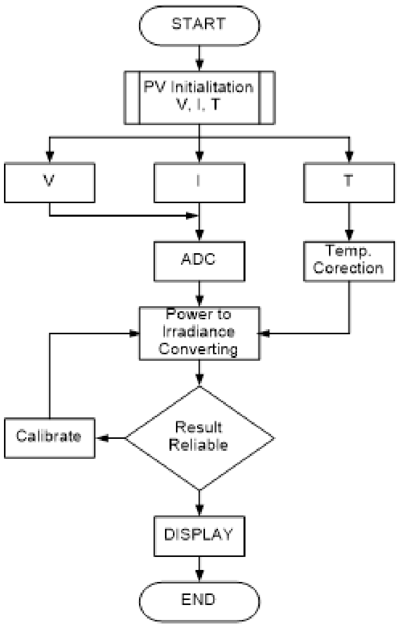


Figure 4. Simulation flowchart

3.2. Prototype implementation

The prototype design starts with the PV cell preparation according to the specifications presented previously. The PV cell is polycrystalline, with a dimension of 6.5×6.5 cm, which is available in the market. A single DS18B20-type intelligent temperature sensor is mounted on the back surface of the PV cell to determine its surface temperature. This sensor belongs to a new generation of adaptive intelligent temperature sensors that can directly convert temperature signals into serial digital signals in processing units. The load connected directly to the PV cell is from a 56 ohm resistor, determined based on the calculation of the maximum voltage and current according to the specification data.

Next, the PV power and temperature readings are converted into digital values by the analog to digital converter (ADC) provided in the internal processing unit. The processing unit, which is an Arduino Uno microcontroller board equipped with an 8-bit AVR ATmega328p microprocessor, is used to program the input reading results using the NPI formula and to display them on the LCD module. The hardware implementation is illustrated in Figure 5.

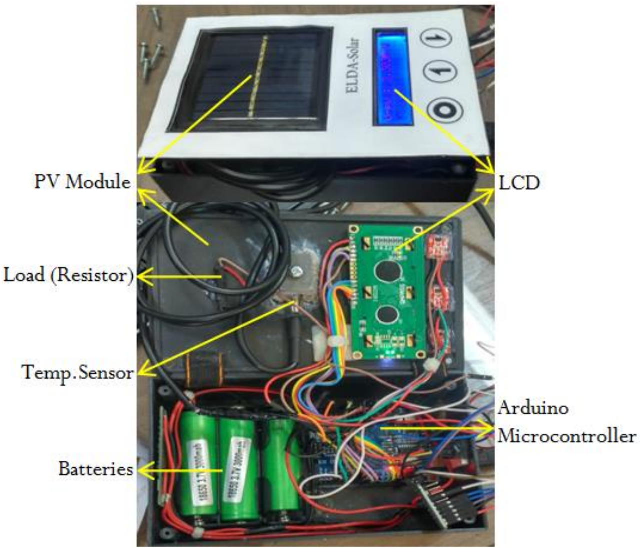


Figure 5. Measurement system hardware

Sunlight hits the PV cell, and the measurement data are displayed on the LCD in the form of irradiance data (W/m^2) as well as several additional measurement data options, such as PV temperature (°C), ambient temperature (°C) and humidity (%), which can be used for further analysis. The accuracy of the measurement data from the prototype is determined by comparing the data from the prototype with the data from a standard solar radiation meter, namely, a Tenmars TM-207 BTU solar power meter with a remote sensor/pyranometer. The testing of the measurement system is depicted in Figure 6.

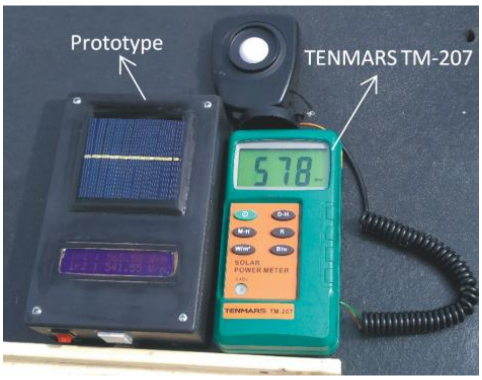


Figure 6. Irradiance measurement system testing

4. RESULTS AND DISCUSSION
4.1. Simulation

The simulated circuit presented in Figure 3 uses the PSIM software. The first step is to determine the PV output power by providing an irradiance (irr) of 100–2,000 W/m^2. To determine the effect of temperature, PV power measurements are conducted at temperatures of 25 °C (P_25) and 60 °C (P_60). Figure 7 shows the simulation results according to the software display with irradiance (Irr) as input in Figure 7(a) and PV power (P) as output in Figure 7(b).

An increase in irradiance per 100, from 0 to 2,000 W/m^2 linearly as shown in Figure 7(a), will result in an increase in the PV power, from 0.006 to -0.76 W nonlinearly as shown in Figure 7(b). This outcome can be seen in the shape of the resulting PV power curves resembling the letter S. Another interesting observation is that in the irradiance range of 0 to 2,000 W/m^2, the effect of increasing temperature from 25 °C to 60 °C lead to a decrease in the efficiency of the PV output power by approximately 0.393% for every 1°C. In the second step, the measured power data are used as a reference for the values listed on the x-axis, with a power range of 0–0.76 W, whereas the y-axis is irradiated within the range of 0–2,000 W/m^2. With the NPI equation solved in Microsoft Excel, a curve similar to that depicted in Figure 8 is obtained.

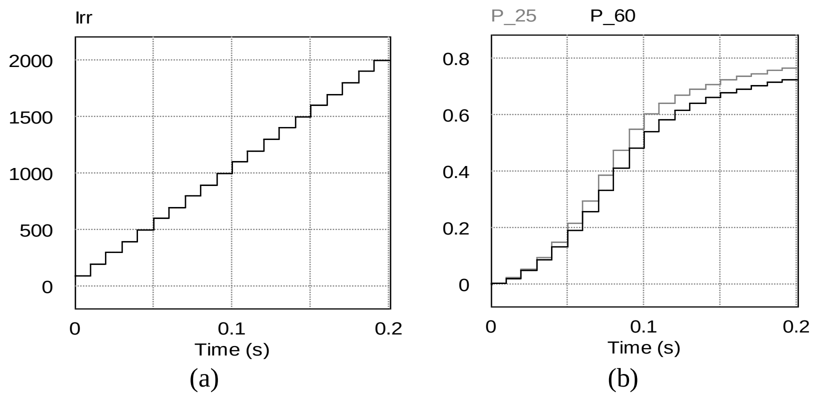


Figure 7. Simulation results comparison between radiation and PV output power: (a) irradiance and (b) PV power output at 25 °C and 60 °C

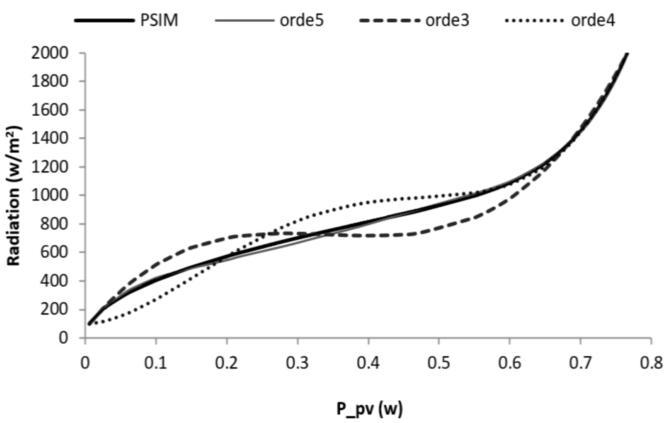
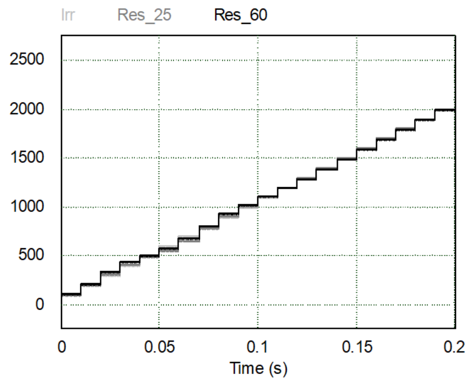


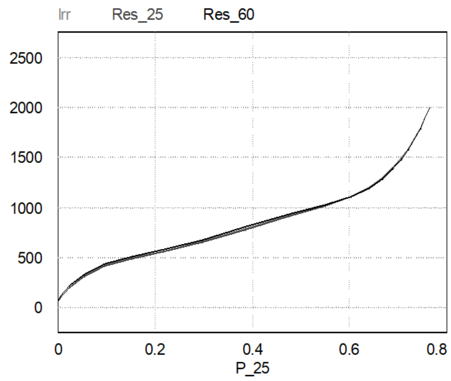
Figure 8. PV power versus irradiance curve using NPI equation

The solid black curve represents the irradiance curve given in the simulation and will become the reference curve. The NPI equation can be used in several stages based on the order level to make the PV power curve similar/close to the irradiance curve. The results of each NPI equation order are then compared with the reference curve. The 3rd-order NPI equation yields inaccurate results. Similarly, the 4th order produces inaccurate curves but approaches the trend of the reference curve. As the results of the 4th order are unsatisfactory, the equation is continued to the 5th order, which generates nearly accurate results as indicated by the solid gray curve. In the final step, the 5th-order NPI equation is chosen for the calculation of the conversion process then retested with the circuit shown in Figure 3, with the results obtained based on the measurements at the output point (result).

Figure 9 shows irradiance measurement simulation results with the time based in Figure 9(a) and PV power based in Figure 9(b). It can be explained that the irradiance measurements at temperatures of 25 °C and 60 °C follow the trend of the radiation reference curve, with the lowest error rate of 0.084% in an irradiance of 1,300 W/m^2 and the highest error rate of 7.03% in an irradiance of 700 W/m^2. This indicates that the irradiance measurement is not affected by the temperature of the PV cell. In the simulation measurement results, the average error percentage of the proposed method is 1.63%.



(a)



(b)

Figure 9. Irradiance measurement simulation results (a) time based and (b) PV power based

4.2. Prototype implementation

Prototype testing is conducted outdoors on a field on a sunny day using the standard irradiance meter (Tenmars TM-207), as shown in Figure 7. The prototype and Tenmars TM-207 meters are attached together side by side in a vertical position from the ground (90 degrees from the horizontal line). Measurements and data retrieval are conducted manually from 7:00 to 16:30, at 30 minute intervals, and the results are presented in Figure 10. Overall, the irradiance measurement curve from the prototype successfully follows the same trend as the measurement curve from the standard irradiance meter. In this study, a change in PV temperature does not affect the irradiance reading owing to the temperature correction factor value, which is also included in the NPI equation. However, errors are observed at certain reading points, such as at 21:00 and from 13.00 to 15:00, which exhibit an average maximum error of 4.65%, and at 10:30 to 00:00, which exhibit a minimum error of 0.39%.

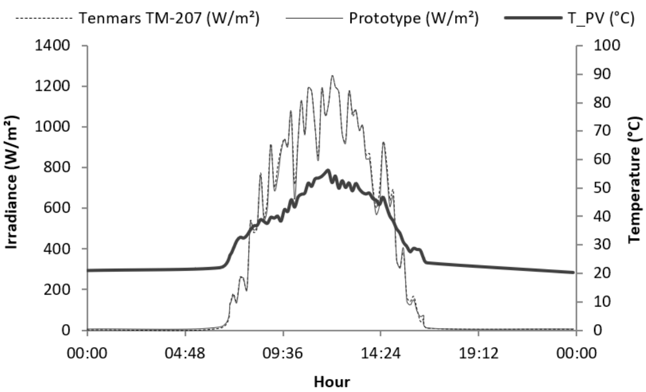


Figure 10. Irradiance and PV temperature measurement results of prototype and Tenmars TM-207 meters

Overall, the average error in the measurement implementation in the field is 2.72%. The error value indicates that the proposed method has high accuracy in irradiation measurement and the prototype has shown good measurement performance even though it was built with low-cost materials. Generally, differences in errors in simulations with implementations are common owing to various factors. Some of these factors can be attributed to differences in the value of the component parameter between the simulation tool and the actual component, differences in the response time of the reading between the simulation and actual implementation, and the influence of other environmental conditions that do not consider the parameters.

5. CONCLUSION

The simulation and implementation of a solar radiation meter are presented in this paper. In addition, the method for converting PV cells' power into irradiance using the NPI approach is discussed. The simulation and prototype implementation show the same characteristic trends and measurement results, which do not differ considerably between the simulation and implementation. In various solar radiation meters, changes in temperature can affect the PV power output but do not affect the irradiation values displayed in the measurement, because temperature correction is considered in the conversion equation. Overall, the proposed methods can be used as a low-cost alternative for measuring solar radiation, especially relating to the collection and analysis of measurement data for solar system applications.

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REFERENCES

[1] A. Al Mansur *et al.*, "Mitigation of mismatch power loss in aged photovoltaic arrays following a comparative investigation into module rearrangement techniques," *Energy Reports*, vol. 8, pp. 1896–1906, Nov. 2022, doi: 10.1016/j.egyr.2022.01.013.

[2] T. Dwi Atmaja *et al.*, "Fuel saving on diesel genset using PV/battery spike cutting in remote area microgrid," *MATEC Web of Conferences*, vol. 164, Apr. 2018, doi: 10.1051/matecconf/201816401045.

[3] N. S. Nazri *et al.*, "Exergy and improvement potential of hybrid photovoltaic thermal/thermoelectric (PVT/TE) air collector," *Renewable and Sustainable Energy Reviews*, vol. 111, pp. 132–144, Sep. 2019, doi: 10.1016/j.rser.2019.03.024.

[4] A. Fudholi and K. Sopian, "Review on exergy and energy analysis of solar air heater," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 9, no. 1, pp. 420–426, Mar. 2018, doi: 10.11591/ijpeds.v9.i1.pp420-426.

[5] A. Fudholi and K. Sopian, "Review on solar collector for agricultural produce," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 9, no. 1, pp. 414–419, Mar. 2018, doi: 10.11591/ijpeds.v9.i1.pp414-419.

[6] A. Fudholi, M. Othman, M. Ruslan, M. Yahya, A. Zaharim, and K. Sopian, "Design and testing of solar dryer for drying kinetics of seaweed in Malaysia," *Recent Research in Geography, Geology, Energy, Environment and Biomedicine*, pp. 119–124, 2011.

[7] V. Shenoy, P. Tripathi, A. Mahadik, P. Nalawade, and A. Mahajan, "Devices used for measuring solar radiation-a review," *International Conference on Innovative and Advanced Technologies in Engineering. IOSR Journal of Engineering (IOSRJEN)*, pp. 2250–3021, 2018.

[8] A. K. Podder, N. K. Roy, and H. R. Pota, "MPPT methods for solar PV systems: a critical review based on tracking nature," *IET Renewable Power Generation*, vol. 13, no. 10, pp. 1615–1632, Jul. 2019, doi: 10.1049/iet-rpg.2018.5946.

[9] B. Abdelilah, A. Mouna, N. KouiderM'Sirdi, and A. El Hossain, "Implementation of maximum power point tracking (MPPT) solar charge controller using arduino," *IOP Conference Series: Materials Science and Engineering*, vol. 353, May 2018, doi: 10.1088/1757-899X/353/1/012024.

[10] O. Lopez-Lapena, M. T. Penella, and M. Gasulla, "A new MPPT method for low-power solar energy harvesting," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 9, pp. 3129–3138, Sep. 2010, doi: 10.1109/TIE.2009.2037653.

[11] A. Al Mansur, S. M. Ferdous, Z. Bin Shams, M. R. Islam, M. Rokonuzzaman, and M. A. Hoque, "An experimental investigation of the real time electrical characteristics of a PV panel for different atmospheric conditions in Islamic University of Technology (OIC), Gazipur, Bangladesh," in *2011 International Conference and Utility Exhibition on Power and Energy Systems: Issues and Prospects for Asia (ICUE)*, Sep. 2011, pp. 1–8, doi: 10.1109/ICUEPES.2011.6497767.

[12] L. Martin, P. Vladislav, and K. Pavel, "Temperature changes of I-V characteristics of photovoltaic cells as a consequence of the Fermi energy level shift," *Research in Agricultural Engineering*, vol. 63, no. 1, pp. 10–15, Apr. 2017, doi: 10.17221/38/2015-RAE.

[13] A. Q. Jakhrani, S. R. Samo, S. A. Kamboh, J. Labadin, and A. R. H. Rigit, "An improved mathematical model for computing power output of solar photovoltaic modules," *International Journal of Photoenergy*, pp. 1–9, 2014, doi: 10.1155/2014/346704.

[14] T. Khatib, W. Elmenreich, and A. Mohamed, "Simplified I-V characteristic tester for photovoltaic modules using a DC-DC boost converter," *Sustainability*, vol. 9, no. 4, Apr. 2017, doi: 10.3390/su9040657.

[15] K. N. Poudyal, B. K. Bhattarai, B. K. Sapkota, B. Kjeldstad, and N. R. Karki, "Estimation of global solar radiation using pyranometer and NILU-UV irradiance meter at Pokhara Valley in Nepal," *Journal of the Institute of Engineering*, vol. 9, no. 1, pp. 69–78, Jun. 2014, doi: 10.3126/jie.v9i1.10672.

[16] J.-C. Baltazar, Y. Sun, and J. Haberl, "Improved methodology to measure normal incident solar radiation with a multi-pyranometer array," *Energy Procedia*, vol. 57, pp. 1211–1219, 2014, doi: 10.1016/j.egypro.2014.10.109.

[17] G. Sanchez, A. Serrano, M. L. Cancillo, and J. A. Garcia, "Pyranometer thermal offset: measurement and analysis," *Journal of Atmospheric and Oceanic Technology*, vol. 32, no. 2, pp. 234–246, Feb. 2015, doi: 10.1175/JTECH-D-14-00082.1.

[18] A. Patil, K. Haria, and P. Pashte, "Photodiode based pyranometer," *International Journal of Advances in Science Engineering and Technology*, vol. 1, no. 1, pp. 29–33, 2013.

[19] S. Gagliano, D. Neri, N. Pitrone, N. Savalli, and G. Tina, "Low-cost solar radiation sensing transducer for photovoltaic systems," *WSEAS Transactions on Environment and Development*, vol. 5, no. 2, pp. 119–125, 2009.
[20] R. C. de Barros, J. M. S. Callegari, D. do C. Mendonca, W. C. S. Amorim, M. P. Silva, and H. A. Pereira, "Low-cost solar irradiance meter using LDR sensors," in *2018 13th IEEE International Conference on Industry Applications (INDUSCON)*, Nov. 2018, pp. 72–79, doi: 10.1109/INDUSCON.2018.8627176.
[21] I. Alboteanu, C. Bulucea, and S. Degeratu, "Estimating solar irradiation absorbed by photovoltaic panels with low concentration located in Craiova, Romania," *Sustainability*, vol. 7, no. 3, pp. 2644–2661, Mar. 2015, doi: 10.3390/su7032644.
[22] A. Al Mansur, B. Shil, K. K. Islam, M. A. Hoque, and M. H. Bhuyan, "Design and implementation of a solar radiation meter using PV panel as a sensor," *Green University Journal, Bangladesh*, vol. 1, no. 1, 2014.
[23] J. Cruz-Colon, L. Martinez-Mitjans, and E. I. Ortiz-Rivera, "Design of a low cost irradiance meter using a photovoltaic panel," in *2012 38th IEEE Photovoltaic Specialists Conference*, Jun. 2012, pp. 2911–2912, doi: 10.1109/PVSC.2012.6318195.
[24] H. Ibrahim and N. Anani, "Variations of PV module parameters with irradiance and temperature," *Energy Procedia*, vol. 134, pp. 276–285, Oct. 2017, doi: 10.1016/j.egypro.2017.09.617.
[25] C. Morcillo-Herrera, F. Hernández-Sánchez, and M. Flota-Bañuelos, "Method to calculate the electricity generated by a photovoltaic cell, based on its mathematical model simulations in MATLAB," *International Journal of Photoenergy*, pp. 1–12, 2015, doi: 10.1155/2015/545831.
[26] A. Al Mansur, M. I. Islam, M. A. ul Haq, M. H. Maruf, A. Shihavuddin, and M. R. Amin, "Investigation of PV modules electrical characteristics for laboratory experiments using halogen solar simulator," in *2020 2nd International Conference on Sustainable Technologies for Industry 4.0 (STI)*, Dec. 2020, pp. 1–6, doi: 10.1109/STI50764.2020.9350496.
[27] J. Ma, H. Jiang, K. Huang, Z. Bi, and K. L. Man, "Novel field-support vector regression-based soft sensor for accurate estimation of solar irradiance," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 64, no. 12, pp. 3183–3191, Dec. 2017, doi: 10.1109/TCSI.2017.2746091.
[28] B. Nayak, A. Mohapatra, and B. Misra, "Non linear IV curve of PV module: Impacts on MPPT and parameters estimation," *International Journal of Engineering Research and Technology (IJERT)*, vol. 1, no. 8, pp. 1–8, 2012.
[29] S. Bogning Dongue, D. Njomo, and L. Ebengai, "An improved nonlinear five-point model for photovoltaic modules," *International Journal of Photoenergy*, pp. 1–11, 2013, doi: 10.1155/2013/680213.
[30] F. B. Pelap, P. D. Dongo, and A. D. Kapim, "Optimization of the characteristics of the PV cells using nonlinear electronic components," *Sustainable Energy Technologies and Assessments*, vol. 16, pp. 84–92, Aug. 2016, doi: 10.1016/j.seta.2016.05.005.
[31] D. V. Griffiths and I. M. Smith, *Numerical methods for engineers*. CRC press, 2006.

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