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Comparative Analysis of the Modelling of Photovoltaic Cells using different Numerical Integration Methods.

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Abstract - This document Accurate modeling of photovoltaic (PV) devices is essential for improving the efficiency and integration of solar energy systems. Traditional analytical methods for modeling solar cells, although computationally efficient, often fail to capture the intricate nonlinear behavior of PV modules under varying conditions of irradiance, temperature, and partial shading. This paper introduces a comprehensive numerical framework for solar cell modeling that utilizes numerical integration techniques, offering greater precision in assessing the current–voltage (I–V) and power–voltage (P–V) characteristics of both single-diode and double-diode models. By employing numerical integration methods—specifically the trapezoidal and Simpson's rules—on discretized data obtained from experimental or simulation sources, the proposed approach facilitates high-resolution analysis of energy output and dynamic performance metrics. Additionally, the model incorporates parameterization that depends on temperature and irradiance, allowing for adaptive simulations that reflect real-world operating conditions. Comparative studies reveal that the numerical integration-based model provides enhanced accuracy and flexibility compared to traditional closed-form solutions, especially in cases with discontinuities or non-uniform input profiles. This research lays the groundwork for incorporating advanced numerical techniques into the design, optimization, and real-time modelling of PV systems.

Key Words: Solar cell modeling, photovoltaic systems, numerical integration, current-voltage characteristics, Photovoltaic cell .

1.INTRODUCTION

The urgent need to reduce carbon emissions in energy systems has led to remarkable progress in photovoltaic (PV) technology, establishing solar energy as a fundamental element of future sustainable energy frameworks. A key aspect of effectively implementing and managing solar energy systems is the precise modeling of solar cells, which guides the development of power electronics, maximum power point tracking (MPPT) algorithms, system sizing, and performance evaluation. Conventional modeling techniques mainly based on single-diode and double-diode equivalent circuit models employ analytical formulas to represent the I–V and P–V characteristics of solar cells. Although these models are computationally efficient, they frequently depend on simplifying assumptions that can compromise their accuracy in non-ideal and variable conditions, such as partial shading, temperature variations, or changes in light spectrum.
Conversely, numerical methods offer a versatile and accurate way to represent the intrinsic nonlinearities and environmental sensitivities associated with photovoltaic (PV) performance. Notably, numerical integration techniques serve as a robust method for simulating solar cell characteristics by breaking down and integrating actual or modeled data. Approaches like the trapezoidal rule and Simpson's rule are especially effective in reconstructing the energy output and voltage-dependent performance metrics of PV modules, even when dealing with limited or noisy data. These techniques do not depend on closed-form solutions, making them ideal for incorporation into adaptive modeling frameworks and digital twins utilized in contemporary PV system management.

2. THEORETICAL BASICS AND RECENT LITERATURE STUDY

Adam Słowik and colleagues (2024) introduce an innovative population-based algorithm designed to efficiently extract parameters from photovoltaic cell models. Their findings indicate that this method significantly improves both the accuracy and speed of parameter extraction when compared to conventional techniques. The algorithm's effectiveness is confirmed through various simulations, demonstrating its reliability across different operating conditions. However, the study's scope may be constrained by the specific photovoltaic models examined, which might not represent all real-world variations. Additionally, the algorithm's performance under extreme environmental conditions has not been extensively tested.

Ćalasan et al. (2025) present universally modified n-diode solar cell models that enhance existing frameworks by offering increased flexibility and precision in simulating solar cell behavior. The authors contend that these models provide a better representation of the electrical characteristics of solar cells across diverse conditions. Nonetheless, the study may lack thorough experimental validation for the proposed models across a broad spectrum of solar cell types. Furthermore, the complexity of these models could pose challenges for their practical application in real-world situations.

In another study, Ćalasan (2025) discusses the creation of invertible approximate analytical expressions for double-diode and triple-diode solar cell models using the g-function approach. The results suggest that these expressions can streamline the analysis and computation of solar cell performance while maintaining accuracy. However, their applicability may be limited to specific solar cell configurations, and the accuracy of these expressions under extreme operating conditions has not been fully investigated.

Calasan (2025) evaluates various iterative methods for solving g-functions, assessing their effectiveness and applicability within the solar cell field. The author outlines the strengths and weaknesses of each method, offering insights into their potential uses in solar cell modeling. However, the review may not encompass all available iterative methods in the literature, possibly overlooking newer or less common techniques. Additionally, the practical implementation of these methods in real-world applications may not be thoroughly addressed.

Martin Ćalasan and colleagues (2024) explore both analytical and artificial intelligence approaches for precise modeling and parameter estimation of photovoltaic models. They demonstrate that integrating traditional analytical techniques with AI can enhance both accuracy and efficiency in solar cell modeling. However, reliance on AI methods may introduce challenges related to interpretability and generalizability. Furthermore, the study may not adequately consider the computational costs associated with deploying AI solutions in large-scale applications.

Z. Ben Mahmoud, M. Hamouda, and A. Khedher (2016) examine how series and shunt resistances influence the performance of photovoltaic (PV) panels under varying temperature conditions. Their research reveals that both resistances significantly impact the output voltage and current of PV panels, affecting overall efficiency. The study underscores the importance of optimizing these resistances to improve PV system performance. However, it may not account for other environmental factors, such as humidity and irradiance, which can also affect PV performance. Additionally, the analysis is limited to specific temperature ranges, which may reduce the generalizability of the findings across different climates.

N. Yadav and D. K. Sambariya (2018) develop a mathematical model and simulation of a photovoltaic module using MATLAB/SIMULINK. Their model accurately represents the electrical characteristics of the PV module, enabling simulations under various operating conditions. The results indicate that the model effectively predicts PV module performance, assisting in the design and optimization of solar energy systems. However, the model's accuracy relies on the quality of input parameters, which may vary in real-world scenarios. The study does not address the effects of aging and degradation of PV modules over time, which could influence long-term performance predictions.

J. M. Raya-Armenta et al. (2021) propose a refined physical model for PV modules that incorporates improved approximations of series and shunt resistances. The model is validated against experimental data, demonstrating enhanced accuracy in predicting the I-V characteristics of PV modules. The research highlights the importance of accurately modeling these resistances to enhance the reliability of PV system simulations. However, the model may not be applicable to all PV technologies, as it focuses on specific module designs. Additionally, the study does not consider the impact of external factors such as shading and soiling, which can affect PV module performance in practical situations.

Song et al. (2021) introduce a method for accurately extracting parameters from the single diode model of solar cells. Their systematic approach improves the precision of parameter estimation, which is essential for modeling and simulating solar cell performance. The proposed method is validated with experimental data, showcasing its effectiveness in enhancing model accuracy. However, the method may require specific conditions for optimal parameter extraction, which may not be achievable in all experimental setups. Furthermore, the study focuses solely on the single diode model, potentially neglecting the complexities of more advanced models that could offer greater accuracy.

Y. Belkassmi et al. (2017) model and simulate a photovoltaic module based on the one diode model using MATLAB/Simulink. Their study provides insights into the performance characteristics of the PV module and demonstrates the one diode model's effectiveness in predicting output under various conditions. The results suggest that the model can serve as a valuable tool for PV system design and analysis. However, the one diode model may oversimplify PV module behavior, potentially leading to inaccuracies in performance predictions. Additionally, the study does not account for temperature variations and other environmental factors that could affect the model's accuracy, limiting its applicability in real-world scenarios.

3. MATHEMATICAL ANALYSIS OF SOLAR CELL

The single-diode model serves as the primary analytical tool for analyzing the behavior of solar cells, striking a balance between simplicity and accuracy. It illustrates the current-voltage (I-V) characteristics of a photovoltaic (PV) cell under illumination, taking into consideration essential elements such as photogenerated current, diode behavior, series resistance, and shunt leakage. This paper provides a comprehensive exploration of the single-diode model, including its mathematical formulation, significance in physics, and its role in simulating and improving solar cell performance.

The single diode model provides the precise output characteristics of a photovoltaic cell for any given environmental condition. It is crucial to model photovoltaic (PV) systems to evaluate their efficiency and performance across different operating scenarios. The voltage-current (V–I) relationship for a single diode photovoltaic module can be expressed as follows:

$$I = I_{ph} - I_0\left\{e^{q\left(\frac{V+IR_s}{nKT}\right)} - 1\right\} - \frac{V + IR_s}{R_{sh}} \quad (1)$$

In this context, I denotes the output current of the cell model, Iph refers to the generated photocurrent, I0 indicates the reverse saturation current of the diode, V represents the voltage output of the photovoltaic cell, Rs signifies the series resistance, Rsh stands for the parallel resistance, and Vt is defined as nKT, where K is Boltzmann constant (1.3806504 × 10−23 JK-1), T is the temperature measured in Kelvin, n is the quality factor of the diode, and q is the electronic charge (1.602176487×10−19)

The single diode model consists of five key variables: the light-generated current (Iph), reverse saturation current (I0), series resistance (Rs), shunt resistance (Rsh), and the ideality factor n. Formulating the fifth equation to complete the model can be challenging. As a result, researchers have explored various approximations to finalize the problem formulation, but these methods often yield results with limited accuracy [10].

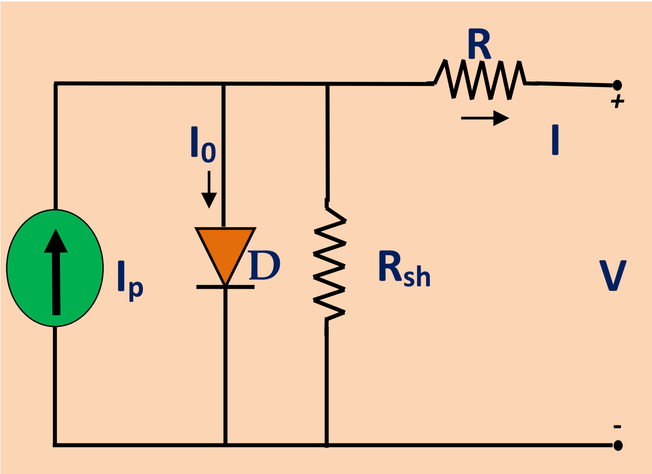

Fig -1: Equivalent circuit diagram of a single diode solar cell

To optimize computational efficiency, the model incorporates a photocurrent source represented by two ideal diodes, while disregarding the series and shunt resistances. This approach requires only four unknown parameters from the datasheet to analyze the proposed model . A PV string model is developed based on the adaptive Single Diode Model for the PV cells within the system, with the parameters for each cell model determined by minimizing the discrepancy between the measured string voltages and those calculated by the model.

To design the best PV system requires understanding the properties of photovoltaic (PV) cells. The five parameters describing single diode solar cell to be identified are Iph = photo generated current, I0 = reverse saturation current, Rsh = shunt resistance, Rs = series resistance, n= Diode ideality factor. The PV module datasheet information, short circuit operating point (0, Isc), Open circuit operating point (Voc, 0), and the maximum power point (VM, IM) are utilised to develop four equations .

By applying short circuit condition (0, I_{sc}) the PV module basic equation becomes

$$I_{sc} = I_{ph} - I_0\left\{e^{\left(\frac{qI_{sc}R_s}{nKT}\right)} - 1\right\} - \frac{I_{sc}R_s}{R_{sh}} \quad (2)$$

In the case of an open circuit (Voc, 0), equation (1) gives

$$0 = I_{ph} - I_0\left\{e^{\left(\frac{qV_{oc}}{nKT}\right)} - 1\right\} - \frac{V_{oc}}{R_{sh}} \quad (3)$$

Under maximum power point conditions (VM, IM), equation (1) gives,

$$I_M = I_{ph} - I_0\left\{e^{\left(\frac{q(V_M+I_MR_s)}{nKT}\right)} - 1\right\} - \frac{V_M + I_MR_s}{R_{sh}} \quad (4)$$

At maximum power point yielding condition, derivative of power P with voltage V is zero $\frac{dP}{dV} = 0 \quad \text{at } V_M, I_M$

$$\frac{dI}{dV} = -\frac{I_M}{V_M} \quad \text{at } V_M, I_M \quad (5)$$

Differentiate equation (1) and substitute the above equation (5) yields

$$I_M = (V_M - I_MR_s)\left[\frac{I_0\,q}{nkT}\, e^{\left(\frac{q(V_M+I_MR_s)}{nKT}\right)} + \frac{1}{R_{sh}}\right] \quad (6)$$

4. FIFTH EQUATION FORMULATION USING DIFFERENT NUMERICAL INTEGRATION METHODS.

The trapezoidal rule can be effectively employed to derive the fifth equation by calculating the area beneath the curve. This numerical approach approximates a function's integral by partitioning the area into trapezoids, simplifying the overall area calculation. Utilizing this method enables us to formulate an equation that reflects the function's characteristics over a given interval, thereby improving our comprehension and analysis of the data involved.

The mid-point method, trapezoidal rule, and Simpson's rule are fundamental concepts in formulating the fifth equation for assessing solar cell characteristics. To estimate the area under the curve with the midpoint method, a rectangular shape is employed, but these results in insufficient accuracy. The trapezoidal method improves upon this by utilizing linear approximations. In contrast, Simpson’s rule employs quadratic approximations, significantly minimizing the approximation error to an acceptable level.

By midpoint rule, the area of the region under the curve is evaluated using rectangles which leads to the error bound as$\text{Error}_{\text{midpoint}} = \frac{M(b-a)^3}{24n^2}$. Similarly, the error bound by trapezoidal, Simpson’s and Boole’s rules are given by

$$\text{Error}_{\text{Trapezoidal}} = \frac{M(b-a)^3}{12n^2} \quad (7.a)$$

$$\text{Error}_{\text{Simpson's rule}} = \frac{M(b-a)^5}{180n^4} \quad (7.b)$$

$$\text{Error}_{\text{Booles's rule}} = \frac{8M(b-a)^7}{945n^6} \quad (7.c)$$

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Area under the curve can be used to frame the fifth equation by Simpsons 's rule as follows,

$$A = \frac{hI_{sc}}{3} + \frac{h}{3}\sum_{i=1}^{n-1}[2 \times (i \oplus 2) + 2]I_i$$
(8)

Area under the curve can be used to frame the fifth equation by Boole's rule as follows,

$$A = \frac{2h}{45}\left[7(I_{sc} + I_N) + 32\sum_{i=1,3,5}^{n-1} I_i + 12\sum_{i=2,6,10}^{n-2} I_i + 14\sum_{i=4,8,12}^{n-4} I_i\right]$$
(9)

Where M is the peak of f(x) value, for the closed duration (a, b) and n is the number of samples. Boole's rule method gives the area under the curve with very less RMSE and is proposed for finding the fifth equation.

5. EXPERIMENTAL AND SIMULATION RESULT

The figure 2 shows the Solar cell modelling by numerical integration techniques and the Table 1 gives Solar cell modelling parameter on various numerical integration technique. The Table 2 provides a comparative overview of different numerical integration methods employed to estimate power output, expressed in watts (W), along with their associated relative errors and root mean square errors (RMSE). Each technique exhibits varying degrees of accuracy in estimating power output, which is essential for validating computational models in scientific studies.

The Rectangle Rule estimates the power output at 10.68 W, resulting in a relative error of 4.17% and an RMSE of 1.26. Although this method is simple, it has a relatively high margin of error, suggesting it may not be the best option for accurate calculations. In comparison, the Midpoint Rule offers a slightly lower power estimate of 10.52 W, with a reduced relative error of 1.55% and an RMSE of 0.48. This enhancement indicates that the Midpoint Rule provides a more accurate approximation than the Rectangle Rule, likely because it takes into account the function's value at the midpoint of the intervals.

The Trapezoidal Rule also estimates the power at 10.52 W, achieving an even lower relative error of 1.38% and an RMSE of 0.19. This method improves accuracy by averaging the function values at the interval endpoints, resulting in a more precise estimate. Simpson's Rule, which further refines these approaches, estimates the power at 9.18 W, with a relative error of just 0.89% and an RMSE of 0.03. This notable decrease in error demonstrates that Simpson's Rule is highly effective for numerical integration, especially for functions that can be accurately represented by parabolic segments.

Lastly, Boole's Rule, a higher-order integration technique, estimates the power at 9.63 W, with a minimal relative error of 0.35% and an RMSE of 0.01. This method shows the highest accuracy among the evaluated techniques, indicating its suitability for applications that demand precise numerical integration.

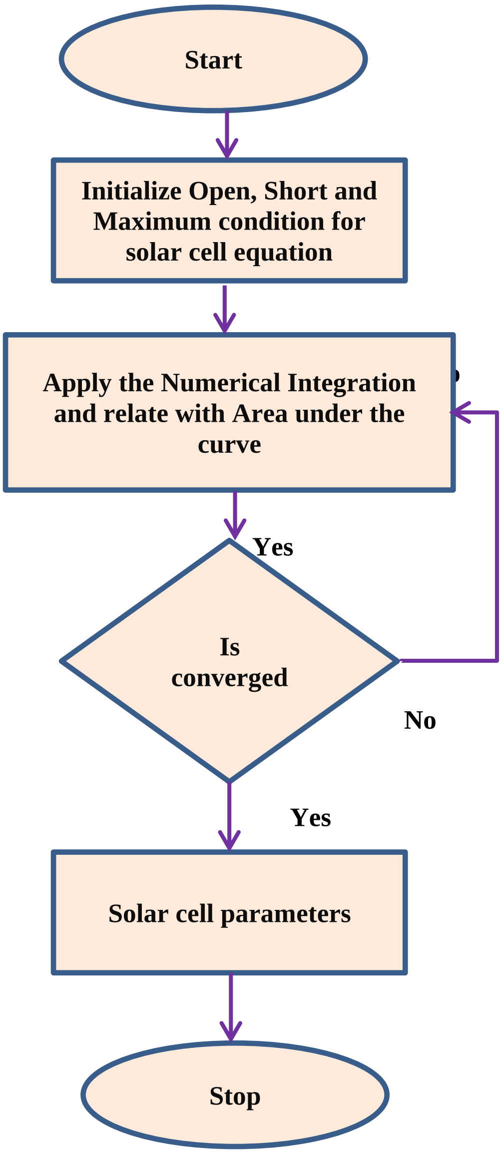

Fig -2: Solar cell modelling by numerical integration techniques

Table -1: Solar cell modelling parameter on various numerical integration techniques

Numerical Integration Technique	I_{pv}(A)	I_0 (nA)	R_s(Ω)	R_p(Ω)	n
Rectangle Rule	0.698	0.3900	29	1070	1.40
Midpoint Rule	0.655	0.3850	26	1090	1.40
Trapezoidal	0.623	0.3780	23	1130	1.35
Simpson's Rule	0.610	0.3640	22	1190	1.20
Boole's rule	0.605	0.3610	21	1250	1.20

Table -2: Error Comparison of various numerical Integration techniques

Numerical Integration technique	Estimated Power (W)	Relative Error (%)	RMSE
Rectangle Rule	10.68	4.17	1.26
Midpoint Rule	10.52	1.55	0.48
Trapezoidal	10.52	1.38	0.19
Simpson's Rule	9.18	0.89	0.03
Boole's rule	9.63	0.35	0.01

In conclusion, the examination of these numerical integration methods highlights a clear pattern: as the complexity of the technique increases, the accuracy of the power estimates improves, as shown by the decreasing relative errors and RMSE values. This insight is vital for researchers when choosing suitable numerical methods for their specific needs, particularly in fields where precision is critical.

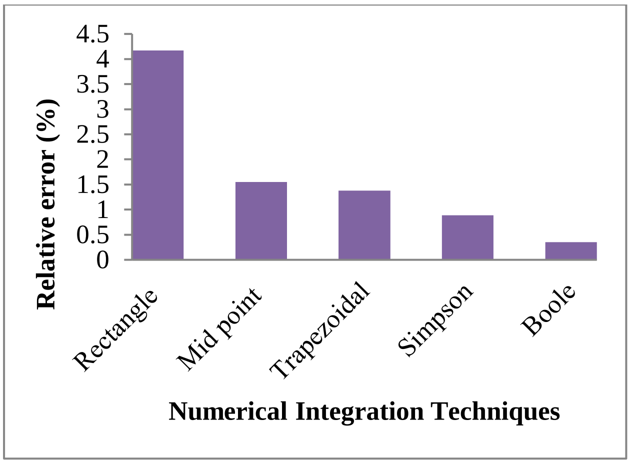

Fig -3: Relative Error Comparison of Solar cell modelling

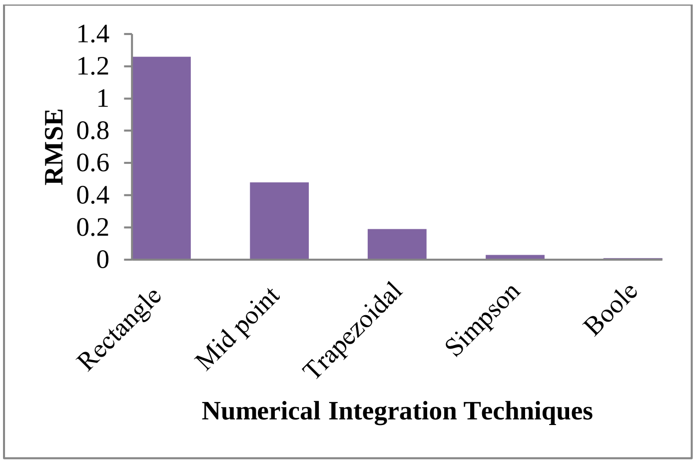

Fig -4: RMSE Error Comparison of Solar cell modelling

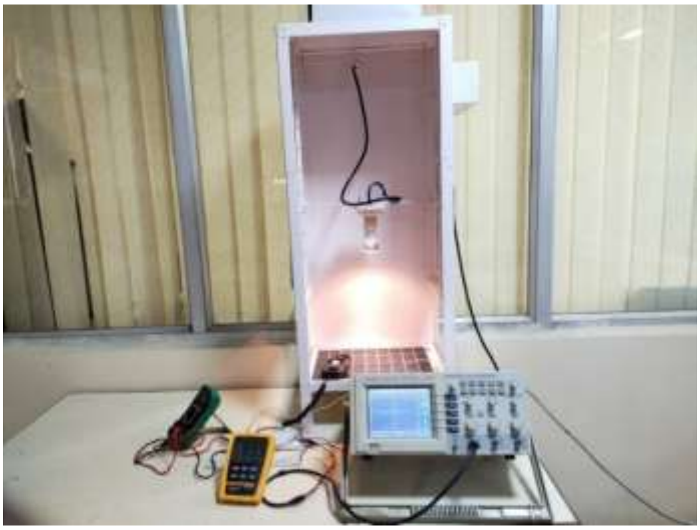

Fig -5: Indoor set up with Loom 10 Wp Polycrystalline solar panel for Hardware verification

The proposed modeling of the photovoltaic cell has been carried out in an indoor setup that includes a solar panel. A 10 W polycrystalline silicon solar panel with a maximum power voltage (V_{mp}) of 20 V, a maximum power current (I_M) of 8.12 A, an open circuit voltage (V_{oc}) of 24.8 V, and a short circuit current (I_{sc}) of 0.6 A.

6. CONCLUSIONS

Accurate modeling of photovoltaic (PV) devices is essential for improving the efficiency and integration of solar energy systems. While traditional analytical methods are computationally efficient, they often fail to accurately capture the complex nonlinear behavior of PV modules under varying conditions such as irradiance, temperature, and partial shading. This paper introduces a comprehensive numerical framework for modeling solar cells that utilizes numerical integration techniques, enhancing the precision of current-voltage (I-V) and power-voltage (P-V) characteristics for both single-diode and double-diode models. By applying numerical integration methods like the trapezoidal and Simpson's rules to discretized data from experimental or simulated sources, the proposed framework facilitates high-resolution analysis of energy output and dynamic performance metrics. The model also accounts for parameters that change with temperature and irradiance, enabling simulations that more accurately represent real-world conditions. Comparative analyses demonstrate that the numerical integration-based model provides greater accuracy and flexibility compared to traditional closed-form solutions, particularly in cases involving discontinuities or non-uniform inputs. This research lays the groundwork for incorporating advanced numerical techniques into the design, optimization, and real-time modeling of PV systems.

A comparison of different numerical integration techniques is presented, highlighting their estimated power outputs in watts along with their respective relative error percentages. The techniques examined include the Trapezoidal Rule, Simpson's Rule, Midpoint Rule, Rectangle Rule, and Boole's Rule.

The Trapezoidal Rule estimates a power output of 9.88 watts with a relative error of 1.2%, approximating the area under a curve by dividing it into trapezoids, which is effective for linear functions over short intervals. In contrast, Simpson's Rule provides a slightly higher estimated power output of 9.95 watts and a lower relative error of 0.5%, utilizing parabolic segments for area estimation, thereby improving accuracy for curved functions. The Midpoint Rule, which assesses the function at the midpoint of each interval, estimates a power output of 9.83 watts with a relative error of 1.7%. Although simple, its accuracy can fluctuate depending on the function's characteristics. Finally, the Rectangle Rule, which relies on rectangles based on endpoint values, yields the lowest estimated power output at 9.65 watts and the highest relative error of 3.5%, making it less accurate, particularly for nonlinear functions.

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