A Systematic Review of Solar Photovoltaic Cell Modeling, I–V Characteristics, and Energy Optimization Techniques

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ABSTRACT

The increasing global demand for renewable energy has established solar photovoltaic (PV) systems as a reliable alternative to fossil fuels. The efficiency of solar cells, however, depends strongly on environmental conditions such as irradiance, temperature, and load variations. Accurate modelling and optimization are therefore essential for maximizing performance. MATLAB Simulink provides a robust simulation environment for analysing solar cells through equivalent circuit models, enabling the study of current-voltage (I-V) and power-voltage (P-V) characteristics. Furthermore, the platform supports the implementation of Maximum Power Point Tracking (MPPT) algorithms, including Perturb and Observe, Incremental Conductance, and intelligent approaches, to enhance energy extraction. By integrating solar cells with power converters, storage, and grid systems, MATLAB Simulink facilitates comprehensive optimization of PV systems. Such analysis and optimization are crucial to improving efficiency, reliability, and scalability of solar technology for both standalone and grid-connected applications.

Keywords: Solar Photovoltaic (PV) Systems, MATLAB Simulink, Maximum Power Point Tracking (MPPT).

1. Introduction

The rising demand for renewable energy sources has positioned solar photovoltaic (PV) technology as one of the most promising alternatives to conventional fossil fuels. Solar cells, which directly convert sunlight into electricity, have gained considerable attention due to their environmental benefits, scalability, and decreasing costs. However, the efficiency and reliability of solar energy systems remain critical challenges that require systematic analysis and optimization. Since the performance of solar cells is highly dependent on factors such as solar irradiance, temperature, and load conditions, accurate modelling and simulation techniques are essential to predict behaviour under varying environmental scenarios. Among various simulation environments, MATLAB Simulink has emerged as a powerful platform that enables researchers and engineers to model, analyse, and optimize PV systems effectively. The analysis of solar cells involves understanding their electrical characteristics, energy conversion efficiency, and response under dynamic operating conditions [1]. A solar cell can be represented mathematically by equivalent circuit models such as the single-diode or double-diode models, which account for parameters like series resistance, shunt resistance, and diode idealist factor. These models serve as the foundation for investigating current-voltage (I-V) and power-voltage (P-V) characteristics, which are essential for predicting output power under different irradiance and temperature levels. MATLAB Simulink provides built-in libraries and customizable blocks for replicating these models, making it easier to evaluate the influence of various parameters and external conditions. This capability supports not only theoretical analysis but also experimental validation of PV performance.

Another critical aspect of solar cell analysis is the optimization of energy extraction. Since solar panels exhibit nonlinear I-V characteristics, they operate most efficiently at a unique point known as the Maximum Power Point (MPP). However, this point varies with changing irradiance and temperature, which necessitates the use of Maximum Power Point Tracking (MPPT) techniques. MATLAB Simulink enables the design and implementation of different MPPT algorithms such as Perturb and Observe (P&O), Incremental Conductance (IncCond), and advanced methods based on fuzzy logic or neural networks. Through simulating these algorithms under real-time conditions, researchers can compare their efficiency, stability, and speed of convergence to determine the most suitable method for specific applications. This makes Simulink a versatile environment for studying both conventional and intelligent MPPT techniques for energy optimization [2]. Beyond MPPT, energy optimization also involves the integration of solar cells with power electronic converters, storage systems, and grid interfaces. Simulink allows the modelling of DC-DC converters, inverters, and control strategies that ensure stable energy transfer from PV arrays to loads or the utility grid. It also facilitates long-term energy yield analysis by simulating irradiance and temperature profiles over extended periods. Such studies help optimize system design parameters, improve component selection, and ensure maximum utilization of available solar energy. Furthermore, optimization studies in MATLAB Simulink provide valuable insights into reducing losses, enhancing efficiency, and improving the reliability of PV systems, which are crucial for scaling solar technology in both standalone and grid-connected applications [3].

1.1 Growing Importance of Solar Photovoltaic (PV) Technology

The global energy sector is undergoing a transformative shift, driven by the urgent need to reduce dependence on fossil fuels and mitigate the adverse impacts of climate change. Rising population, rapid industrialization, and increasing urbanization have collectively resulted in a steep escalation in global energy demand. Conventional energy resources such as coal, oil, and natural gas, while dominant for decades, have been associated with greenhouse gas emissions, environmental degradation, and resource depletion. In this context, renewable energy sources have gained prominence as cleaner, sustainable, and more resilient alternatives. Among these, solar photovoltaic (PV) technology has emerged as one of the most promising solutions due to its direct conversion of sunlight into electricity, its universal availability, and its potential to contribute significantly to global energy security. Solar PV technology plays a crucial role in meeting global renewable energy targets and in addressing energy access challenges, particularly in developing nations. Unlike fossil fuels, which are finite and unevenly distributed across the globe, solar energy is abundant and inexhaustible, with the Earth receiving far more solar radiation in a single hour than the total annual global energy consumption. The ability of solar cells to harness this immense energy resource and convert it into usable electricity makes PV systems a cornerstone of sustainable energy development. Furthermore, solar PV is highly versatile, enabling deployment at different scales from small rooftop systems for households to large-scale solar farms that can power entire cities. This scalability has made solar PV one of the fastest-growing renewable technologies worldwide [4].

The advantages of solar cells extend beyond energy production to include significant environmental benefits. PV systems operate without emitting greenhouse gases during their functional lifetime, thereby helping to reduce the carbon footprint of electricity generation. This makes solar energy a key contributor to climate change mitigation strategies and to international efforts such as the Paris Agreement, which emphasizes reducing global warming through renewable energy integration. Moreover, solar PV installations do not produce noise pollution, require minimal water for operation, and can be deployed in diverse geographic regions, including arid zones and rural areas where conventional grid infrastructure is limited. Another major factor contributing to the rising importance of solar PV is the steady decline in system costs. Advances in manufacturing processes, improvements in conversion efficiency, and supportive government policies have collectively driven down the cost of PV modules and associated components. As a result, the levelized cost of electricity (LCOE) from solar PV has become increasingly competitive with, and in some cases even cheaper than, conventional fossil fuel-based generation. This economic competitiveness, combined with environmental and social benefits, underscores the vital role of solar photovoltaic technology in shaping a cleaner and more sustainable energy future [5].

1.2 Basic Principle and Physics of solar cells

The Photovoltaic Effect: The working of a solar cell is rooted in the photovoltaic effect, discovered by Edmond Becquerel in 1839. When sunlight, composed of packets of energy known as photons, strikes the surface of a solar cell, the energy is absorbed by electrons in the semiconductor material. If the photon energy is sufficient, it excites an electron from its bound state in the valence band into the conduction band, leaving behind a hole (an empty electron state). This electron–hole pair is the fundamental charge carrier unit responsible for current generation. However, if these charges simply recombine, no useful energy is produced. To prevent this, a built-in electric field created by the p–n junction acts like a diode, forcing the electron toward the n-side and the hole toward the p-side. When an external circuit connects both sides, electrons flow through the circuit, performing useful work (e.g., lighting a bulb or charging a battery). This continuous flow of charge carriers is what we recognize as electric current [6].

Structure of a Solar Cell: A typical solar cell is a layered structure designed to maximize the conversion of sunlight into electricity. The top surface has a transparent front contact made of materials such as indium tin oxide (ITO) or other conductive coatings that allow light to enter while conducting electrons outward. Just beneath it lies an anti-reflective coating, which ensures that most of the sunlight enters the cell instead of being reflected away, as reflection can reduce efficiency significantly. The active region of the solar cell is made of two differently doped semiconductor layers: an n-type silicon layer, doped with elements like phosphorus to create an excess of electrons, and a p-type silicon layer, doped with boron to create an abundance of holes. The junction between them forms the p–n junction, where the electric field develops. Finally, at the bottom, a metallic back contact provides structural support and allows electrons to flow back into the system, completing the circuit. This carefully engineered structure ensures maximum light absorption, charge separation, and current flow [7].

Energy Band Physics and the Bandgap: At the heart of solar cell physics lies the concept of the energy bandgap (Eg). The bandgap represents the minimum energy required for an electron to jump from the valence band to the conduction band, enabling conduction. For crystalline silicon, the most widely used material, this bandgap is about 1.1 electron volts (eV). Photons with energy less than this value pass through the material without interaction, contributing nothing to electricity generation. Photons with energy just above the bandgap are the most efficient because they transfer their energy directly into creating useful electron–hole pairs. However, photons with energy far above the bandgap waste their excess energy as heat, a process known as thermalization loss. This explains why solar cells cannot convert 100% of sunlight into electricity. The optimal bandgap for maximum solar spectrum absorption is around 1.3–1.5 eV, which is why researchers explore materials like gallium arsenide (GaAs) and perovskites in addition to silicon [8].

Current–Voltage (I–V) Characteristics: The performance of a solar cell is described by it's I–V characteristics, which display how current and voltage vary under illumination. When the cell's terminals are shorted, it delivers its maximum current known as the short-circuit current (Isc), determined largely by the intensity of incoming light. Conversely, when the circuit is open, the maximum voltage appears across the terminals, called the open-circuit voltage (Voc). Between these two extremes lies a point where the cell delivers the maximum power ($P_{max} = V \times I$). The "squareness" of the I–V curve is expressed by the Fill Factor (FF), with higher FF values indicating lower internal losses and better quality. The efficiency (η) of a solar cell is calculated as the ratio of maximum electrical output power to incident solar power. In practice, silicon-based solar cells typically achieve efficiencies between 15–25%, while advanced multi-junction devices can exceed 40% under concentrated sunlight [9].

Loss Mechanisms in Solar Cells: Not all incident sunlight is successfully converted into electricity, as several physical processes cause energy losses. First, a portion of sunlight is lost due to reflection at the surface, even with anti-reflective coatings. Second, recombination losses occur when electron–hole pairs recombine before being separated by the electric field, a major limiting factor. Third, resistive losses arise from poor conductivity of materials or electrical contacts, reducing the effective current. Additionally, thermalization losses waste high-energy photon input as heat rather than electricity. Collectively, these losses explain why even the best solar cells cannot exceed the Shockley–Queisser theoretical limit of around 33% for single-junction devices. Research efforts therefore focus on minimizing each of these losses to push practical efficiencies closer to theoretical limits [10].

Maximum Power Point Tracking (MPPT): The amount of power a solar cell can deliver depends on sunlight intensity, shading, and temperature, all of which change throughout the day. A fixed operating point would not always yield maximum efficiency. This challenge is addressed by Maximum Power Point Tracking (MPPT), a control method that continuously adjusts the electrical load to ensure operation at the point of maximum power output. Various MPPT algorithms exist, including Perturb and Observe (P&O), which adjusts the operating voltage and checks whether power increases, and Incremental Conductance (INC), which calculates the slope of the I–V curve for precision. More advanced techniques involve fuzzy logic and artificial intelligence for real-time optimization. Without MPPT, significant amounts of potential energy would be wasted in real-world solar systems, especially in grid-connected or battery-charging applications [11].

1.3 Challenges in Solar Energy Systems

Efficiency Variations with Irradiance: The performance of solar photovoltaic (PV) systems is highly sensitive to changes in solar irradiance. Fluctuations due to cloud movement, shading, or seasonal changes directly affect the current output of solar cells, thereby reducing the overall energy yield. Maintaining consistent efficiency under such variations is one of the major challenges in solar energy utilization.

Impact of Temperature on Performance: Solar cells exhibit temperature-dependent behaviour, where an increase in temperature typically decreases the open-circuit voltage and overall efficiency. In hot climates, the efficiency loss can be significant, leading to reduced energy output even under high irradiance conditions. This makes thermal management an important aspect of PV system design and operation.

Load Matching and Reliability Issues: Since the current-voltage (I-V) characteristics of solar cells are nonlinear, the operating point must align with the load requirements to achieve optimal energy transfer. Variations in load conditions can cause mismatches, resulting in energy losses. Furthermore, long-term reliability issues such as degradation of modules and component failures add to the complexity of system performance.

Need for Accurate Modelling and Simulation: To address these challenges, accurate modelling and simulation techniques are essential. Tools like MATLAB Simulink help in predicting system behaviour under dynamic conditions, enabling optimization of design parameters, implementation of control strategies, and evaluation of efficiency-enhancing techniques such as Maximum Power Point Tracking (MPPT) [12].

1.4 Role of MATLAB Simulink in Solar Cell Analysis

MATLAB Simulink has emerged as one of the most effective platforms for the modelling, analysis, and optimization of solar photovoltaic (PV) systems. Its graphical environment, combined with mathematical computing capabilities, allows researchers and engineers to design and simulate solar cell models under diverse environmental and operating conditions. The platform provides a wide range of built-in libraries, including specialized blocks for renewable energy systems, power electronics, and control strategies. These libraries enable the development of comprehensive PV system models without the need for building every component from scratch, thereby saving time and ensuring accuracy in simulation. Additionally, Simulink supports customizable function blocks, giving users the flexibility to implement their own mathematical models or modify existing ones to suit specific requirements.

A key advantage of MATLAB Simulink lies in its ability to replicate the electrical behaviour of solar cells using equivalent circuit models. Among these, the single-diode model and the double-diode model are the most widely adopted. The single-diode model considers parameters such as the photo-generated current, diode saturation current, series resistance, shunt resistance, and diode duality factor. This model effectively represents the current-voltage (I-V) and power-voltage (P-V) characteristics of solar cells under varying irradiance and temperature conditions. For more detailed analysis, the double-diode model incorporates two diodes to account for recombination losses, offering greater accuracy in low-irradiance scenarios. By employing these models within the Simulink environment, researchers can simulate the nonlinear behaviour of PV cells and investigate their dynamic response to external factors such as shading, temperature rise, and partial load variations. Furthermore, Simulink facilitates the integration of solar cell models with power electronic converters and Maximum Power Point Tracking (MPPT) algorithms, enabling a holistic study of PV systems. This makes MATLAB Simulink an indispensable tool for advancing solar cell analysis and ensuring efficient energy optimization [13].

1.5 Energy Optimization through Maximum Power Point Tracking (MPPT)

One of the most critical aspects of photovoltaic (PV) system performance is the ability to extract maximum power under varying environmental conditions. Solar cells exhibit nonlinear current-voltage (I-V) and power-voltage (P-V) characteristics, meaning that there exists a unique operating point known as the Maximum Power Point (MPP). The location of this point is not fixed, as it shifts with changes in solar irradiance, temperature, and shading conditions. Without specialized control strategies, a PV system may operate away from the MPP, leading to significant energy losses and reduced overall efficiency. Thus, Maximum Power Point Tracking (MPPT) plays a central role in ensuring optimal utilization of solar energy. In practice, MPPT algorithms are implemented through power electronic converters that adjust the operating voltage and current of the PV system to track the MPP continuously. MATLAB Simulink provides a versatile platform for designing, testing, and comparing various MPPT algorithms in a controlled simulation environment. Among conventional methods, the Perturb and Observe (P&O) algorithm is widely used due to its simplicity and ease of implementation, though it suffers from oscillations around the MPP. The Incremental Conductance (IncCond) method offers improved accuracy and faster convergence, especially during rapid irradiance changes.

Beyond traditional approaches, MATLAB Simulink also supports the integration of intelligent control strategies such as fuzzy logic-based MPPT and neural network-based MPPT. These advanced methods are capable of handling nonlinearities more effectively and can adapt to rapidly changing conditions with higher precision. By simulating these techniques, researchers can evaluate trade-offs in terms of tracking speed, stability, and computational complexity. Overall, MATLAB Simulink enables comprehensive analysis and comparison of MPPT methods, helping to identify the most suitable algorithm for specific PV applications. This optimization not only maximizes energy output but also enhances the reliability and long-term performance of solar photovoltaic systems [14].

2. Reviews of Literature

Patra, Nema, Khan, and Khan (2023) explained that solar energy was discharged by the sun in the form of light radiation, which was then utilized by humans through various methods such as photovoltaic cells. They indicated that it was an unlimited source of energy, belonging to no one and available at no cost. The quantity of solar energy acknowledged by the world was reported to range between 3000–50,000 EJ, which was far greater than the total global energy utilization of 600 EJ. They mentioned that Maximum Power Point Tracking (MPPT) could be integrated into charge control to extract the highest obtainable output from photovoltaic cells under specific conditions. The input for a photovoltaic module capable of generating maximum possible output power was referred to as the Maximum Power Point (MPP) or highest voltage, which varied with the sun's energy parameters and the required temperature of the PV module. They further noted that different tracking techniques, including the P-O method, were applied, and several components used to compute input parameters carried inherent uncertainties. These uncertainties, however, were eliminated through devices equipped with sensors employing Industry 4.0 techniques, which returned accurate values for error-free solar energy estimation. The researchers concluded that this approach delivered excellent outcomes and could be employed in developing charge controllers using a microcontroller-based circuit for a DC-DC buck converter with integrated MPPT.

Çinici, Karaca, and Acır (2023) explained that with technological advancement and the increase in global population, the demand for energy had been growing rapidly, and most of this demand had been met through fossil fuels. They stated that the limited reserves of fossil fuels, along with their harmful effects on the environment and contribution to global warming, had increased the shift toward alternative energy sources such as solar, wind, wave, and biomass, among which solar energy systems had been the most preferred. They mentioned that before implementing any photovoltaic (PV) project, technological and economic feasibility was required to optimize electricity generation, reliability, and costs. They noted that several simulation tools had already been developed to predict and optimize PV systems, and their study had examined the differences between photovoltaic solar energy systems designed using PVsyst and MATLAB/Simulink software, focusing on how these differences affected energy production and system performance. They reported that regression analysis was conducted by comparing the output data, which revealed the advantageous and disadvantageous directions. A 75 kW PV system had been designed in Ankara using both PVsyst and MATLAB/Simulink software, and the simulation outputs from the two platforms had been compared. They explained that three different PV systems were designed: Design-1 (PVsyst System), Design-2 (MATLAB/Simulink with MPPT Algorithm), and Design-3 (MATLAB/Simulink without MPPT Algorithm). The monthly differences between the two software and three designs were found to vary significantly, ranging from 0.36% to 10.72% between Design-1 and Design-2, from 14.21% to 43.71% between Design-1 and Design-3, and from 17.65% to 49.32% between Design-2 and Design-3. According to their findings, MATLAB/Simulink was more sensitive to temperature variations than PVsyst, and factors such as variable MPPT algorithms and whether the data were entered manually or automatically were also found to influence the differences.

Puente-López and Pal (2023) explained that they had carried out numerical modelling of copper antimony sulfide ($CuSbS_2$) solar cells to examine the influence of several interrelated physical parameters of the absorber layer and absorber/buffer interface, including bulk versus interface defect density, energy band gap versus electron affinity of $CuSbS_2$, absorber thickness versus acceptor density, along with device shunt versus series resistance on device efficiency. They indicated that a benchmark simulation of the experimental $CuSbS_2$ solar cell had initially been performed in the SCAPS-1D (Solar Cell Capacitance Simulator in one dimension) environment by considering a suitable defect model, which yielded an efficiency of 3.19%, comparable to the experimental value. They further stated that after systematically optimizing various material properties and interface defect density, the power conversion efficiency had increased up to 10.71%, accompanied by a significant improvement in open-circuit voltage, photocurrent, and fill factor. Additionally, they mentioned that a detailed analysis of heterojunction features such as built-in potential, depletion width, diffusion length, and carrier recombination had been conducted to understand the impact of these physical parameters on solar cell performance. The findings were reported to provide important guidelines for identifying the limitations of $CuSbS_2$ solar cells, thereby assisting researchers in designing and fabricating more efficient CAS solar cells.

Craciunescu and Fara (2023) proposed an enhanced method for investigating and optimizing photovoltaic (PV) modules by applying the Maximum Power Point Tracking (MPPT) technique to improve their output power. They explained that the performance of PV panels was strongly influenced by operating conditions such as solar irradiance, temperature, configuration, and shading caused by passing clouds or nearby buildings, which led to energy conversion losses and non-linearity in the I-V characteristics. Their study was considered highly relevant as it aimed to improve the performance and efficiency of shaded photovoltaic panels through a complex approach combining numerical modelling and experimental validation. To better understand issues caused by partial shading and to enhance MPP tracking, the authors emphasized the need to study individual panels. For accuracy, they carried out a comparative analysis of PV modules considering the influence of temperature and irradiance, evaluated their behavior under partial shading, compared the optimized output power of four algorithms (FLC, P&O, IncCond, and RC), and identified FLC as the most effective. They also discussed improvements in the FLC algorithm by introducing five operation points to increase module efficiency under fluctuating weather conditions and uncertainties. Furthermore, the FLC provided predictive rules for current–voltage behaviour and maximum power points, and was implemented in MATLAB/Simulink. The authors described the development and implementation of a numerical simulation model to analyse PV module behaviour under different conditions, stabilize performance, and enhance efficiency. Their findings on shading effects and patterns were experimentally validated and demonstrated, showing applicability for both stand-alone and grid-connected PV systems.

Abed, F. T., Altai, H. D. S., Hazim, H. T., and ALRikabi, H. T. S. (2022) stated that the growing demand for electrical energy and the availability of renewable sources worldwide, particularly in Iraq, such as solar and wind energy, had attracted significant attention from researchers. They mentioned that major efforts had been directed toward exploring environmentally friendly methods of generating electricity and reducing reliance on fossil fuels. Their study suggested the use of a simulation program to determine the optimal location for installing a solar cell and the appropriate duration of exposure to sunlight for powering a household through solar energy. They further indicated that the program had been used to calculate the losses associated with converting light energy into electrical energy, with the aim of identifying solutions to enhance the efficiency of solar cells.

Banik et al. (2022) stated that, in order to meet the world's future energy demand, alternative renewable green energy supplies needed to be widely promoted, and among all DERs, Solar PV had been identified as the most prevalent option for several important reasons. They explained that their study analysed various aspects of the Single-Phase Solar Photovoltaic Rooftop System using MATLAB. It was mentioned that a new grid synchronization methodology had been devised to analyse the characteristics of the output current, while the INC control technique had been adopted for maximum power tracking. The authors further indicated that the output of the solar DC power system had been synchronized with the grid through hysteresis current loop control, and extensive testing had verified the practicality of the proposed power grid model along with its promising outcomes.

Tayeb, A. M., Solyman, A. A., Hassan, M., and el-Ella, T. M. A. (2022) discussed that a generalized photovoltaic simulation model was realized using the MATLAB/SIMULINK interface. They explained that the model had been developed on the basis of fundamental photovoltaic (PV) cell circuit equations, considering the effects of solar radiation and temperature variations. It was indicated that this modelling approach enabled the understanding of the I–V and P–V curves of PV cells and could be employed to forecast the behaviour of solar PV cells under different environmental conditions such as irradiation and temperature. They further noted that these effects were simultaneously considered in real time, and due to the nonlinear features of PV cells, modelling was necessary to design and simulate their maximum power point. The study highlighted that the model was applicable to dye-sensitized solar cells with three semiconductors, namely TiO_2, ZnO, and SnO_2, using N3 dye. It was reported that, according to variations in atmospheric parameters like solar radiation and temperature, as well as operating parameters such as semiconductor type, dye concentration, and particle size, the characteristic dimensions of photovoltaic systems, including power supply voltage (PV) and current–voltage (I–V) characteristics, were observed through MATLAB/SIMULINK. The simulation results revealed that these parameters and the corresponding photovoltaic models influenced the maximum operating performance of PV modules. Among them, the battery fabricated with TiO_2 semiconductor and N3 dye showed the highest consistency with the model battery, followed by the ZnO-based battery, and finally the SnO_2-based battery with the same dye.

Badi, N., Khasim, S., Al-Ghamdi, S. A., Alatawi, A. S., and Ignatiev, A. (2021) explained that they had developed a unique procedure to model and simulate a 36-cell-50 W solar panel using analytical methods. They indicated that the generalized expression of the solar cell equivalent circuit had been validated and implemented in the Simulink/MATLAB R2020a environment without making influential assumptions. The authors stated that their approach had been based on extracting all the required parameters by utilizing data sheet values of commercial PV panels and by estimating the slopes at both short-circuit and open-circuit conditions of the current–voltage characteristics, as usually provided by solar panel manufacturers under standard test conditions (STC). They mentioned that both solar irradiance and temperature had been considered in the modelling, and that a system of coupled nonlinear simultaneous equations for diode saturation current, diode duality factor, and series and shunt resistances had been solved. It was further highlighted that, to ensure accuracy, the temperature-dependent parameters of the PV module had been extracted for the first time for simulation and analysis. The authors noted that at STC irradiance of 1000 W/m², the modelled I-V curve had matched the experimental one provided by the manufacturer. They observed that the maximum power output of the PV module had increased from 8.75 W to 50 W when irradiance varied from 200 W/m² to 1000 W/m² at STC temperature. They also reported that at temperatures above STC, the power output of the PV module had decreased by about 14.5% when the operating temperature reached 65 °C, whereas at temperatures below STC, the output had increased by approximately 7.4% above the rated maximum power. Finally, they concluded that the calculated power temperature coefficient had been around −0.39%/°C, which had been very close to the value provided by the solar panel manufacturer.

Murali, M., Hussaian Basha, C. H., Kiran, S. R., Akram, P., and Naresh, T. (2021, October) reported that solar photovoltaic (PV) technology played a major role in hybrid and distribution power generation systems due to its low sustainability requirements and abundant availability in nature. They mentioned that in their work, different types of solar PV cell topologies had been designed and analysed using the MATLAB/Simulink environment. The study included single-diode, two-diode, and three-diode PV cell models, and a comparative analysis had been carried out in terms of peak power extraction, efficiency, and fill factor. Furthermore, they indicated that PV cell characteristics had been examined under varying atmospheric conditions.

Nadimuthu (2021) investigated the performance of a solar photovoltaic integrated thermoelectric cooler (TEC) using MATLAB Simulink. The study reported that efficiency enhancement was achieved through an effective heat removal mechanism from the hot side heat sink, since the hot side temperature was considered a crucial parameter. The intrinsic material properties such as the Seebeck coefficient (α), thermal conductance (K), and electrical resistance (R) of the thermoelectric module were estimated analytically and documented. Based on these estimated properties, a MATLAB Simulink Peltier module was developed. The influence of system voltage (V) and current (A) on thermal parameters such as cooling capacity (QC) and coefficient of performance (COP) was analysed. The simulation outcomes were validated through a series of experimental analyses, in which a 100 Wp polycrystalline solar photovoltaic module was used to power a 12V/5A, 60-Watt thermoelectric cooler. The findings further indicated that ambient and hot side temperatures significantly affected the performance of the thermoelectric cooler. To ensure efficient heat removal, a fin-type conductive heat transfer mechanism was employed along with a convective forced air-cooling system, and the effectiveness of heat removal was confirmed using infrared thermographic investigation.

Alayi, R., Harasii, H., and Pourderogar, H. (2021) conducted a study in which they modelled and analysed a solar tracking system to determine the optimal angle in photovoltaic systems for maximizing power generation using a genetic algorithm (GA). They explained that the proposed control system, based on GA, optimized the output energy of the PV system by adjusting the spatial angles of the solar panel in both vertical and horizontal directions. It was mentioned that, without requiring additional hardware, the optimal panel position angles were calculated using MATLAB software to capture maximum sunlight and enhance energy output. The authors pointed out that the main advantage of the method was its discrete operation, which reduced losses and ensured that even under cloudy conditions, solar radiation could still be received, thereby improving output energy. They concluded that the optimization resulted in a 15.85% increase in the output power of the photovoltaic system compared to a fixed array mode.

Pardhu and Kota (2021) proposed a new swarm-based stochastic radial movement optimization (RMO) algorithm for extracting unknown solar photovoltaic (PV) cell parameters. They indicated that the explicit modelling of a solar PV cell had been highly influential in assessing the performance of maximum power point tracking methods. The performance of the Single-Diode Model (SDM) and Double-Diode Model (DDM) of a Kyocera KC200GT 200 W panel had been verified and validated under different test conditions in the MATLAB Simulink environment. The study aimed to validate the accuracy of solar PV cell modelling and to identify the best optimization algorithm among RMO, particle swarm optimization (PSO), and differential evolution technique (DET). The RMO-based I-V and P-V curves were reported to have been compared with those obtained using DET and PSO. Furthermore, statistical and error analyses had been conducted to calculate the relative error (RE), individual absolute error (IAE), and root mean square error (RMSE) of the proposed method for deeper evaluation. It was found that with the RMO method, the IAE and RE for the DDM of the solar PV cell had been 0.0224 and 0.0509, respectively, while the fitness function value of the RMO for the DDM had been 3.01E−4. The findings suggested that the RMO method had outperformed PSO and DET in curve fitting for SDM, DDM, and datasheet values. Curve fitting with the RMO had been strongly aligned with the datasheet curve, resembling the RMO curve, and was considered a suitable optimization approach for extracting the parameters of the DDM of the solar PV cell.

Abd Alhussain and Yasin (2020) explained a procedure for modelling a Photovoltaic (PV) cell and applying maximum power point tracking (MPPT) step by step using MATLAB/Simulink. They mentioned that the one-diode model had been used to examine the I–V and P–V characteristics of a 60W PV module. Since the PV characteristics were non-linear and time-varying, the generated power continuously changed with atmospheric conditions such as temperature and irradiation, which made MPPT technology essential for tracking the maximum power point (MPP) on the P–V curve to achieve maximum output power from the PV array. The study highlighted two commonly used MPPT algorithms, namely perturb and observe (P&O) and incremental conductance (INC), and further indicated that a DC–DC boost converter had been implemented to regulate the PV array's voltage output and enable the application of the MPPT algorithm.

Diab et al. (2020) stated that developing an accurate mathematical model with the help of experimentally measured data of solar cells and photovoltaic (PV) modules, as a tool for simulation and performance evaluation of PV systems, had attracted the attention of many researchers. They reported that the Coyote Optimization Algorithm (COA) was applied for extracting the unknown parameters involved in various models of solar cells and PV modules, including the single diode, double diode, and three diode models. The authors indicated that COA was chosen due to its good tracking characteristics and its ability to balance exploration and exploitation phases, with the added advantage of having only two control parameters, making it simple to apply. They further mentioned that the Root Mean Square Error (RMSE) value between the data optimized for each model and the measured data of the solar cell and PV modules was adopted as the objective function. In addition, they explained that parameter estimation for different PV module types—mono-crystalline, thin-film, and multi-crystalline—was studied under varying operating scenarios such as changes in solar radiation intensity and cell temperature. Finally, they emphasized that a comprehensive statistical study had been conducted to validate the accuracy and stability of COA as a strong competitor to other optimization algorithms in the optimal design of PV module parameters.

Meskani and Haddi (2019) stated that the world had been suffering from air pollution caused by chemicals, particulate matter, and biological materials in the air, all of which had negative impacts on human health, the environment, and the economy. They mentioned that vehicle emissions were considered a major source of air pollution and that transportation had been one of the main contributors globally. Vehicle pollution, according to them, took two forms: the emission of greenhouse gases, which had a global impact such as global warming, and particulate emissions, which had a local impact through the deterioration of air quality. To address this problem, they suggested encouraging the development of hybrid vehicles. Their paper highlighted a new hybrid generator topology equipped with a photovoltaic energy conversion system and a battery with its DC/DC converter, which had been adopted to replace fuel cells in order to reduce high energy consumption and cost. They also pointed out another contribution of their work, which consisted of the use of fuzzy logic as an autonomous control device, primarily applied to adapt control parameters for improving the overall robustness of the system while maintaining its stability.

Dhaundiyal and Atsu (2019) explained that their study focused on the modelling and simulation of the characteristics and electrical performance of photovoltaic (PV) solar modules. They mentioned that genetic coding had been applied to obtain optimized parameter values within the constraint limits using MATLAB software. A single diode model, which considered series and shunt resistances, had been proposed to analyse the effects of solar irradiance and temperature on the power-voltage (P-V) and current-voltage (I-V) characteristics and to predict the output of PV modules. They further indicated that the model had been validated under standard test conditions (STC) as well as for different temperature and insolation values, with an evaluation carried out using experimental data collected from outdoor operating PV modules. The results were reported to be consistent with the manufacturer’s data, thereby ensuring that the proposed model did not exceed the prescribed tolerance range. They observed that the current and voltage variations lay between 8.21–8.5 A and 22–23 V, respectively, while the predicted values ranged from 8.28–8.68 A and 23.79–24.44 V, respectively. They also noted that the measured experimental power of the PV module, estimated between 148–152 W, had been well-predicted by the mathematical model, with simulated results lying between 149–157 W. Conclusively, they asserted that the proposed scheme had been highly effective in determining the influence of input factors on PV modules, an aspect difficult to ascertain through experimental methods alone.

III. Energy Estimation of Solar Cell

Solar Cell Current–Voltage Equation (Diode Law with Illumination)

$$I = I_{ph} - I_0 \left(e^{\frac{qV}{nkT}} - 1 \right)$$

This is the fundamental equation of a solar cell, showing the net current as the difference between photocurrent (Iph) and the diode’s recombination current.

Open-Circuit Voltage

$$V_{OC} = \frac{nkT}{q} \ln \left(\frac{I_{ph}}{I_0} + 1 \right)$$

Defines the maximum voltage when no current flows (open circuit).

Fill Factor (FF)

A measure of “squareness” of the I–V curve; higher FF means better performance.

$$FF = \frac{V_{mp} \cdot I_{mp}}{V_{OC} \cdot I_{SC}}$$

Efficiency (η)

$$\eta = \frac{V_{OC} \cdot I_{SC} \cdot FF}{P_{in}}$$

The most important performance metric — ratio of maximum output power to incident solar power [15].

I–V curve of a solar cell

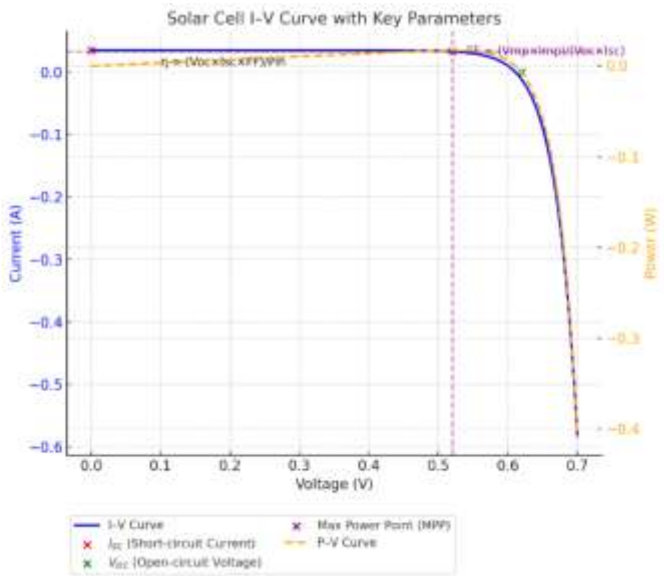

Fig 1: I–V curve of a solar cell (General Parameter based Curve)

The I–V curve of a solar cell is one of the most important graphical tools for understanding its performance. At the leftmost point, where the voltage is zero, the cell delivers its maximum current called the short-circuit current (I_{SC}). This value depends on the intensity of sunlight and the ability of the material to absorb photons and generate electron–hole pairs. On the other hand, at the rightmost point where the current drops to zero, we observe the open-circuit voltage (V_{OC}), which represents the maximum potential difference the cell can produce when no current is drawn. Between these two extremes lies the Maximum Power Point (MPP), where the product of voltage and current is highest. The ratio of the area represented by the rectangle at MPP (Vmp×ImpV) to the rectangle formed by V_{OC}×IS_{CV} defines the Fill Factor (FF), a critical indicator of how "square" the I–V curve is and thus how efficient the device is. Finally, the efficiency (η) of the solar cell is determined by how much of the incident solar energy is converted into electrical energy, expressed as $\eta=V_{OC}\cdot I_{SC}\cdot FF/ P_{in}$. Together, these four parameters I_{SC} , V_{OC}, FF, and η summarize the fundamental physics and performance of solar cells [16].

IV. Conclusion

The analysis and optimization of solar cells using MATLAB Simulink provide valuable insights into improving the performance and efficiency of PV systems under diverse operating conditions. Through accurate modelling of electrical characteristics and the application of advanced MPPT algorithms, energy extraction can be maximized while minimizing losses. Additionally, the simulation of converters, storage, and grid integration enhances system stability and long-term reliability. Overall, MATLAB Simulink serves as a powerful tool for advancing research and practical applications in solar energy, making it a critical component in promoting sustainable and scalable renewable energy solutions.

References

1. Patra, B., Nema, P., Khan, M. Z., & Khan, O. (2023). Optimization of solar energy using MPPT techniques and industry 4.0 modelling. *Sustainable Operations and Computers*, *4*, 22-28.
2. Çinici, O. K., Karaca, B., & Acır, A. (2023). Comparison study in terms of the results of photovoltaic solar energy systems designed with PVsyst and MATLAB Simulink software. *Politeknik Dergisi*, *26*(4), 1635-1649.
3. Puente-López, E., & Pal, M. (2023). Numerical simulation and optimization of physical properties for high efficiency CuSbS2 thin film solar cells. *Optik*, *272*, 170233.
4. Craciunescu, D., & Fara, L. (2023). Investigation of the partial shading effect of photovoltaic panels and optimization of their performance based on high-efficiency FLC algorithm. *Energies*, *16*(3), 1169.
5. Abed, F. T., Altai, H. D. S., Hazim, H. T., & ALRikabi, H. T. S. (2022). Enhancement of the efficiency of solar energy cells by selecting suitable places based on the simulation of PV System. *Periodicals of Engineering and Natural Sciences (PEN)*, *10*(2), 80-88.
6. Banik, A., Shrivastava, A., Potdar, R. M., Jain, S. K., Nagpure, S. G., & Soni, M. (2022). Design, modelling, and analysis of novel solar PV system using MATLAB. *Materials today: proceedings*, *51*, 756-763.
7. Tayeb, A. M., Solyman, A. A., Hassan, M., & el-Ella, T. M. A. (2022). Modeling and simulation of dye-sensitized solar cell: Model verification for different semiconductors and dyes. *Alexandria Engineering Journal*, *61*(12), 9249-9260.
8. Badi, N., Khasim, S., Al-Ghamdi, S. A., Alatawi, A. S., & Ignatiev, A. (2021). Accurate modeling and simulation of solar photovoltaic panels with simulink-MATLAB. *Journal of Computational Electronics*, *20*(2), 974-983.
9. Murali, M., Hussaian Basha, C. H., Kiran, S. R., Akram, P., & Naresh, T. (2021, October). Performance analysis of different types of solar photovoltaic cell techniques using MATLAB/simulink. In *Proceedings of Fourth International Conference on Inventive Material Science Applications: ICIMA 2021* (pp. 203-215). Singapore: Springer Singapore.
10. Nadimuthu, L. P. R. (2021). Simulation and experimental study on performance analysis of solar photovoltaic integrated thermoelectric cooler using MATLAB Simulink. *Thermal Science*.
11. Alayi, R., Harasii, H., & Pourderogar, H. (2021). Modeling and optimization of photovoltaic cells with GA algorithm. *Journal of Robotics and Control (JRC)*, *2*(1), 35-41.
12. Pardhu, B. G., & Kota, V. R. (2021). Radial movement optimization-based parameter extraction of double diode model of solar photovoltaic cell. *Solar Energy*, *213*, 312-327.
13. Abd Alhussain, H. M., & Yasin, N. (2020). Modeling and simulation of solar PV module for comparison of two MPPT algorithms (P&O & INC) in MATLAB/Simulink. *Indonesian Journal of Electrical Engineering and Computer Science*, *18*(2), 666-677.
14. Diab, A. A. Z., Sultan, H. M., Do, T. D., Kamel, O. M., & Mossa, M. A. (2020). Coyote optimization algorithm for parameters estimation of various models of solar cells and PV modules. *Ieee Access*, *8*, 111102-111140.
15. Meskani, A., & Haddi, A. (2019). Modeling and simulation of an intelligent hybrid energy source based on solar energy and battery. *Energy Procedia*, *162*, 97-106.
16. Dhaundiyal, A., & Atsu, D. (2019). Modeling of photovoltaic module using the MATLAB. *JNRD-Journal of Natural Resources and Development*, *9*, 59-69.