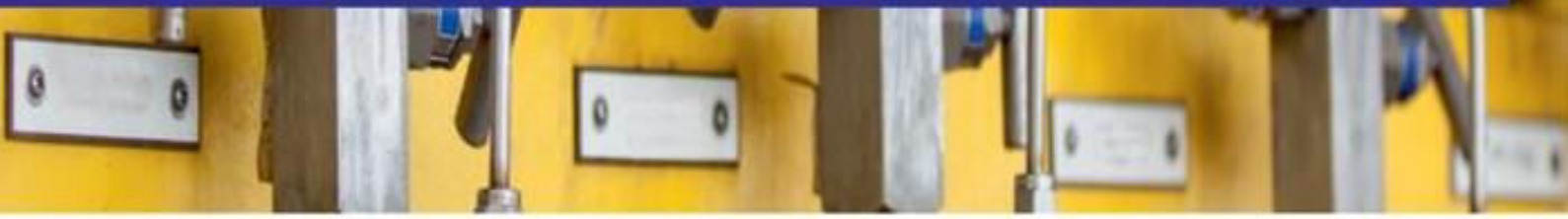


IJAREEIE

e-ISSN: 2278-8875
p-ISSN: 2320-3765

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

Volume 15, Issue 11, November 2026



INTERNATIONAL STANDARD SERIAL NUMBER INDIA

Impact Factor: 9.867

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (IJAREEIE)

| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 9.867 | A Monthly Peer Reviewed & Refereed Journal |

|| Volume 15, Issue 11, November 2026 ||

| DOI:10.15662/IJAREEIE.2026.1511017 |

Artificial Intelligence, Machine Learning, and Data Analytics in Smart Power Systems: A Comprehensive Review of Intelligent Solar PV Monitoring, Partial Shading Management, and Maximum Power Point Tracking

Ch. Sowmya, B.sravani, B.Anand Sagar, K.Minna Rao

Dept. of EEE, GMRIT Deemed to be University, Rajam, Vizianagram, Andhrapradesh, India

ABSTRACT: The growing demand for clean and sustainable energy has increased the use of Artificial Intelligence and advanced technologies in modern power systems. Solar Photovoltaic systems are an important source of renewable energy, but their performance is affected by changing weather conditions, temperature variations, and partial shading. Partial shading reduces power generation and creates multiple peaks, making it difficult for conventional Maximum Power Point Tracking techniques to identify the Global Maximum Power Point. This review explores AI-based techniques, including Artificial Neural Networks, Fuzzy Logic, Machine Learning, Deep Learning, Support Vector Machines, and hybrid optimization methods, to improve solar PV performance. These techniques help detect shading conditions, predict system behaviour, improve MPPT accuracy, and reduce power losses. Computer vision, thermal image analysis, sensor-based monitoring, and data analytics also support fault detection and predictive maintenance. Beyond solar energy, AI and ML contribute to electricity demand forecasting, renewable energy integration, fault diagnosis, voltage stability assessment, and smart grid management. This review compares different techniques based on accuracy, tracking speed, computational complexity, reliability, and practical applicability. It also discusses challenges such as limited data availability, cybersecurity risks, computational requirements, and real-time implementation. Finally, future research directions are presented to support the development of efficient, reliable, and sustainable power systems.[1]-[4],[25],[36-39],[45],[49],[55],[59]

KEYWORDS: Artificial Intelligence, Machine Learning, Deep Learning, Solar Photovoltaic Systems, Partial Shading, MPPT, Fault Detection, Smart Grid, Renewable Energy.[1]-[2]

I. INTRODUCTION

A Smart Power System is a modern electricity system that uses new technologies like Artificial Intelligence (AI), Machine Learning (ML), sensors, and communication systems to manage electricity. It helps to generate, supply, and use electricity in a better way. Unlike traditional power systems, smart power systems can monitor electricity usage and find problems quickly. They help to reduce power losses, balance electricity supply and demand, and provide a reliable power supply. They also support renewable energy sources like solar and wind power. AI and ML are used to predict electricity demand, detect faults, and improve system performance. Smart meters help users monitor their electricity consumption and avoid unnecessary energy usage. Overall, smart power systems help to save energy, reduce electricity waste, and make the power supply cleaner, smarter, and more reliable

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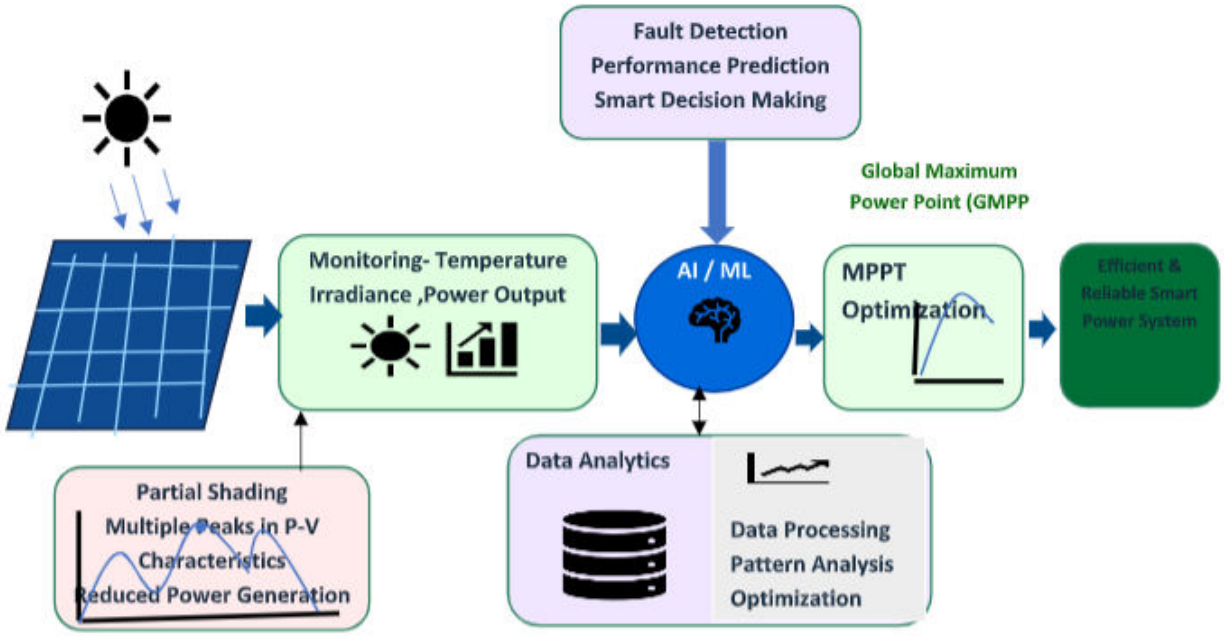


Fig-1: Modern Power Systems

1.1 Evolution of Modern Power Systems

Power systems have evolved significantly over the past century. Initially, electricity was generated through small local power stations. In the late 19th century, the War of the Currents took place between DC and AC systems. AC became widely used because it was suitable for long-distance transmission. By the mid-20th century, interconnected power grids improved electricity supply and reliability. Today, renewable energy sources, smart sensors, digital communication, and automation are making power systems more efficient and sustainable.

1.2 Role of Data Analytics, Artificial Intelligence, and Machine Learning in Smart Power Systems

Data Analytics, Artificial Intelligence (AI), and Machine Learning (ML) play an important role in modern power systems. Data analytics helps collect and analyse information from solar panels, smart meters, and sensors to monitor performance and detect faults. AI and ML improve solar power generation through MPPT and partial shading management. They also help predict renewable energy generation and forecast electricity demand. These technologies reduce energy losses, improve reliability, and support efficient power system management.

II. OVERVIEW OF CONVENTIONAL METHODS

2.1 Conventional MPPT Methods

1. Perturb and Observe (P&O) MPPT Method

P&O is a simple and low-cost method used to track maximum solar power. It slightly changes the PV voltage and observes the change in power. If power increases, it continues in the same direction; otherwise, it reverses the direction. Energy Waste: It oscillates around the maximum power point, causing small power losses. False Peaks: Under partial shading, it may get trapped at local peaks.

2. Incremental Conductance (INC) MPPT Method

INC identifies the maximum power point by analysing changes in PV voltage and current. When the slope becomes zero (), the controller identifies the maximum power point. It provides better tracking under changing sunlight conditions.It requires more calculations and may get trapped at local peaks during partial shading.

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2.2 Conventional Method of Partial Shading

1. Bypass Diodes

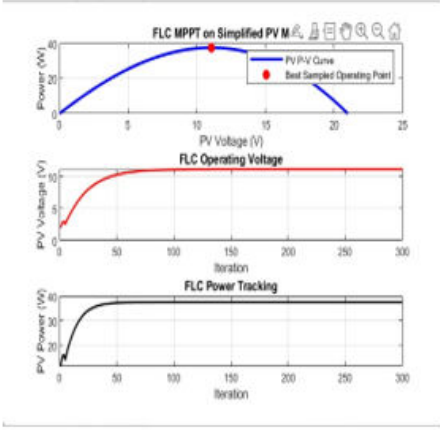
Bypass diodes protect solar cells during partial shading. They provide an alternative path for current when some cells are shaded, preventing overheating and hot spots. Voltage Drop and Power Loss: Bypassing shaded cells reduces the overall power output. Multiple False Peaks: They create multiple peaks in the P–V curve, making it difficult to identify the Global Maximum Power Point.

III. OVERVIEW OF AI-BASED MPPT METHODS

A. AI Based MPPT Methods

1. Fuzzy Logic Controller (FLC)-Based MPPT

A Fuzzy Logic Controller (FLC) is an intelligent technique used in solar photovoltaic (PV) systems to track the maximum power point under changing environmental conditions. It uses fuzzy rules and membership functions to control the system without needing an exact mathematical model. This helps the PV system respond to changes in solar irradiance and temperature.[36]-[39],[60] In FLC-based MPPT, changes in power (ΔP) and voltage (ΔV) are used as inputs. Membership functions classify these changes as negative, zero, or positive. Based on predefined fuzzy rules, the controller adjusts the duty cycle (ΔD) of the DC–DC converter to move the system towards the maximum power point. This process continues as conditions change to maintain maximum power output. The performance of FLC depends design of its membership functions, fuzzy rules, and controller setting.



FLC Equations:

$$P(k) = V(k) \times I(k)$$

Change in power:

$$\Delta P(k) = P(k) - P(k-1)$$

Change in voltage:

$$\Delta V(k) = V(k) - V(k-1)$$

A common FLC-MPPT design uses the slope of the PV power-voltage curve:

$$E(k) = \frac{\Delta P(k)}{\Delta V(k)}$$

Where p-power ,v-voltage, k is constant

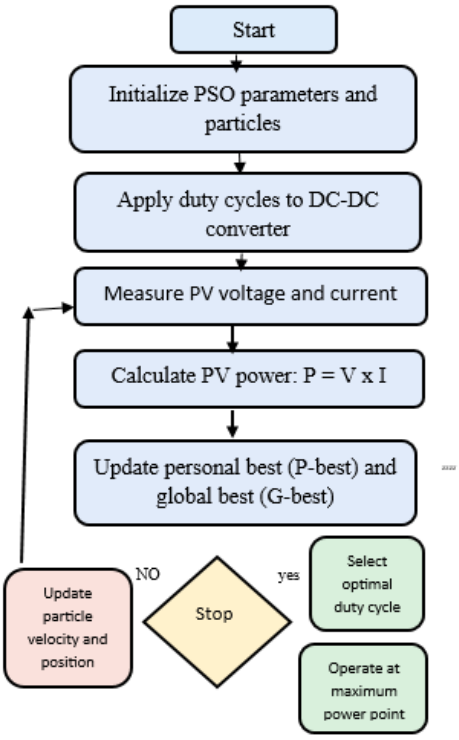
2. Particle Swarm Optimization (PSO)-Based MPPT

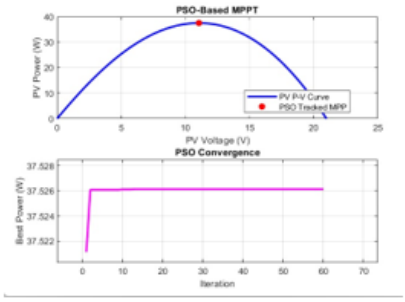
Particle Swarm Optimization (PSO) is an optimization technique inspired by the group movement of birds and fish. In solar photovoltaic (PV) systems, it is used to find the Global Maximum Power Point (GMPP), especially under partial shading conditions, where multiple peaks appear in the power-voltage curve. In PSO-based Maximum Power Point Tracking (MPPT), each particle represents a possible duty cycle of the DC–DC converter. The PV voltage and current are measured to calculate power using (**P = V × I**). Each particle records its personal best (P best), while the best solution among all particles is called the global best (G best).[25]-[35]

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PSO : p-v curve and respective parameters

PSO MPP Voltage= 11.065 V

PSO Maximum Power= 37.526 W

Reference MPP Voltage = 11.068 V

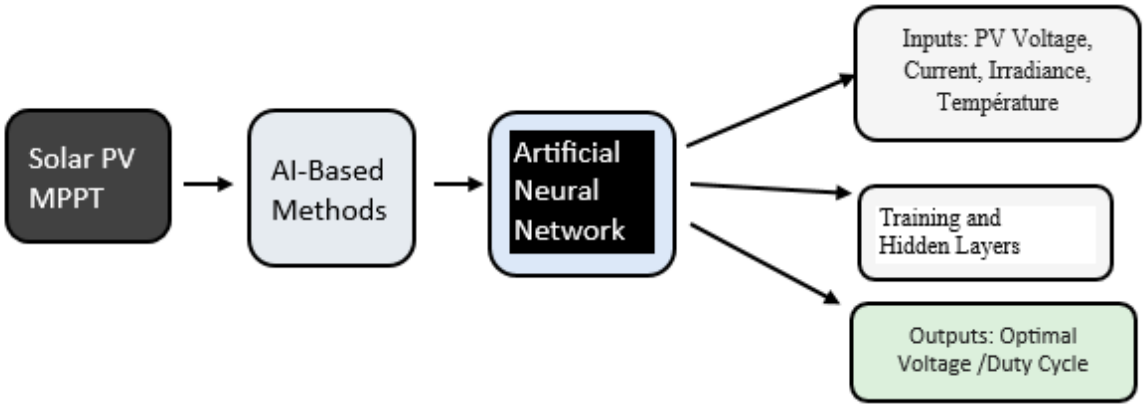
Reference Maximum Power = 37.526 W

F1g-2: Flowchart of Particle Swarm Optimization (PSO)

B.AI-based machine learning methods for partial shading

1. Artificial Neural Network (ANN)-Based MPPT

An Artificial Neural Network (ANN) is an AI-based technique inspired by the working of the human brain. It learns the relationship between solar PV system parameters and maximum power output using training data. ANN consists of input, hidden, and output layers that process information to predict the required control values.[38]-[48].In solar PV systems, ANN-based Maximum Power Point Tracking (MPPT) uses parameters such as PV voltage, current, solar irradiance, and temperature as inputs. Based on the learned patterns, it predicts the maximum power point voltage, current, or the duty cycle of the DC–DC converter. [25]-[46]



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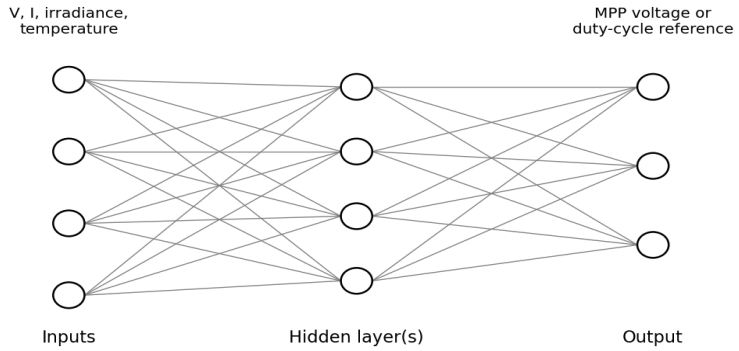


Fig-4: Artificial Neural Network (ANN)

2. Support Vector Machine (SVM)

Support Vector Machine (SVM) is a Machine Learning method used to separate data into different groups. In solar PV systems, it helps identify whether a solar panel is working normally, affected by partial shading, or has any faults. SVM works by taking input values such as voltage, current, power, temperature, and sunlight intensity. It studies these values and learns from previously collected data. It then uses a dividing line or boundary called a *hyperplane* to separate different conditions. The points near this boundary are called *support vectors*.

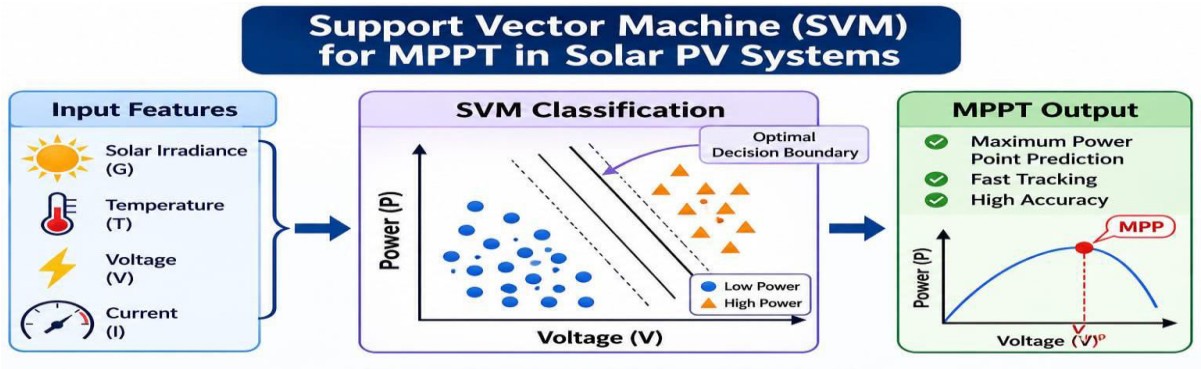


Fig-5: Support Vector Machine (SVM)

C. Performance Analysis of Conventional methods and AI- Based MPPT Method

Parameters	Conventional methods		PSO Method	FLC Method	ANN Method	SVM Method
	Perturb and Observe (P&O) MPPT Method	Incremental Conductance (INC) MPPT Method				
Working Principle	Changes the PV voltage slightly and observes the change in power.	Uses changes in voltage and current to identify the maximum power point.	Uses particle movement to search for the best operating point.	Uses fuzzy rules and membership functions to control the system.	Learns from training data to predict the maximum power point.	Uses a hyperplane to separate different operating conditions.
Main Purpose	Tracks the Maximum Power Point (MPP).	Tracks the MPP accurately under changing	Finds the Global Maximum Power Point (GMPP).	Tracks maximum power under changing	Predicts the required voltage, current, or duty cycle.	Identifies partial shading and faults in PV systems.

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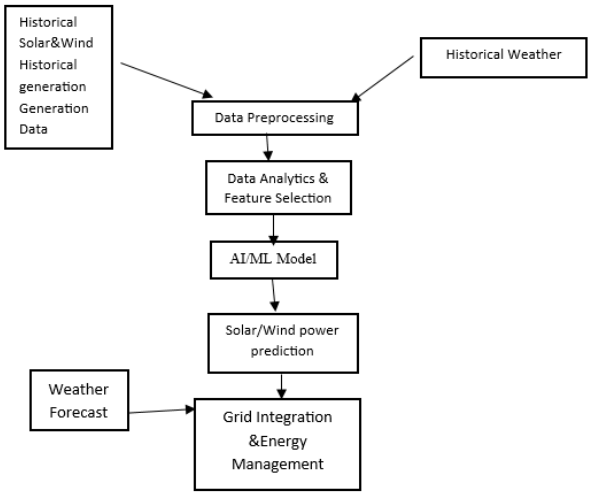
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		solar conditions.		environmental conditions.		
Input Parameters	PV voltage and current.	PV voltage and current.	PV voltage and current.	Change in power (ΔP) and change in voltage (ΔV).	Voltage, current, irradiance, and temperature.	Voltage, current, power, temperature, and irradiance.
Accuracy	Provides good tracking under normal sunlight conditions.	Generally provides better tracking accuracy than P&O under	Provides good tracking accuracy under partial shading.	Provides good tracking performance when properly designed.	Depends on training data and network structure.	Depends on training data and model selection.
Response Time	Simple and responds quickly under steady conditions.	Responds well to changes in solar irradiance.	Depends on the number of particles and iterations.	Responds well to changes in solar irradiance.	Provides fast predictions after training.	Can provide fast classification after training.
Complexity	Easy to design and implement.	Requires more calculations than P&O.	Requires optimization calculations.	Requires proper fuzzy rules and membership functions.	Requires training and network design.	Requires proper model selection and parameter tuning.
Main Limitation	Oscillates around MPP and may get trapped at local peaks during partial shading.	May get trapped at local peaks during partial shading and requires more computational effort.	May take more time to converge under changing conditions.	Performance depends on rule design and controller settings	Needs sufficient and accurate training data.	Performance may decrease with poor-quality training data.

D. Modern power systems and data analytics methods:

1. Renewable Energy Integration

Solar and wind power generation depends on weather conditions, which can change throughout the day. AI and ML techniques use past weather and power generation data to predict future energy production. Factors such as sunlight, temperature, wind speed, and humidity help these models make predictions. Data Analytics helps identify patterns in energy These predictions help power system operators plan electricity generation, manage energy demand, and store excess energy when needed. They also help maintain a balance between electricity supply and demand. However, prediction accuracy depends on the quality of the data and changes in weather weather conditions.[60]-[66]



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2. Load Forecasting

Load forecasting is the process of predicting the future electricity demand. It helps power system operators understand how much electricity will be needed in the coming hours or days. AI and ML techniques use past electricity consumption, weather conditions, time, and other data to make these predictions. Data Analytics helps study electricity usage patterns and changes in demand. Two commonly used techniques are Artificial Neural Networks (ANN) and Support Vector Machines (SVM). ANN learns from previous electricity usage and predicts future demand, while SVM identifies relationships between different factors affecting electricity consumption. These techniques help in planning electricity generation, managing power supply, reducing operating costs, and improving the efficiency and reliability of the power system.[61]-[65]

Time	Actual Load	ANN Forecast
1	420	415
2	450	455
3	480	475
4	510	515
5	490	485
6	530	525

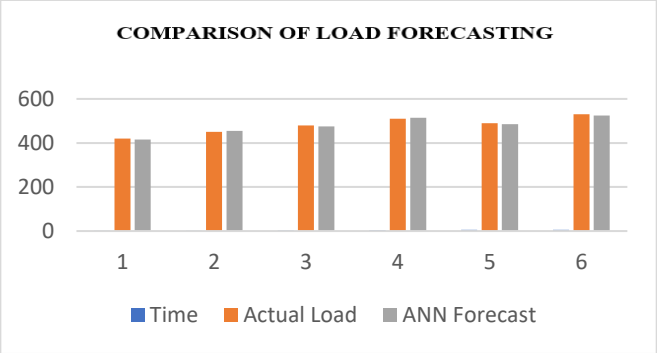


Fig:7-Comparison of load forecasting

3. Comparison: Load Forecasting vs Renewable Energy Integration

Parameter	Load Forecasting	Renewable Energy Integration
Main Problem	Electricity demand changes depending on time, weather, and consumer usage.	Solar and wind power generation changes depending on weather conditions.
Conventional Methods	Statistical methods, regression, time-series models, and past load data.	Traditional forecasting, fixed scheduling, and reserve management.
Drawbacks of Conventional Methods	Difficult to predict sudden changes in electricity demand.	Difficult to handle changes and uncertainty in solar and wind power generation.
AI/ML Can Address It By	Using past data and weather information to predict future electricity demand.	Using weather and past generation data to predict solar and wind power generation.
Why Use AI/ML?	To improve prediction accuracy and plan electricity supply.	To improve renewable energy generation and grid management.
Input Data	Past electricity demand, weather, time, and temperature	Solar irradiance, wind speed, temperature, and weather data.
Output	Predicted future electricity demand	Predicted solar and wind power generation.
Benefits	Better planning, proper power supply, and reduced energy mismatch.	Better use of renewable energy and improved power system reliability.

IV. KEY CHALLENGES

Challenges and Limitations

- High Cost: AI requires advanced hardware, increasing system costs.
- Data Availability: Insufficient or inaccurate data affects model accuracy.
- Real-Time Performance: Some algorithms take longer to track GMPP under changing shading conditions. \[55\], \[59\]

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V. FUTURE SCOPE

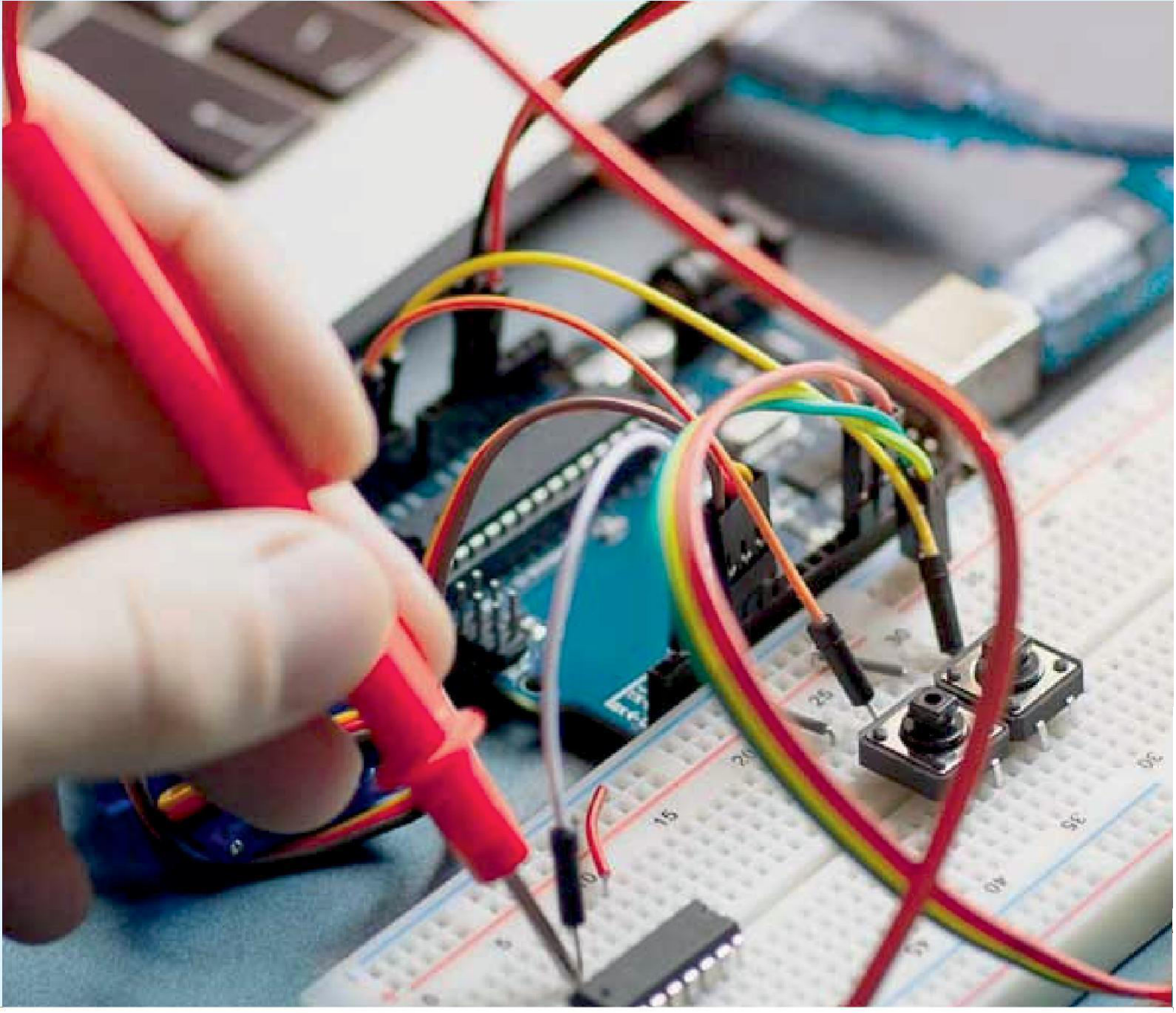
- Edge AI: Reduces processing time and cost.
- Hybrid Techniques: Improve MPPT performance under partial shading.
- Digital Twin: Helps monitor PV systems, detect faults, and plan maintenance.

VI. CONCLUSION

AI, ML, and Data Analytics improve the efficiency and reliability of smart power systems. They support PV monitoring, MPPT, fault detection, and load forecasting. Despite challenges, these technologies offer a promising future for sustainable power systems**. \[1\]–\[4\], \[25\]–\[46\], \[54\]–\[60\]**

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