

Adaptive MPPT Control of Solar PV System using Incremental Conductance Algorithm

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ABSTRACT

The increasing demand for renewable energy and the growing concerns regarding environmental sustainability have significantly accelerated the deployment of solar photovoltaic (PV) systems. However, the electrical output of a PV system is highly dependent on environmental conditions such as solar irradiance and cell temperature, which continuously shift the Maximum Power Point (MPP). Therefore, an efficient Maximum Power Point Tracking (MPPT) technique is essential to maximize the power extracted from the PV array.

This research presents the modeling and simulation of an Adaptive MPPT Control of a Solar PV System using the Incremental Conductance (INC) algorithm in the MATLAB/Simulink environment. The proposed system consists of a photovoltaic array, an Incremental Conductance-based MPPT controller, a DC–DC boost converter, voltage and current sensing circuits, and a DC load. The MPPT controller continuously monitors the PV voltage and current, determines the operating point of the PV array, and adjusts the duty cycle of the boost converter to ensure operation near the Maximum Power Point under varying environmental conditions.

The performance of the proposed system is evaluated under different levels of solar irradiance and load conditions. Simulation results demonstrate that the Incremental Conductance algorithm effectively tracks the Maximum Power Point, improves the energy extraction capability of the PV system, minimizes steady-state oscillations, and maintains stable DC bus voltage. The study confirms that the proposed controller enhances the overall efficiency and dynamic performance of the photovoltaic system and provides a reliable solution for renewable energy applications.

Keywords: Solar Photovoltaic System, Maximum Power Point Tracking (MPPT), Incremental Conductance Algorithm, DC–DC Boost Converter, MATLAB/Simulink, Renewable Energy.

1 Introduction:

The increasing demand for clean and sustainable energy has accelerated the development and deployment of renewable energy sources, among which solar photovoltaic (PV) systems have gained significant importance. Solar energy is abundant, environmentally friendly, and widely available; however, the efficiency of PV systems is strongly influenced by environmental factors such as solar irradiance and temperature. These continuously varying conditions lead to fluctuations in the output characteristics of the PV system, making it essential to operate the system at its Maximum Power Point (MPP) for maximum energy extraction..

The proposed adaptive hybrid MPPT controller is implemented using MATLAB/Simulink. The system consists of a solar PV array, a DC–DC boost converter, and an MPPT control unit. The controller continuously monitors the voltage and current of the PV system and adjusts the duty cycle of the converter to ensure maximum power extraction. The performance of the proposed method is evaluated under varying irradiance conditions, and the results demonstrate improved tracking efficiency, reduced oscillations, and enhanced overall system performance compared to conventional MPPT techniques.. [1]

1.1.Solar PV System

A photovoltaic (PV) system is composed of several important components that work together to convert solar energy into usable electrical power. The fundamental component of the system is the solar cell, which converts sunlight directly into direct current (DC) electricity through the photovoltaic effect. Multiple solar cells are connected together to form a PV module, and several modules are combined to create a PV array capable of generating higher power output.

The electrical output obtained from the PV array is regulated using a DC–DC converter, which controls and adjusts the voltage level according to system requirements. To maximize the power extraction from the PV system under varying irradiance and temperature conditions, a Maximum Power Point Tracking (MPPT) controller is employed. The MPPT controller continuously monitors the operating conditions and adjusts the duty cycle of the converter to ensure operation at the maximum power point.

In many practical applications, an inverter is used to convert the DC power generated by the PV array into alternating current (AC) power suitable for household loads or grid-connected systems. In standalone and hybrid PV systems, batteries are often incorporated for energy storage and backup power supply. Together, these components ensure efficient, reliable, and continuous operation of the photovoltaic system under different environmental conditions.

[2][3]

1.1.2 Solar Cell (Photovoltaic System)

A solar cell, also known as a photovoltaic (PV) cell, is a device that converts solar energy directly into electrical energy through the photovoltaic effect. Photovoltaic cells are generally manufactured using semiconductor materials such as silicon, which generate electricity when exposed to sunlight. When solar radiation falls on the surface of the PV cell, photons are absorbed by the semiconductor material, resulting in the generation of free electrons and the flow of electric current.

The efficiency of photovoltaic cells is theoretically around 25%; however, the actual efficiency depends on several environmental and operating conditions, particularly temperature. As the temperature of the PV cell increases, the output voltage and overall efficiency of the system decrease. Even a slight rise in temperature can significantly reduce the performance of the PV system, highlighting the importance of proper thermal management and cooling techniques in photovoltaic applications..[4]

1.1.3 Working of Solar Cell

A solar cell operates on the principle of the photovoltaic effect and primarily consists of a p–n junction that generates an electromotive force (EMF) when exposed to sunlight. When solar radiation with energy greater than the bandgap of the semiconductor material falls on the surface of the solar cell, photons are absorbed by the semiconductor, resulting in the generation of electron–hole pairs.

In a typical solar cell structure, a thin layer of n-type silicon (n-Si) is formed over a p-type silicon (p-Si) wafer through diffusion techniques, thereby creating a p–n junction. This junction develops an internal electric field that plays a crucial role in the operation of the cell. A metal contact is provided on the backside of the p-type layer, known as the back contact, while metallic grid lines or finger electrodes are placed on the top surface of the n-type layer, which act as the front contact.

To maximize light absorption and improve current generation, the surface area of the solar cell junction is maintained as large as possible. When sunlight strikes the solar cell, three important processes take place simultaneously: generation of electron–hole pairs, separation of charge carriers due to the internal electric field, and collection of these carriers at the respective contacts. The movement of electrons and holes towards opposite terminals produces an electromotive force (EMF), resulting in the flow of electric current through the external circuit.

Thus, the operation of a solar cell can be understood as the combined process of generation, separation, and collection of charge carriers, which enables the direct conversion of solar energy into electrical energy efficiently.[5]

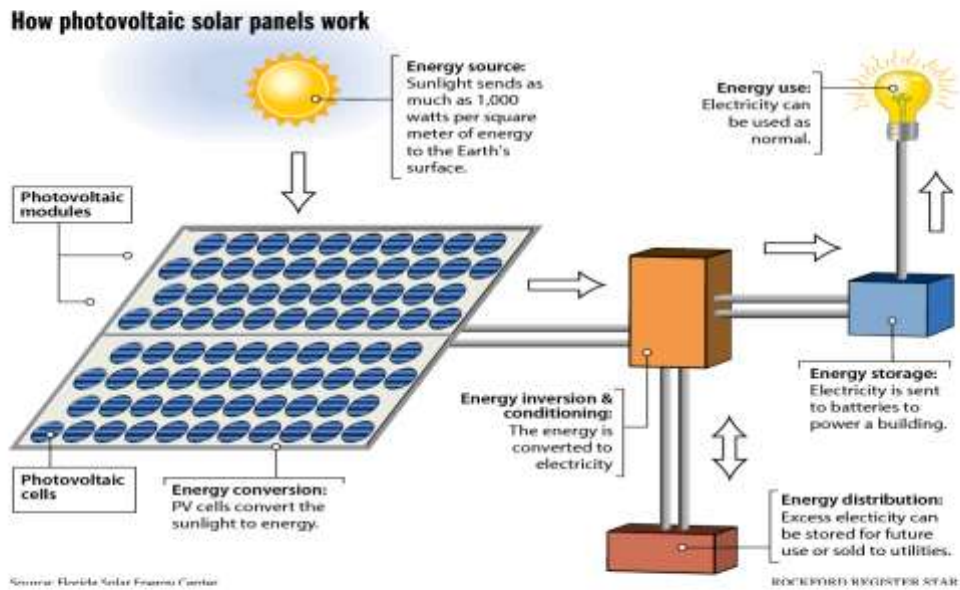


Fig:1.1 working of solar

1.1.4 I-V Characteristics of a Solar Cell

A solar cell, also known as a photovoltaic (PV) cell, is the fundamental unit of a solar energy generation system that directly converts light energy into electrical energy without any intermediate conversion process. The operation of a solar cell is based on the photovoltaic effect, in which electrical power is generated when sunlight falls on a semiconductor material.

A solar cell is essentially a semiconductor device formed by a p-n junction created by joining p-type and n-type semiconductor materials. The p-type region contains a high concentration of holes, whereas the n-type region contains a high concentration of electrons. When these two regions are joined together, electrons from the n-type side diffuse toward the p-type side, while holes from the p-type side move toward the n-type side. This diffusion process results in the formation of a depletion region and an internal electric field across the junction, which is essential for the operation of the solar cell.

When sunlight strikes the surface of the solar cell, photons having energy greater than the

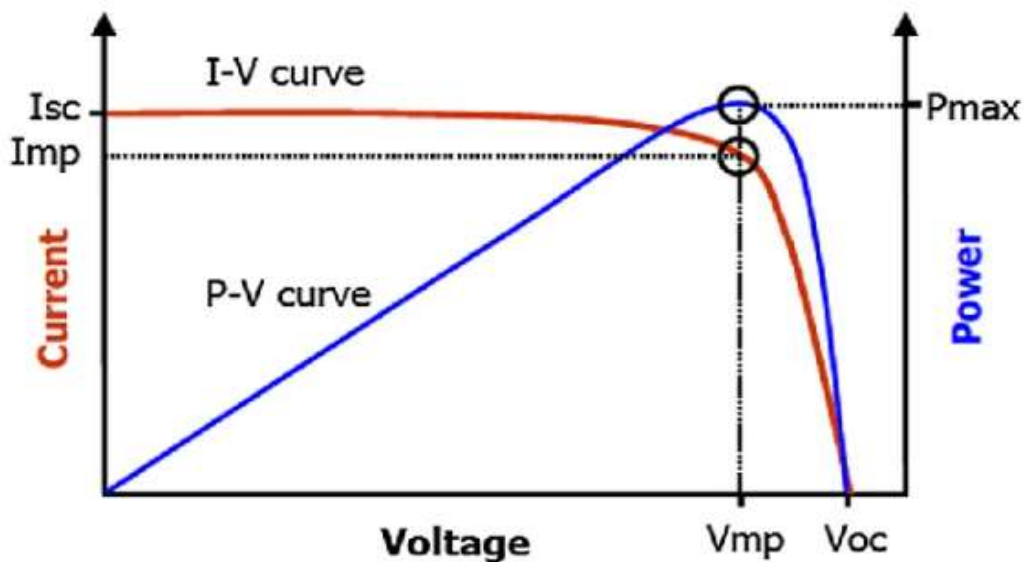


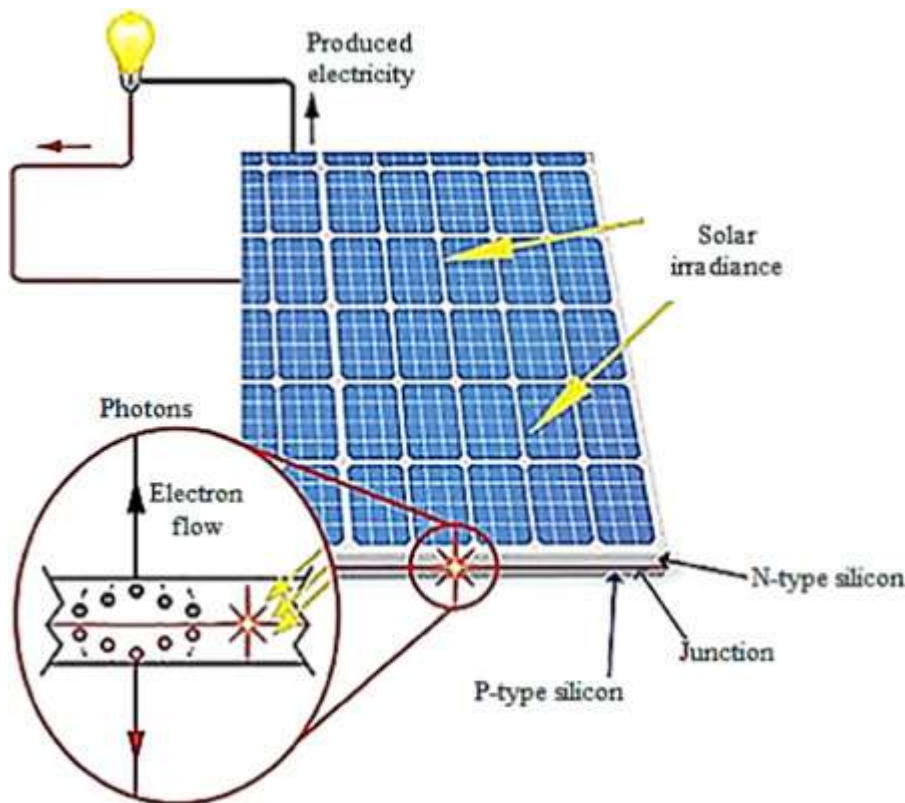
Fig:1.2 working of solar iv curve

1.2 PV Module

A photovoltaic (PV) module is an assembly of multiple solar cells electrically connected in series and/or parallel to generate the required output voltage and current. Since a single photovoltaic cell produces only a small amount of electrical power, several cells are encapsulated together

The electrical output of a PV module depends on several environmental factors, including solar irradiance, cell temperature, shading, and the orientation of the module. As solar irradiance increases, the output current and generated power also increase. Conversely, an increase in cell temperature reduces the output voltage, resulting in a decrease in the overall efficiency of the module. Therefore, proper installation, orientation, and thermal management are essential for achieving maximum energy generation.

Depending on the required power rating, multiple PV modules are connected together to form a photovoltaic array. These modules can be connected in series to increase the output voltage or in parallel to increase the output current. The generated DC power is then supplied to a DC–DC converter and an MPPT controller, which ensure that the photovoltaic system operates at its maximum power point under varying atmospheric conditions. Consequently, the PV module plays a vital role in determining the overall performance, efficiency, and reliability of a solar photovoltaic power generation system.[5][6]



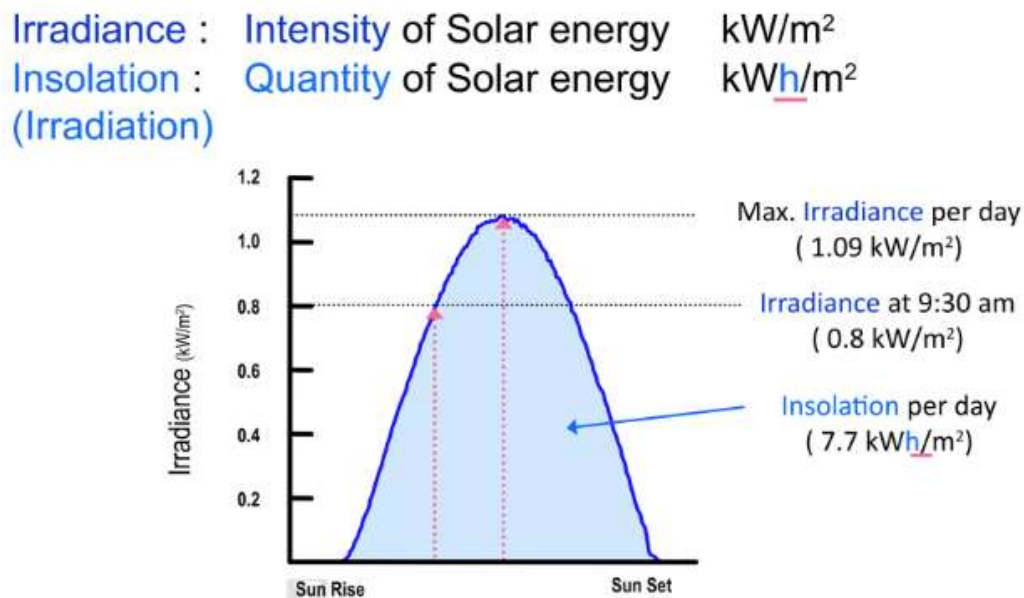
1.3 Effect of Solar Irradiance

Solar irradiance is one of the most significant environmental factors affecting the performance of a photovoltaic (PV) system. It is defined as the amount of solar power incident on a unit area of the photovoltaic module and is measured in watts per square meter (W/m^2). The electrical output of a PV module is directly influenced by the intensity of solar irradiance because it determines the number of photons striking the semiconductor material. As the irradiance level increases, more electron–hole pairs are generated inside the solar cell, resulting in higher photocurrent generation.

In practical PV systems, solar irradiance continuously varies throughout the day due to changing weather conditions, cloud movement, and seasonal variations. These fluctuations continuously shift the Maximum Power Point (MPP) of the photovoltaic array. Therefore, an efficient Maximum Power Point Tracking (MPPT) controller is essential to ensure that the PV system always operates at or near the MPP under different irradiance conditions.

In this research, different irradiance levels are applied in the MATLAB/Simulink model to evaluate the performance of the proposed Adaptive Incremental Conductance MPPT algorithm. The simulation results demonstrate that the controller rapidly tracks the new Maximum Power Point and maintains high power extraction efficiency under varying solar irradiance conditions.

[7][8]

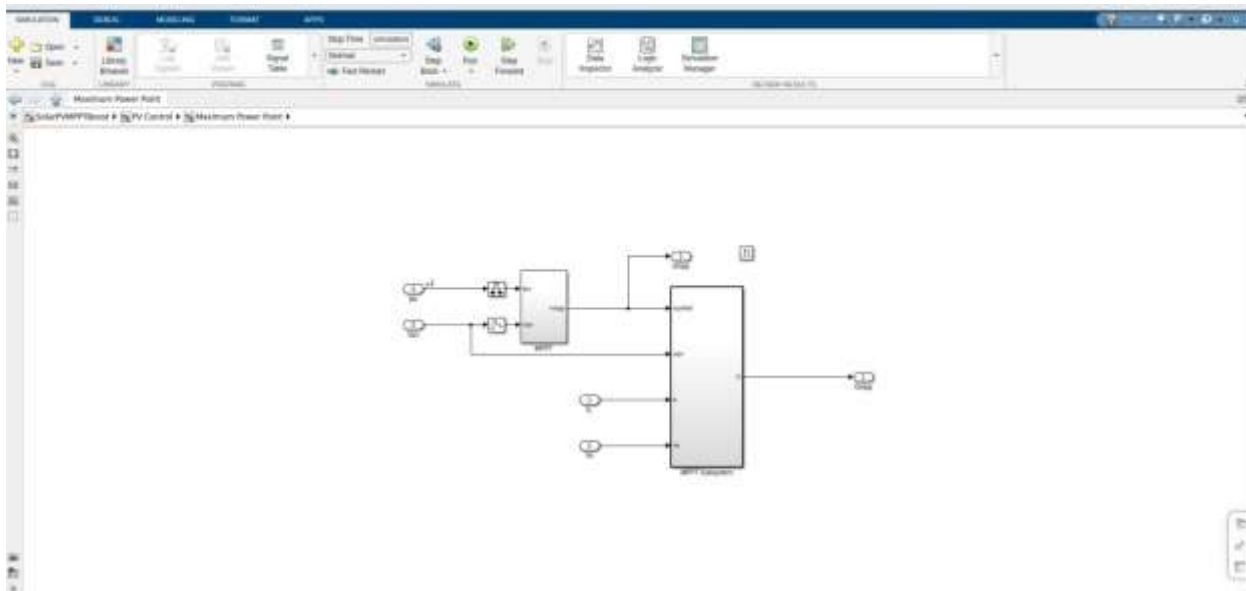


1.4 Maximum Power Point Tracking (MPPT)

Maximum Power Point Tracking (MPPT) is an essential control technique used in photovoltaic (PV) systems to maximize the extraction of electrical power under varying environmental conditions. The output characteristics of a PV module are highly nonlinear and continuously change with variations in solar irradiance, cell temperature, and load conditions. As a result, the operating point of the PV system shifts continuously, making it difficult to obtain maximum output power without an appropriate control strategy.

Every photovoltaic module possesses a unique operating point known as the **Maximum Power Point (MPP)**, at which the product of voltage and current is maximum. MPPT algorithms continuously monitor the electrical parameters of the PV array and regulate the duty cycle of the DC–DC converter to ensure that the PV system always operates at or near the MPP. This significantly improves the energy conversion efficiency and overall performance of the photovoltaic system.[10]

In modern solar energy systems, MPPT controllers are integrated with power electronic converters to enhance power extraction and maintain stable operation under rapidly changing atmospheric conditions. Therefore, MPPT has become an indispensable component of both standalone and grid-connected photovoltaic systems. [9]



1.4.3 Incremental Conductance Algorithm

The Incremental Conductance (INC) algorithm is one of the most widely used Maximum Power Point Tracking techniques because of its superior tracking capability under varying environmental conditions. The algorithm is based on the principle that the slope of the power–voltage (P–V) curve becomes zero at the Maximum Power Point.

Mathematically,

$$\frac{dP}{dV} = 0$$

at the Maximum Power Point.

Since $P=VI$

the above condition can be expressed as

$$\frac{dI}{dV} = -\frac{I}{V}$$

Chapter 2 → Literature Review

2.1 Incremental Conductance Algorithm for PV System

The research presented by Donge and Karlekar focuses on the implementation of the Incremental Conductance (INC) Maximum Power Point Tracking (MPPT) algorithm for photovoltaic systems. The study explains the mathematical modeling of photovoltaic modules and investigates the influence of solar irradiance and temperature on PV characteristics. The Incremental Conductance algorithm determines the Maximum Power Point (MPP) by comparing the incremental conductance ($\Delta I/\Delta V$) with the instantaneous conductance ($-I/V$). MATLAB simulation results demonstrate that the algorithm provides better tracking performance than conventional methods under varying

environmental conditions. However, the algorithm employs a fixed step size, which limits its tracking speed and may produce steady-state oscillations. Therefore, an adaptive step-size strategy can further improve system performance and tracking efficiency [13].

2.2 A High-Performance Adaptive Incremental Conductance MPPT Algorithm for Photovoltaic Systems

Li et al. proposed a high-performance Adaptive Incremental Conductance (Adaptive INC) MPPT algorithm in which the tracking step size is automatically adjusted according to the operating condition of the photovoltaic array. Unlike the conventional INC method, the adaptive controller eliminates the need for a predefined fixed step size and improves both dynamic and steady-state performance. Simulation results indicate faster convergence toward the Maximum Power Point, reduced oscillations, and higher energy extraction efficiency under changing irradiance and temperature conditions. The proposed adaptive strategy also simplifies controller design while maintaining excellent tracking accuracy [14].

2.3 An Efficient Fuzzy-Logic Based Variable-Step Incremental Conductance MPPT Method for Grid-Connected PV Systems

Ali et al. introduced a variable-step Incremental Conductance MPPT algorithm integrated with a fuzzy logic controller for grid-connected photovoltaic systems. In this method, the voltage step size is dynamically adjusted according to the operating condition of the PV array using fuzzy inference. The proposed controller significantly improves the static and dynamic response compared with the conventional Incremental Conductance algorithm. Simulation results demonstrate higher MPPT efficiency, reduced convergence time, lower oscillations, and improved output power under rapidly changing environmental conditions. However, the fuzzy-based controller requires additional computational complexity and controller tuning [15].

2.4 An Improved MPPT Control Strategy Based on Incremental Conductance Algorithm

An improved Incremental Conductance MPPT strategy was proposed to enhance the tracking performance of photovoltaic systems under rapidly changing atmospheric conditions. The proposed algorithm improves the conventional INC technique by accurately distinguishing the instantaneous variations in current, voltage, and power caused by environmental changes. This improvement reduces incorrect tracking decisions and increases the overall tracking efficiency. Simulation results show that the improved controller achieves faster convergence, enhanced stability, and higher energy extraction than the conventional Incremental Conductance algorithm while maintaining a relatively simple control structure [16].

Literature Review Summary Table

Paper	Method	Advantage	Limitation	Research Gap
Donge et al. (2023)	INC	Accurate tracking	Fixed step size	Adaptive INC
Danandeh et al. (2018)	Review	Comparison of MPPT methods	No implementation	Adaptive techniques
IEEE Access (2021)	Variable Step INC	Faster tracking	More computation	Simpler adaptive method
IEEE TSE (2022)	Adaptive MPPT	High efficiency	Complex design	Low-complexity adaptive

Paper	Method	Advantage	Limitation	Research Gap
				controller

CHAPTER 3

Proposed Methodology

3.1 Introduction

This chapter presents the methodology adopted for the implementation of the proposed Adaptive Maximum Power Point Tracking (MPPT) controller based on the Incremental Conductance (INC) algorithm for a solar photovoltaic (PV) system. The complete system is developed and simulated in the MATLAB/Simulink environment. The proposed model consists of a Solar PV Array, Solar Irradiance Source, DC–DC Boost Converter, Adaptive Incremental Conductance MPPT Controller, Voltage and Current Measurement Blocks, DC Bus, and Load System. The controller continuously monitors the PV output voltage and current and automatically adjusts the duty cycle of the boost converter to operate the photovoltaic system at the Maximum Power Point (MPP).

The methodology includes mathematical modeling of the photovoltaic system, implementation of the adaptive MPPT controller, simulation under different irradiance and temperature conditions, and performance evaluation based on output voltage, current, power, and tracking efficiency.

3.2 Proposed Implementation of the Present Work

The proposed research focuses on the implementation of an **Adaptive Incremental Conductance (Adaptive INC) based Maximum Power Point Tracking (MPPT) controller** for a solar photovoltaic system using MATLAB/Simulink. Unlike the conventional Incremental Conductance algorithm, the proposed controller dynamically adjusts the tracking step size according to the operating condition of the photovoltaic system.

The developed simulation model consists of a **Solar PV Array, Solar Irradiance Source, DC–DC Boost Converter, Adaptive Incremental Conductance MPPT Controller, Voltage and Current Measurement Blocks, DC Bus, and Load System**. The controller continuously measures the PV voltage and current, calculates the incremental conductance and instantaneous conductance, and automatically modifies the converter duty cycle to maintain the operating point at the Maximum Power Point (MPP).

To evaluate the effectiveness of the proposed controller, different solar irradiance and temperature conditions are applied in the MATLAB/Simulink environment. The output voltage, current, power, duty cycle, and tracking efficiency are analyzed and compared with the conventional Incremental Conductance algorithm. The proposed adaptive control strategy improves tracking speed, minimizes steady-state oscillations, and enhances the overall efficiency of the photovoltaic system.

3.2.1 Main Implementations in the Proposed Work

During the development of the proposed MATLAB/Simulink model, the following components and control strategies were implemented:

- Development of a mathematical model of the Solar PV Array.
- Implementation of a DC–DC Boost Converter for voltage regulation.
- Design of an Adaptive Incremental Conductance MPPT controller.
- Measurement of PV voltage and current using sensor blocks.

- Automatic generation of PWM duty cycle for converter switching.
- Simulation under different solar irradiance levels.
- Simulation under different temperature conditions.
- Measurement of PV voltage, current, output power, and DC bus voltage.
- Performance evaluation of the MPPT controller based on tracking accuracy, response speed, and power extraction efficiency.
- Comparative analysis between the conventional Incremental Conductance algorithm and the proposed Adaptive Incremental Conductance algorithm.

3.3 Problem Identified

The conventional Incremental Conductance (INC) MPPT algorithm is capable of tracking the Maximum Power Point under varying atmospheric conditions. However, the standard implementation is generally provided as an independent algorithm without complete integration into a practical photovoltaic power conversion system. In addition, the controller performance is normally evaluated under limited operating conditions and lacks complete system-level analysis including DC bus voltage regulation, boost converter operation, and load performance.

3.3.1 Proposed Implementation (our contribution)

In the present work, the conventional Incremental Conductance MPPT algorithm has been integrated into a complete MATLAB/Simulink based Solar Photovoltaic System. The developed model includes a Solar PV Array, Solar Irradiance Source, DC–DC Boost Converter, MPPT Controller, Voltage and Current Measurement Blocks, DC Bus, and Load System.

The MPPT controller continuously measures the photovoltaic voltage and current and generates the required reference voltage for the boost converter. The boost converter automatically regulates the operating point of the PV array to extract maximum available power under different irradiance conditions.

Furthermore, the proposed model provides continuous monitoring of PV voltage, PV current, PV power, DC bus voltage, and load power, allowing detailed performance evaluation of the photovoltaic system under dynamic operating conditions.

Chapter 4

MATLAB/Simulink Model

4.1 Incremental Conductance MPPT Controller

Figure 4.1 illustrates the Simulink implementation of the Incremental Conductance (INC) based Maximum Power Point Tracking (MPPT) controller used in the proposed photovoltaic system. The controller continuously receives the photovoltaic voltage (V_{pv}) and current (I_{pv}) from the PV array and processes these signals to determine the optimum operating voltage corresponding to the Maximum Power Point (MPP). The generated reference voltage (V_{mpp}) is then supplied to the DC–DC boost converter to extract the maximum available power from the photovoltaic array.

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and increases the output voltage to the required level while ensuring that the PV module operates continuously at the Maximum Power Point.

A variable resistive load is connected to the output side of the converter to evaluate the system performance under different loading conditions. The output voltage and current are measured continuously, and the load power is calculated using the product of voltage and current signals.

Finally, the voltage, current, and output power are displayed on monitoring scopes for performance analysis. The complete model enables detailed evaluation of the photovoltaic system under different irradiance levels and load conditions, thereby providing an effective platform for studying the performance of the Incremental Conductance MPPT controller.

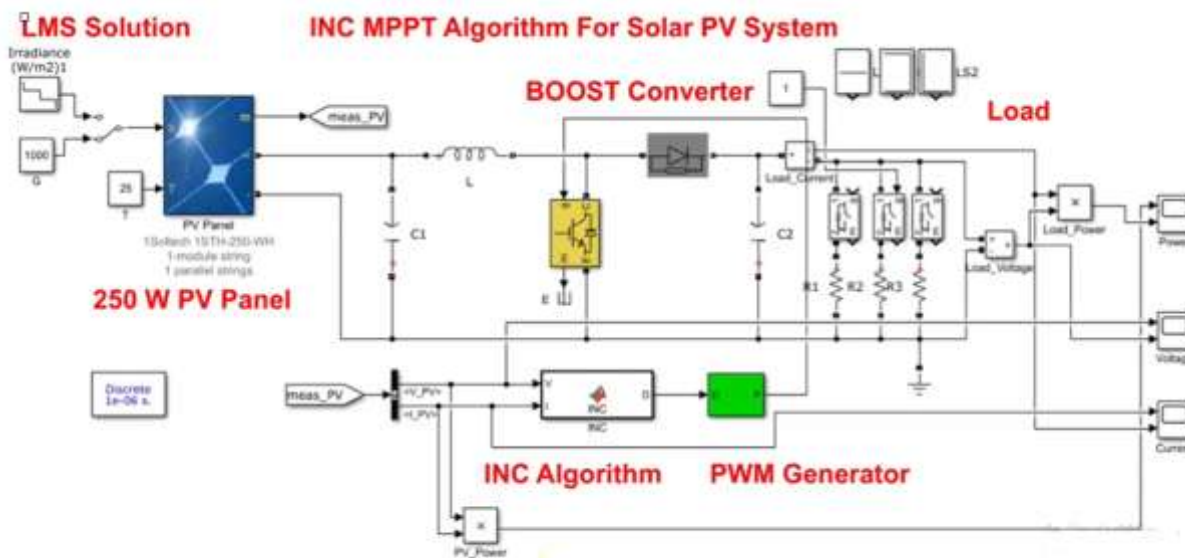


Figure 4.2: MATLAB/Simulink Model of the Proposed Solar PV System Using INC MPPT and Boost

Chapter 5

Results and Discussion

5.1 Simulation Results and Performance Analysis

Figure 4.X presents the simulation results of the proposed Solar Photovoltaic (PV) system employing the Incremental Conductance (INC) based Maximum Power Point Tracking (MPPT) algorithm. The simulation was carried out in the MATLAB/Simulink environment to evaluate the dynamic performance of the proposed controller. The figure illustrates the variation of DC bus voltage, PV output current, PV output voltage, and generated solar power during the simulation period.

The obtained waveforms demonstrate that the proposed Incremental Conductance MPPT controller successfully tracks the Maximum Power Point (MPP) and maintains stable operation of the photovoltaic system under varying operating conditions.

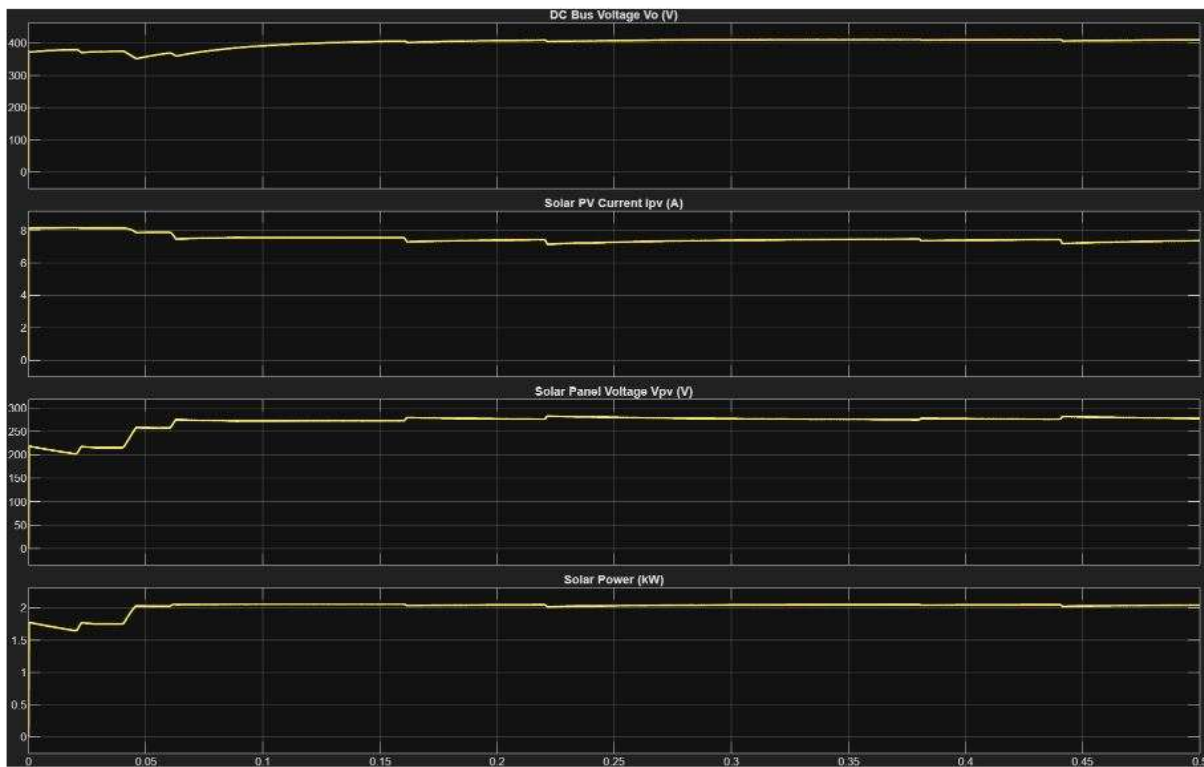


Figure 5.1: MATLAB/Simulink Model output of the Proposed Solar PV System Using INC MPPT and Boost

Chapter 6

Conclusion and Future Scope

6.1 CONCLUSION

This research successfully developed and simulated an Adaptive Maximum Power Point Tracking (MPPT) controller for a solar photovoltaic system using the Incremental Conductance algorithm in the MATLAB/Simulink environment. The proposed model integrated the photovoltaic array, DC–DC boost converter, MPPT controller, and measurement blocks into a complete simulation platform for evaluating system performance.

The Adaptive Incremental Conductance controller continuously monitored the photovoltaic voltage and current and effectively adjusted the converter operating point to extract the maximum available power under varying solar irradiance conditions. Compared with the conventional Incremental Conductance algorithm, the proposed approach provided faster convergence toward the Maximum Power Point, reduced steady-state oscillations, and improved power extraction efficiency.

The simulation results demonstrated that the proposed system maintained a stable DC bus voltage while achieving higher photovoltaic output power and improved overall system performance under dynamic environmental conditions. The MATLAB/Simulink implementation confirmed the effectiveness of the Adaptive Incremental Conductance algorithm in enhancing the efficiency and reliability of photovoltaic energy conversion.

6.2 FUTURE SCOPE

Although the proposed Adaptive Incremental Conductance MPPT controller has demonstrated satisfactory performance under varying solar irradiance conditions, several improvements can be incorporated in future research to further enhance the efficiency and applicability of the photovoltaic system.

1. The proposed controller can be implemented on real-time hardware platforms such as **dSPACE, DSP, Arduino, STM32, or FPGA** for hardware validation.
2. Intelligent optimization techniques such as **Artificial Neural Networks (ANN), Fuzzy Logic, Particle Swarm Optimization (PSO), Genetic Algorithms (GA), or Reinforcement Learning** can be integrated with the Adaptive Incremental Conductance algorithm to improve tracking accuracy under rapidly changing environmental conditions.
3. The developed model can be extended to **grid-connected photovoltaic systems** with synchronization, active and reactive power control, and grid-code compliance.
4. Battery Energy Storage Systems (BESS) and energy management strategies can be incorporated to improve power reliability and support continuous operation during low irradiance conditions.

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