



DESIGN AND IMPLEMENTATION OF A HIGH-EFFICIENCY SYNCHRONOUS BUCK CONVERTER MPPT CHARGE CONTROLLER USING ARDUINO

¹Nilesh Kumbhar, ²Vaibhav Lonkar, ³Rohan Nalage, ⁴Rushikesh Avchar, ⁵ Dr.H.S.Avchat

¹UG Scholar, Department of Electrical Engineering, HSBPVT's GOI Kashti, Ahilyanagar

²UG Scholar, Department of Electrical Engineering, HSBPVT's GOI Kashti, Ahilyanagar

³UG Scholar, Department of Electrical Engineering, HSBPVT's GOI Kashti, Ahilyanagar

⁴UG Scholar, Department of Electrical Engineering, HSBPVT's GOI Kashti, Ahilyanagar

⁵Assistant Prof., Department of Electrical Engineering, HSBPVT's GOI Kashti, Ahilyanagar

nileshkumbhar791@gmail.com

ABSTRACT- Better techniques for solar energy capture have been developed as a result of the growing need for renewable energy. Because they are environmentally friendly, sustainable, and clean, solar panels are a popular kind of solar energy system. However, elements like temperature, shadows, and the amount of sunshine may have a big influence on how well they work. Specialized methods known as Maximum Power Point Tracking (MPPT) are needed to optimize the energy production from solar panels. In this research, a novel solar charge controller utilizing an Arduino Uno microcontroller and some sophisticated control techniques is presented. The technology combines a classic approach called Perturb and Observe (P&O) with smart control features to make solar energy consumption more efficient. Using sensors called INA219, the system continually measures the voltage and current and utilizes the information to calculate the current power output. In order to maintain the system functioning near the maximum power point, the controller modifies the DC-DC buck converter's parameters based on these data. Along with a Battery Management System (BMS) to safeguard the battery, the system also offers a method for safely storing energy in a lithium-ion battery. An XL4015 buck converter, an Arduino Uno, an INA219 sensor, an RC filter, an LCD display, and a lithium-ion battery pack are among the hardware elements utilized. The experimental findings demonstrate that this device can efficiently charge the battery, extract more power, and function dependably even when the amount of sunshine varies.

The system is inexpensive, simple to put up, and ideal for research, teaching, and small-scale solar energy initiatives. The paper also identifies some practical issues, such as making sure the



system boots up properly in low light, and proposes a voltage threshold control as a helpful remedy. The created system shows how power electronics, smart control technologies, and embedded systems may be used in renewable energy projects.

keywords Solar Energy, MPPT, Arduino Uno, Perturb and Observe, Fuzzy Logic, INA219, Buck Converter, Renewable Energy, Solar Charge Controller.

I. INTRODUCTION

One of the most crucial requirements for contemporary living is energy. The globe now requires far more energy than it did in the past due to rapid industrial progress and an increase in urban population. In addition to becoming depleted, conventional energy sources like coal, oil, and gas also contribute to pollution and climate issues. Renewable energy sources are becoming more popular as a result of these problems. Solar energy is one of the cleanest and most durable renewable energy sources. Solar panels directly convert sunlight into power by using certain materials. Because they don't generate noise, are simple to maintain, and are environmentally friendly, they are utilized in homes, workplaces, industries, and even isolated locations.

Despite their many advantages, solar panels are not particularly effective. Sunlight, temperature, weather, dust, and shadow all affect how much power they generate. The amount of electricity that the panels can produce is influenced by these variables, which are always changing. Finding the optimal method for the panels to function at their best is therefore quite difficult.

The Maximum Power Point (MPP) is a unique location on each solar panel where the maximum amount of energy is produced. For the system to function as efficiently as possible, it's critical to capture that maximum power. However, in various circumstances, the MPP varies. To assist identify and maintain the optimal operating point, a unique technology known as Maximum Power Point Tracking (MPPT) is required. MPPT systems keep checking the solar panel's performance and adjust things to get the most energy.

There are several methods used, including:

- Perturb and Observe (P&O)
- Incremental Conductance
- Hill Climbing
- Fractional Open Circuit Voltage
- Artificial Intelligence-Based Techniques
- Fuzzy Logic Controllers



Among these, P&O is widely used because it's easy to set up and doesn't need complex calculations. However, it may not be the fastest or most stable, especially when conditions change quickly. To make solar systems better, smart control methods are being used more often. Techniques like Fuzzy Logic can make systems more adaptable and efficient without requiring complex math.

This paper talks about building a smart MPPT solar charge controller using an Arduino. The system uses sensors to check the current and voltage. The Arduino processes these values and uses an MPPT method to send signals to a DC-DC converter. This converter helps move energy from the solar panel to a battery.

The energy is stored in a lithium-ion battery with an integrated safety mechanism. Even when circumstances change, the system functions effectively and increases the efficiency of energy gathering. The system offers a number of positive attributes, including affordability, real-time monitoring, safe battery charging, increased energy output from the panels, and ease of expansion. The study also examines practical issues such voltage dips, limited sunshine, and converter startup. Setting voltage thresholds is one way to improve the system's dependability. In conclusion, our study demonstrates the interoperability of power electronics, smart control, and renewable energy systems. Future initiatives in smart solar and sustainable energy solutions may use the system as a foundation.

II. PROBLEM STATEMENT

The environment has a significant impact on solar photovoltaic systems. The performance of the solar panel varies with variations in the temperature or intensity of sunshine. The solar panel may not run at its maximum power level without an effective control system, which would result in less energy being collected and less efficiency.

- The solar panel and battery are easily connected with older charging methods.
- This leads to a number of problems:- Loss of power
- - Lower charging efficiency
- - Poor use of solar energy
- - Stress on the battery and overheating

Furthermore, if there is little sunshine, the solar panel may not be able to provide enough power for the buck converter to start at all. This may result in a voltage decrease and unpredictable system behavior. As a result, a clever and reasonably priced MPPT-based solar charging system that can

- - Get the most power from the solar panel



- - Charge the battery safely
- - Work well even when the weather changes
- - Reduce power loss
- - Make the whole system more reliable

III. LITERATURE REVIEW

Efficient solar systems are now crucial due to the quick rise in renewable energy. The quantity of sunshine, temperature, dirt, and shading may all affect how well solar panels convert sunlight into power. In order to overcome these obstacles, researchers have created a variety of methods known as Maximum Power Point Tracking (MPPT) to increase solar panel energy extraction.

Because solar panels' output varies according on the weather, MPPT is crucial. They may not function as efficiently as they might without MPPT, which results in energy loss. Simple strategies like Perturb and Observe (P&O) and more sophisticated ones like Fuzzy Logic Control (FLC), Artificial Neural Networks (ANN), and combinations of clever approaches have been created over time. P&O is a popular MPPT technique due to its affordability and ease of usage.

It operates by varying the voltage and monitoring any changes in power. It keeps going in that direction if the power rises. If not, it veers off course. P&O can wobble about the maximum power point and perform poorly in situations when the environment changes quickly, despite its simplicity and widespread use. Incremental Conductance (INC) techniques were developed to address these problems.

These techniques locate the maximum power point more precisely than P&O by using the power-voltage curve's slope. However, INC might be difficult to implement in low-cost devices since it needs more sophisticated computations and greater processing resources.

Artificial Neural Networks (ANN) and Fuzzy Logic Control (FLC) are two smart control methods that have become more popular for MPPT in recent years. FLC produces speedy judgments by handling complicated systems using arithmetic and rules. Research has indicated that when sunlight levels fluctuate quickly, FLC-based MPPT performs better. Additionally, AI-based techniques including Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and ANN have been investigated.

These techniques are adaptable to changing circumstances since they may learn and get better over time. But they can be expensive since they need greater power, a lot of data for training, and complicated settings. Many researchers have focused on developing affordable MPPT systems using low-cost platforms like Arduino and microcontrollers. Schools, small projects, and portable solar sets can all benefit from these systems. To make MPPT useful and affordable, they employ real-time sensors, PWM control, and simple converters. The way these technologies function in low light is another crucial aspect. There might be issues if solar panels don't provide enough energy to turn on DC-DC converters. To enhance performance in low-light conditions, solutions including voltage regulation and smart converter configurations have been proposed.

The use of the Internet of Things (IoT) for solar energy management and monitoring has also been investigated recently. By using the internet to monitor voltage, current, battery condition, and efficiency, these systems can increase dependability and speed up problem-solving. Most studies show that smart MPPT methods are more efficient than older ones for solar systems. They are more costly and complicated to construct, though. A low-cost, effective MPPT system is therefore required for small-scale solar installations and educational initiatives. By developing an Arduino-based MPPT solar charger that employs the P&O technique with clever modifications, this project seeks to address this demand. To increase the system's stability and efficiency, it integrates sensors, PWM control, battery protection, and low-light handling.

Sr. No.	Author / Year	Technique Used	Main Contribution	Limitations
1	Esram & Chapman (2007)	Comparative MPPT Study	Compared various MPPT techniques	Complex implementation
2	Femia et al. (2005)	P&O Algorithm	Improved P&O optimization	Oscillation near MPP
3	Patel & Agarwal (2008)	PV Modeling	Studied shading effects on PV systems	Simulation-based only
4	Subudhi & Pradhan (2013)	Comparative MPPT Analysis	Compared conventional and intelligent MPPT methods	High computational requirement
5	Hala El-Khozondar (2016)	MPPT Review	Reviewed multiple MPPT algorithms	Lacked hardware validation
6	Zhu et al. (2021)	Fuzzy Logic MPPT	Improved tracking under dynamic conditions	Complex tuning
7	Abidi et al. (2023)	AI-Based MPPT	ANN and ANFIS benchmarking	Higher hardware cost
8	Vidal-Martínez (2025)	Fuzzy Controllers	Compared Mamdani and Type-2 fuzzy systems	Increased complexity
9	Ahmed & Sharif	Embedded MPPT	Low-cost Arduino	Limited large-

	(2026)		implementation	scale testing
10	Proposed Work	Arduino + P&O + Real-Time Monitoring	Low-cost intelligent MPPT with battery protection	Prototype-level implementation

IV. EXISTING SYSTEM

Without using Maximum Power Point Tracking (MPPT) approaches, conventional solar charging systems frequently use direct charging or simple voltage regulator circuits. These systems use a fixed DC-DC converter or a linear regulator to link the solar panel straight to the battery. Although these configurations are straightforward and affordable, they have a number of issues with power consumption, efficiency, and weather and environmental adaptation. The battery voltage or the connected load determine the fixed point at which the solar panel runs in conventional solar charging systems.

However, a solar panel's maximum power production might change based on temperature and sunshine. The solar panel frequently does not run at the optimal power point (MPP), which results in substantial energy loss since the system is unable to automatically modify its operating point. Simple Pulse Width Modulation (PWM) control without intelligent feedback mechanisms is used by the majority of inexpensive solar chargers. The charging process is less effective on cloudy days, in partial shade, or when sunlight fluctuates since these systems do not monitor the voltage and current of the solar panel to obtain the maximum power.

Another major issue with older systems is poor battery charging.

Direct charging can cause:

- Overcharging the battery
- Excess heat
- Reduced battery lifespan
- Inefficient energy transfer

Traditional systems also do not provide real-time updates on important factors like voltage, current, power, or the charging status. This makes it difficult to monitor the system or identify any problems. In low-light conditions, traditional systems perform very poorly.



Voltage dips and uneven charging might result from the solar panel's inability to produce enough current to keep the converter operating. Many of these systems struggle to adapt to environmental changes because they lack sophisticated control.

Although there are some MPPT systems on the market, they are often costly and call for specific hardware and software.

Modifying these systems for research or instructional purposes is difficult. Furthermore, sophisticated MPPT controllers with IoT or AI capabilities may increase the system's complexity and expense. Therefore, there is a need for a low-cost, smart, and flexible MPPT-based solar charging system that can:

- Extract the most power from solar panels
- Function well under different conditions
- Charge batteries safely
- Provide real-time monitoring and control
- Support future upgrades like IoT and AI

The proposed system addresses these issues by combining Arduino-based control, real-time sensing, MPPT algorithms, PWM-based converter control, and battery protection into a compact and affordable solar energy solution.

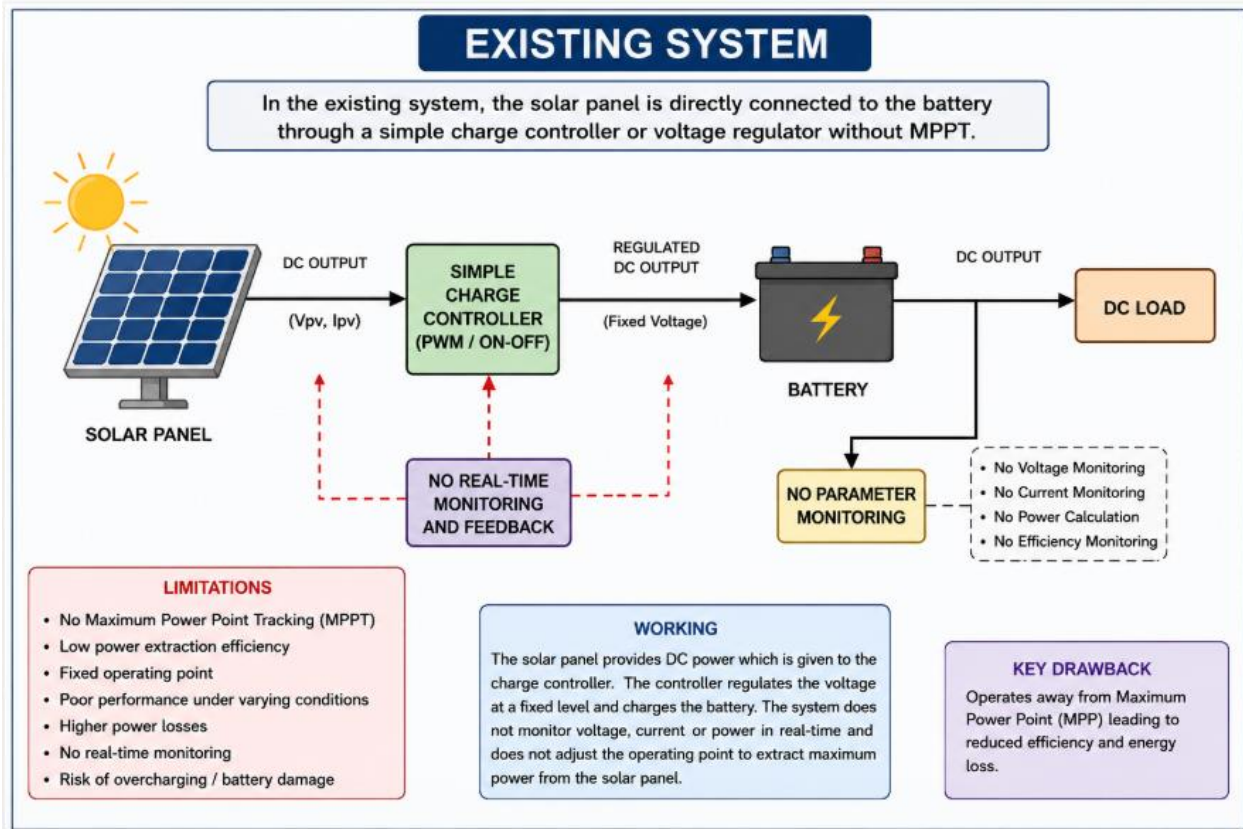


Fig. 1- Existing System

V. SYSTEM ARCHITECTURE

Together, the hardware and software components of the MPPT-based solar charge controller system enable effective solar energy collection, real-time system monitoring, and safe battery charging. Even when the weather changes, the technology makes sure the solar panel runs at its maximum power production. The system includes the following parts:

- Solar Panel
- Protection Diode
- INA219 Current/Voltage Sensor
- Arduino Uno Microcontroller
- XL4015 DC-DC Buck Converter
- RC Filter Circuit
- Battery Management System (BMS)
- Lithium-Ion Battery Pack



- LCD Display Module

The primary energy source is the solar panel, which transforms sunlight into direct current (DC) power. The warmth and quantity of sunshine determine how much power it generates. MPPT is used to extract the greatest power feasible because the output of the solar panel changes during the day. The converter input and the solar panel are separated by a protective diode. This makes the system safer and stops power loss by prohibiting the battery from returning electricity to the solar panel at night or in low light. The solar panel's voltage and current are measured using the INA219 sensor. These measurements are sent to the Arduino Uno via I2C communication. The Arduino uses these values to calculate real-time power and run the MPPT algorithm. The Arduino Uno acts as the main control unit.

In order to regulate the converter, it receives sensor data, computes, applies the Perturb and Observe (P&O) MPPT algorithm, and transmits PWM signals. An RC filter is then used to filter the PWM signal in order to provide a smooth analog control voltage. The XL4015 buck converter regulates the power flow from the solar panel to the battery as well as the output voltage. To maintain the solar panel functioning close to its maximum power point, the Arduino modifies the PWM duty cycle.

The Battery Management System (BMS) protects the lithium-ion battery by preventing:

- Overcharging
- Over-discharging
- Short circuits
- Overcurrent

The LCD display shows real-time information, such as voltage, current, power, and charging status. The system operates in a closed-loop setup where sensor data is continuously used to update the controller, ensuring everything runs as efficiently as possible.

This system design offers:

- Efficient use of solar power
- Stable converter performance
- Safe battery charging
- Real-time monitoring
- Low cost
- A scalable design

This setup is suitable for educational projects, portable solar systems, battery charging, and small renewable energy applications.

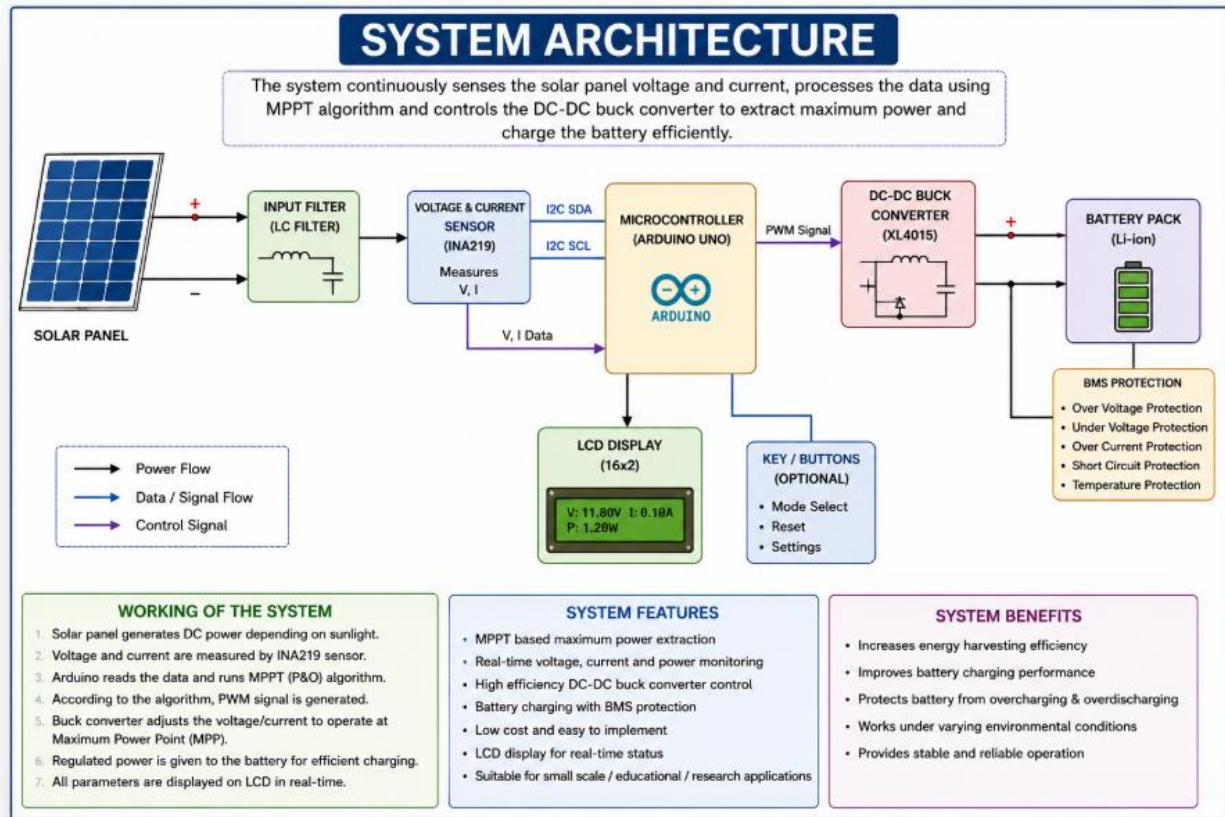


Fig.2 - Architecture

VI. FUTURE SCOPE

This article describes an MPPT-based solar charge controller that effectively maximizes solar energy utilization and charges batteries securely. It makes use of inexpensive, basic components and clever control strategies. Although it functions effectively in a variety of weather circumstances, there are ways to improve its performance for increased dependability, efficiency, and intelligence. Adding IoT monitoring might be a significant boost. The system may transmit real-time data to a mobile app or cloud using Wi-Fi or GSM modules such as ESP8266, ESP32, or SIM800. This enables users to keep an eye on crucial information from any location, including voltage, current, battery levels, power generation, and charging status. IoT may also assist with problem-solving, remote system control, and more intelligent energy management.

Another important improvement is the use of better MPPT algorithms, such as:

- Fuzzy Logic Control (FLC)
- Artificial Neural Networks (ANN)
- Machine Learning for optimization
- Adaptive AI control systems

These advanced techniques can help the system track maximum power more precisely, reduce fluctuations around the best power point, and respond quickly to rapid changes in conditions. Compared to traditional methods like Perturb and Observe (P&O), AI-based approaches significantly improve efficiency and stability. High-efficiency power converters, such as synchronous buck or buck-boost converters, might potentially be added to the system. These cutting-edge designs increase overall efficiency, minimize energy loss, and enhance performance in hot conditions. In the future, the system could include a sun tracking capability.

In order to increase sunlight exposure and enhance energy output, a tracking device automatically modifies the solar panel's angle to follow the sun throughout the day. Better outcomes might be achieved by using both single-axis and dual-axis tracking devices. The system can also be expanded for various applications, including:

- Large-scale solar setups
- Smart microgrids
- Hybrid renewable energy systems
- Charging for electric vehicles
- Portable solar power stations

Another potential enhancement is adding data logging and cloud analysis. System analysis, forecasting maintenance requirements, and energy efficiency may all be aided by storing



historical performance data on SD cards or in the cloud. For lithium-ion batteries, real Constant Current–Constant Voltage (CC-CV) techniques can also increase battery charging. As a result, charging is safer, more durable, and more effective.

User interfaces like:

- TFT displays
- Mobile apps
- Web dashboards

can be added to make the system more user-friendly and easier to use. Future research might also concentrate on leveraging ultra-low-power converter designs and adaptive starting control to address startup problems in low light. All things considered, the suggested approach offers a solid basis for next intelligent renewable energy systems. It can develop into a clever, effective, and scalable solution for actual solar energy utilization with the help of AI, IoT, and better power electronics.

VII. CONCLUSION

An excellent method to increase solar energy and safely charge batteries is to use a solar charge controller that employs MPPT. It makes use of inexpensive, basic components and clever control techniques. It functions well despite weather variations, but there are ways to improve it going forward to make it more intelligent, dependable, and efficient. Adding IoT technologies might be a significant boost. The controller may transmit real-time data to a mobile phone or the cloud by utilizing modules such as ESP8266, ESP32, or SIM800. This enables users to monitor critical parameters from any location, including voltage, current, battery level, power generated, and charging status. IoT may also assist with problem-solving, remote system control, and more intelligent energy management. Another improvement is using better MPPT algorithms like Fuzzy Logic Control, Artificial Neural Networks, Machine Learning optimization, and Adaptive AI control. These clever methods can lessen the system's wobbling, track the optimal power point more precisely, and react to environmental changes more quickly. These AI-based techniques can increase productivity and maintain system stability when compared to more traditional techniques like P&O. The system can potentially be enhanced by using sophisticated power converters such as synchronous buck or buck-boost converters. These converters lower energy loss, perform better in hot conditions, and increase the efficiency of the power conversion process.

A sun tracking device may be added to the system in the future. This allows the solar panel to receive more sunlight and generate more electricity by automatically adjusting its position to



follow the sun throughout the day. For even greater efficiency, single-axis and dual-axis tracking systems can be utilized. Large solar installations, smart microgrids, integrating solar with other renewable energy sources, charging electric cars, and creating portable solar power solutions are just a few of the other applications for which the system may be developed.

Adding cloud-based analytics and data tracking is another potential improvement. In order to analyze the system, forecast when maintenance is required, and maximize efficiency, this would save historical performance data utilizing SD cards or cloud storage. Lithium-ion battery charging may be made safer, more durable, and more effective by employing real Constant Current-Constant Voltage (CC-CV) techniques. TFT displays, mobile applications, and online dashboards are examples of user-friendly interfaces that may be added to improve system monitoring and user interaction. Future research might also look into fixing startup issues during low light by using adaptive control and ultra-low-power converter designs.

All things considered, the technology provides a strong foundation for next intelligent solar energy solutions. AI, IoT, and sophisticated power electronics can make the system smarter, more effective, and simpler to scale for practical uses. Important Line for Report: The solar energy system may become more intelligent, scalable, and efficient in the future by utilizing IoT, AI, and sophisticated converter technology.

REFERENCES

1. M. G. Villalva, J. R. Gazoli, and E. Ruppert Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays," *IEEE Transactions on Power Electronics*, vol. 24, no. 5, pp. 1198–1208, May 2009.
2. N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, "Optimization of Perturb and Observe Maximum Power Point Tracking Method," *IEEE Transactions on Power Electronics*, vol. 20, no. 4, pp. 963–973, July 2005.
3. H. Patel and V. Agarwal, "MATLAB-Based Modeling to Study the Effects of Partial Shading on PV Array Characteristics," *IEEE Transactions on Energy Conversion*, vol. 23, no. 1, pp. 302–310, March 2008.
4. D. P. Hohm and M. E. Ropp, "Comparative Study of Maximum Power Point Tracking Algorithms," *Progress in Photovoltaics*, vol. 11, no. 1, pp. 47–62, 2003.
5. J. A. Gow and C. D. Manning, "Development of a Photovoltaic Array Model for Use in Power Electronics Simulation Studies," *IEE Proceedings*, vol. 146, no. 2, pp. 193–200, 1999.
6. M. A. Green, *Solar Cells: Operating Principles, Technology and System Applications*, Prentice-Hall, 1982.



7. S. Jain and V. Agarwal, “A New Algorithm for Rapid Tracking of Approximate Maximum Power Point in Photovoltaic Systems,” *IEEE Power Electronics Letters*, vol. 2, no. 1, pp. 16–19, 2004.
8. B. Subudhi and R. Pradhan, “A Comparative Study on Maximum Power Point Tracking Techniques for Photovoltaic Power Systems,” *IEEE Transactions on Sustainable Energy*, vol. 4, no. 1, pp. 89–98, Jan. 2013.
9. K. H. Hussein, I. Muta, T. Hoshino, and M. Osakada, “Maximum Photovoltaic Power Tracking: An Algorithm for Rapidly Changing Atmospheric Conditions,” *IEE Proceedings*, vol. 142, no. 1, pp. 59–64, 1995.
10. R. Faranda and S. Leva, “Energy Comparison of MPPT Techniques for PV Systems,” *WSEAS Transactions on Power Systems*, vol. 3, no. 6, pp. 446–455, 2008.
11. Texas Instruments, “INA219 Zero-Drift, Bidirectional Current/Power Monitor Datasheet,” Texas Instruments, 2015.
12. Arduino, “Arduino Uno Technical Specifications,” Arduino Official Documentation, 2024.
13. XLSEMI, “XL4015 DC-DC Buck Converter Datasheet,” XLSEMI Corporation, 2016.
14. J. Surya Kumari and C. Sai Babu, “Mathematical Modeling and Simulation of Photovoltaic Cell Using MATLAB-Simulink Environment,” *International Journal of Electrical and Computer Engineering*, vol. 2, no. 1, 2012.
15. H. Abu-Rub, M. Malinowski, and K. Al-Haddad, *Power Electronics for Renewable Energy Systems*, Wiley, 2014.