Design And Simulation of A PV Solar MPPT System

Project Report submitted in partial fulfillment of
The requirements for the degree of

BACHELOR OF TECHNOLOGY

In

ELECTRICAL ENGINEERING

Of

MAULANA ABUL KALAM AZAD UNIVERSITY OF TECHNOLOGY

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TECHNO CITY, GARIA, KOLKATA – 700152

2024-25

CERTIFICATE

This is to certify that this project report titled **PV Solar MPPT System** submitted in partial fulfillment of requirements for award of the degree Bachelor of Technology (B. Tech) in Electrical Engineering of West Bengal University of Technology is a faithful record of the original work carried out by,

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under my guidance and supervision.

It is further certified that it contains no material, which to a substantial extent has been submitted for the award of any degree/diploma in any institute or has been published in any form, except the assistances drawn from other sources, for which due acknowledgement has been made.

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DECLARATION

We hereby declare that this project report titled

Design And Simulation of A PV Solar MPPT System

Is our own original work carried out as a under graduate student in Netaji Subhash Engineering College except to the extent that assistances from other sources are duly acknowledged.

All sources used for this project report have been fully and properly cited. It contains no material which to a substantial extent has been submitted for the award of any degree/diploma in any institute or has been published in any form, except where due acknowledgement is made.

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Abstract

This project focuses on designing and simulating a **solar power system** using **Maximum Power Point Tracking (MPPT)** to improve its efficiency. Solar panels generate electricity from sunlight, but their power output changes with the weather, time of day, and temperature. To solve this problem and ensure that the solar panel always gives the **maximum possible power**, we use an MPPT technique.

The entire system is created and tested using **MATLAB/Simulink**. A **PV (photovoltaic) panel model** is built, along with a **DC-DC boost converter** and an **MPPT controller**. The MPPT controller uses the **Perturb and Observe (P&O)** method, which keeps adjusting the system to find the point where power output is highest, known as the **Maximum Power Point (MPP)**.

Through simulation, we observed that the system with MPPT gives **much better performance** than one without it. It helps in improving power output and overall system efficiency. This type of system is very useful for generating **clean and reliable energy**, especially in areas where power supply is limited or unstable. This project shows how simulation tools like MATLAB can help design smart and effective solar energy systems for real-world use.

CONTENTS

TITLE – Design And Implementation of A MPPT-Based Solar PV Energy System.

Objective - To design and simulate a solar photovoltaic system integrated with an MPPT controller using MATLAB. It aims to ensure maximum power extraction under varying solar conditions, improve system efficiency, and analyze the performance of the MPPT algorithm through accurate modeling and simulation.

- **Challenge faced during the project work?**

During the project, key challenges included modeling the PV system accurately in MATLAB, implementing and tuning the MPPT algorithm, and simulating real-time environmental variations. Ensuring algorithm stability, handling convergence issues, and optimizing performance under dynamic conditions required iterative testing, debugging, and a deep understanding of simulation tools and solar behavior.

1.Introduction

1.1 The need for Renewable Energy

Renewable energy is the energy which comes from natural resources such as sunlight, wind, rain, tides and geothermal heat. These resources are renewable and can be naturally replenished. Therefore, for all practical purposes, these resources can be considered to be inexhaustible, unlike dwindling conventional fossil fuels. The global energy crunch has provided a renewed impetus to the growth and development of Clean and Renewable Energy sources. Clean Development Mechanisms (CDMs) are being adopted by organizations all across the globe.

Apart from the rapidly decreasing reserves of fossil fuels in the world, another major factor working against fossil fuels is the pollution associated with their combustion. Contrastingly, renewable energy sources are known to be much cleaner and produce energy without the harmful effects of pollution unlike their conventional counterparts.

1.1 Different sources of Renewable Energy

1.1.1 Wind power

Wind turbines can be used to harness the energy available in airflows. Current day turbines range from around 600 kW to 5 MW of rated power. Since the power output is a function of the cube of the wind speed, it increases rapidly with an increase in available wind velocity. Recent advancements have led to airfoil wind turbines, which are more efficient due to a better aerodynamic structure.

1.1.2 Solar power

The tapping of solar energy owes its origins to the British astronomer John Herschel who famously used a solar thermal collector box to cook food during an expedition to Africa. Solar energy can be utilized in two major ways. Firstly, the captured heat can be used as solar thermal energy, with applications in space heating. Another alternative is the conversion of incident solar radiation to electrical energy, which is the most usable for of energy. This can be achieved with the help of solar photovoltaic cells or with concentrating solar power plants.

1.1.2 Small hydropower

Hydropower installations up to 10MW are considered as small hydropower and counted as renewable energy sources. These involve converting the potential energy of water stored in dams into usable electrical energy through the use of water turbines. Run-of-the-river hydroelectricity aims to utilize the kinetic energy of water without the need of building reservoirs or dams.

1.1.3 Biomass

Plants capture the energy of the sun through the process of photosynthesis. On combustion, these plants release the trapped energy. This way, biomass works as a natural battery to store the sun's energy and yield it on requirement.

1.1.4 Geothermal

Geothermal energy is the thermal energy which is generated and stored within the layers of the Earth. The gradient thus developed gives rise to a continuous conduction of heat from the core to the surface of the earth. This gradient can be utilized to heat water to produce superheated steam and use it to run steam turbines to generate electricity. The main disadvantage geothermal energy is that it is usually limited to regions near tectonic plate boundaries, though recent advancements have led to the propagation of this technology.

1.2 Renewable Energy trends across the globe

The current trend across developed economies tips the scale in favour of Renewable Energy. For the last three years, the continents of North America and Europe have embraced more renewable power capacity as compared to conventional power capacity. Renewables accounted for 60% of the newly installed power capacity in Europe in 2009 and nearly 20% of the annual power production.

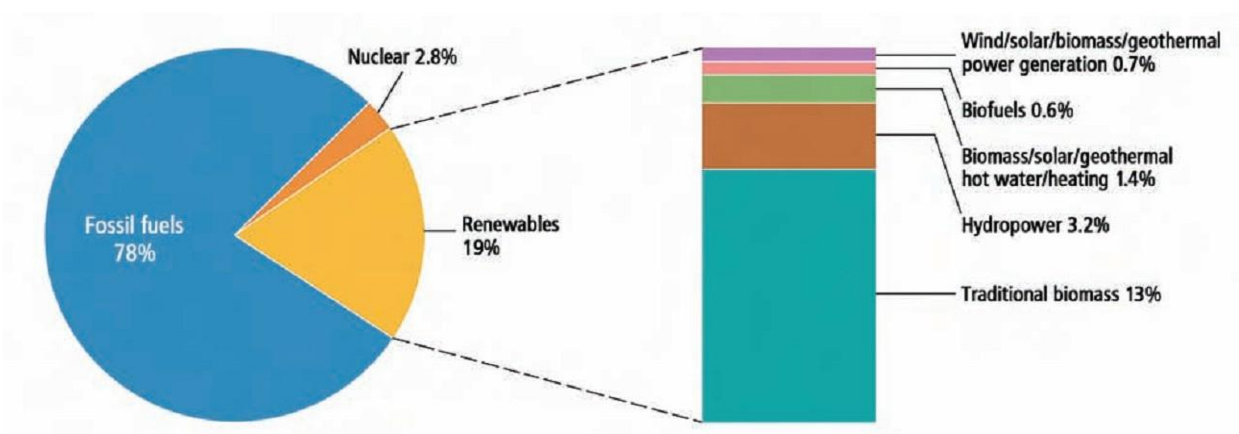


Figure 1.1 : Global energy consumption in the year 2008

As can be seen from the figure 1.1, wind and biomass occupy a major share of the current renewable energy consumption. Recent advancements in solar photovoltaic technology and constant incubation of projects in countries like Germany and Spain have brought around tremendous growth in the solar PV market as well, which is projected to surpass other renewable energy sources in the coming years. By 2009, more than 85 countries had some policy target to achieve a predetermined share of their power capacity through renewables. This was an increase from around 45 countries in 2005. Most of the targets are also very ambitious, landing in the range of 30-90% share of national production through renewables. Noteworthy policies are the European Union's target of achieving 20% of total energy through renewables by 2020 and India's Jawaharlal Nehru Solar Mission, through which India plans to produce 20GW solar energy by the year 2022.

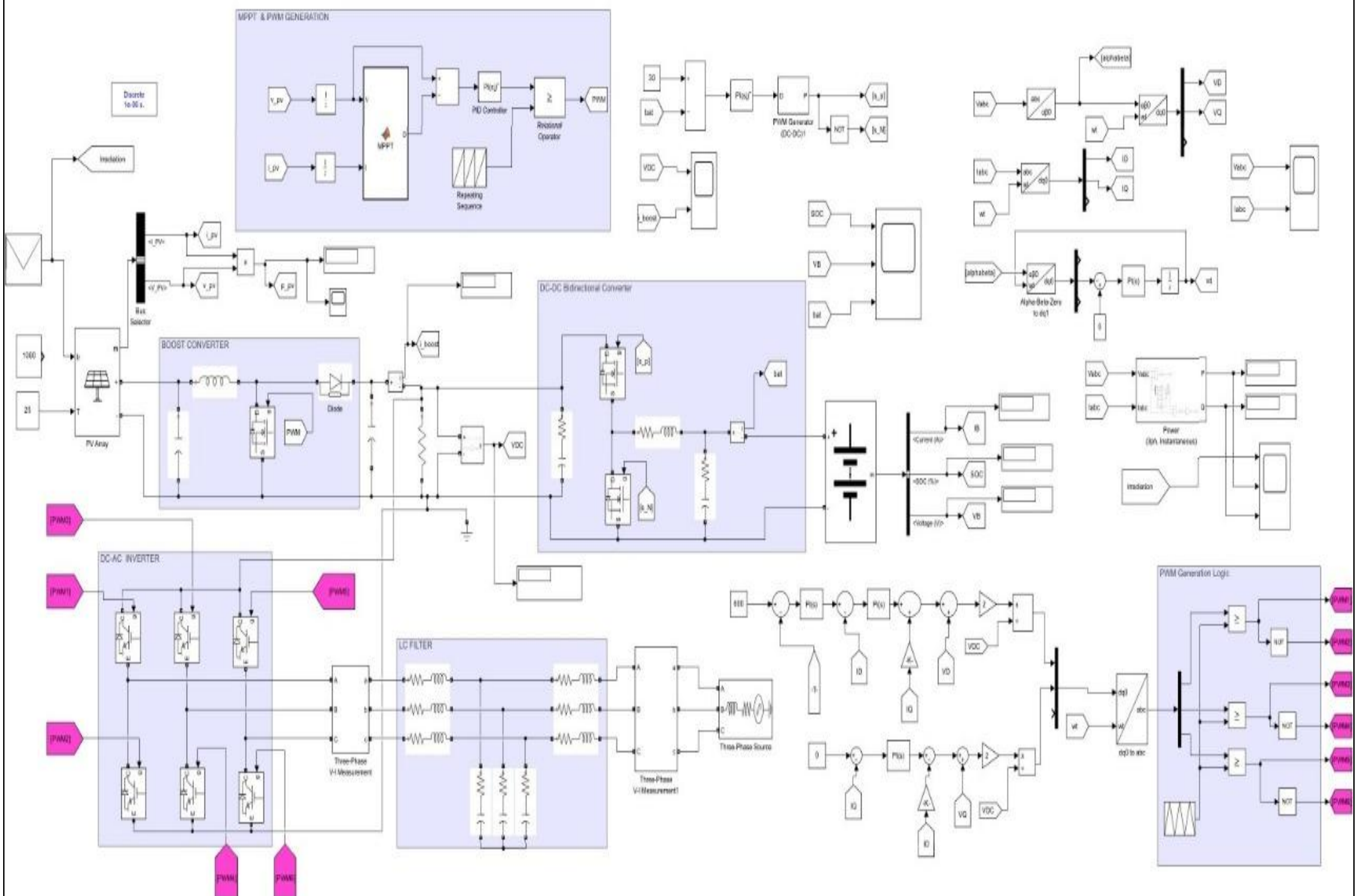
Chapter 2

❖ Literature review.

Studies show that a solar panel converts 30-40% of energy incident on it to electrical energy. A Maximum Power Point Tracking algorithm is necessary to increase the efficiency of the solar panel. There are different techniques for MPPT such as Perturb and Observe (hill climbing method), Incremental conductance, Fractional Short Circuit Current, Fractional Open Circuit Voltage, Fuzzy Control, Neural Network Control etc. Among all the methods Perturb and observe (P&O) and Incremental conductance are most commonly used because of their simple implementation, lesser time to track the MPP and several other economic reasons. Under abruptly changing weather conditions (irradiance level) as MPP changes continuously, P&O takes it as a change in MPP due to perturbation rather than that of irradiance and sometimes ends up in calculating wrong MPP. However, this problem gets avoided in Incremental Conductance method as the algorithm takes two samples of voltage and current to calculate MPP. However, instead of higher efficiency the complexity of the algorithm is very high compared to the previous one and hence the cost of implementation increases. So, we have to mitigate with a trade-off between complexity and efficiency. It is seen that the efficiency of the system also depends upon the converter. Typically, it is maximum for a buck topology, then for buck-boost topology and minimum for a boost topology. When multiple solar modules are connected in parallel, another analog technique TEODI is also very effective which operates on the principle of equalization of output operating points in correspondence to force displacement of input operating points of the identical operating system

Chapter 3

❖ Design And Simulation Circuit Diagram



- ❖ Description of the different components used in this project work.

Components:

- ❑ Solar Photovoltaic (PV) Panel
- ❑ Maximum Power Point Tracking (MPPT) Controller
- ❑ 3.DC-DC Converter (Buck, Boost, or Buck-Boost)
- ❑ 4.Battery Energy Storage System
- ❑ 5.Bidirectional DC-DC Converter
- ❑ 6.DC-AC inverter
- ❑ 8. (AC) Load

Photovoltaic cell

3.1 Photovoltaic cell

A photovoltaic cell or photoelectric cell is a semiconductor device that converts light to electrical energy by photovoltaic effect. If the energy of photon of light is greater than the band gap then the electron is emitted and the flow of electrons creates current.

However, a photovoltaic cell is different from a photodiode. In a photodiode light falls on n- channel of the semiconductor junction and gets converted into current or voltage signal but a photovoltaic cell is always forward biased.

3.2 PV module

Usually, a number of PV modules are arranged in series and parallel to meet the energy requirements. PV modules of different sizes are commercially available (generally sized from 60W to 170W). For example, a typical small scale desalination plant requires a few thousand watts of power.

3.3 PV modeling

A PV array consists of several photovoltaic cells in series and parallel connections. Series connections are responsible for increasing the voltage of the module whereas the parallel connection is responsible for increasing the current in the array.

Typically, a solar cell can be modeled by a current source and an inverted diode connected in parallel to it. It has its own series and parallel resistance.

Series resistance is due to hindrance in the path of flow of electrons from n to p junction and parallel resistance is due to the leakage current.

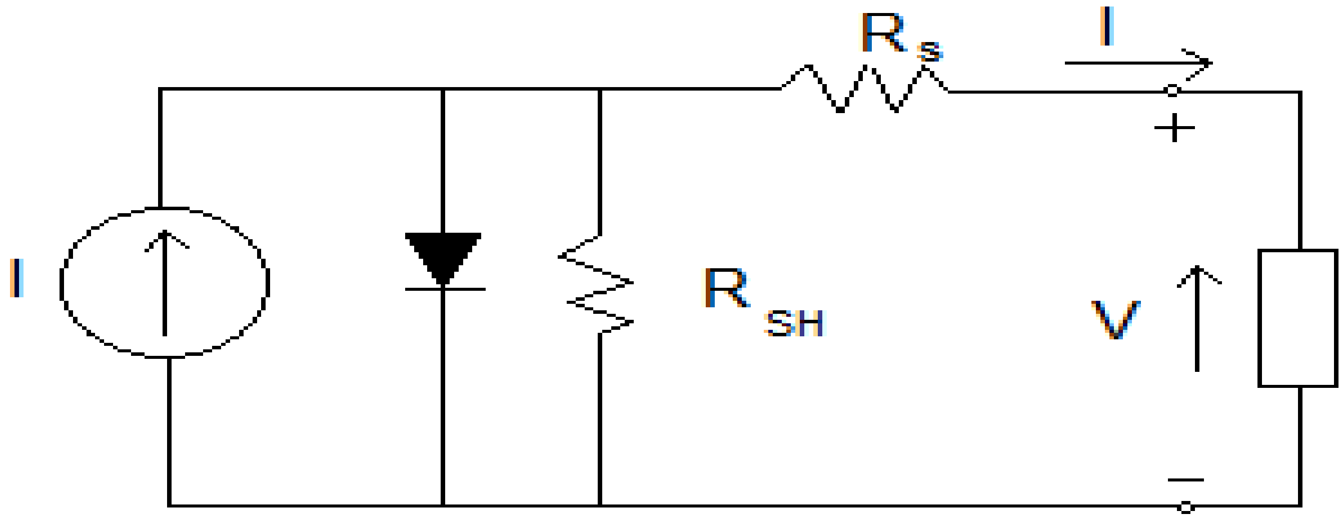


Figure 3.1: Single diode model of a PV cell

In this model we consider a current source (I) along with a diode and series resistance (R_s). The shunt resistance (R_{SH}) in parallel is very high, has a negligible effect and can be neglected.

The output current from the photovoltaic array is

$$I = I_{sc} - I_d \qquad (3.1)$$

$$I_d = I_o (e^{qV_d/kT} - 1) \qquad (3.2)$$

where I_o is the reverse saturation current of the diode, q is the electron charge, V_d is the voltage across the diode, k is Boltzmann constant (1.38 * 10^{-19} J/K) and T is the junction temperature in Kelvin (K)

From eq. 3.1 and 3.2

$$\mathbf{I = I_{sc} - I_o\,(e^{qV}d/kT - 1)} \qquad \mathbf{(3.3)}$$

Using suitable approximations,

$$\mathbf{I = Isc - Io\,(eq((V+IRs)/nkT) - 1)} \qquad \mathbf{(3.4)}$$

where, I is the photovoltaic cell current, V is the PV cell voltage, T is the temperature (in Kelvin) and n is the diode ideality factor

In order to model the solar panel accurately we can use two diode model but in our project our scope of study is limited to the single diode model. Also, the shunt resistance is very high and can be neglected during the course of our study.

PV Pannel Block Use Parameters

PARAMETER	VALUE
Open Circuit Voltage	37.3V
Short Circuit Current	8.21A
Max Current (imp)	8.13A
Max Voltage (vmp)	30.7V
Series Module	2
Parallel Strings	2
Total Power	1kw (approx..)
Irradiance input	1000 w/m2
Temperature input	25 degree celcius

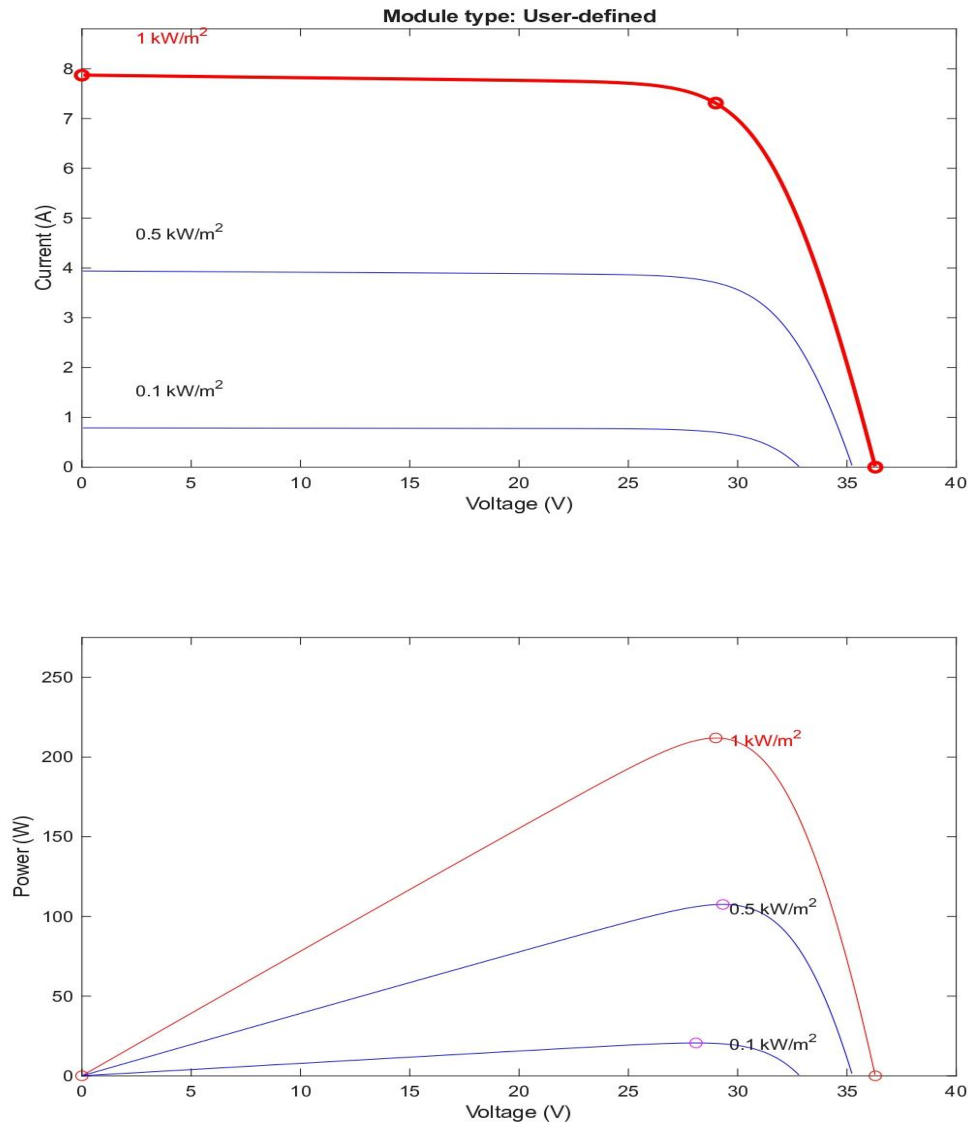


Figure 3.2 I-V characteristics of a solar panel

The I-V characteristics of a typical solar cell are as shown in the Figure 3.2. When the voltage and the current characteristics are multiplied, we get the P-V characteristics as shown in Figure 3.3. The point indicated as MPP is the point at which the panel power output is maximum.

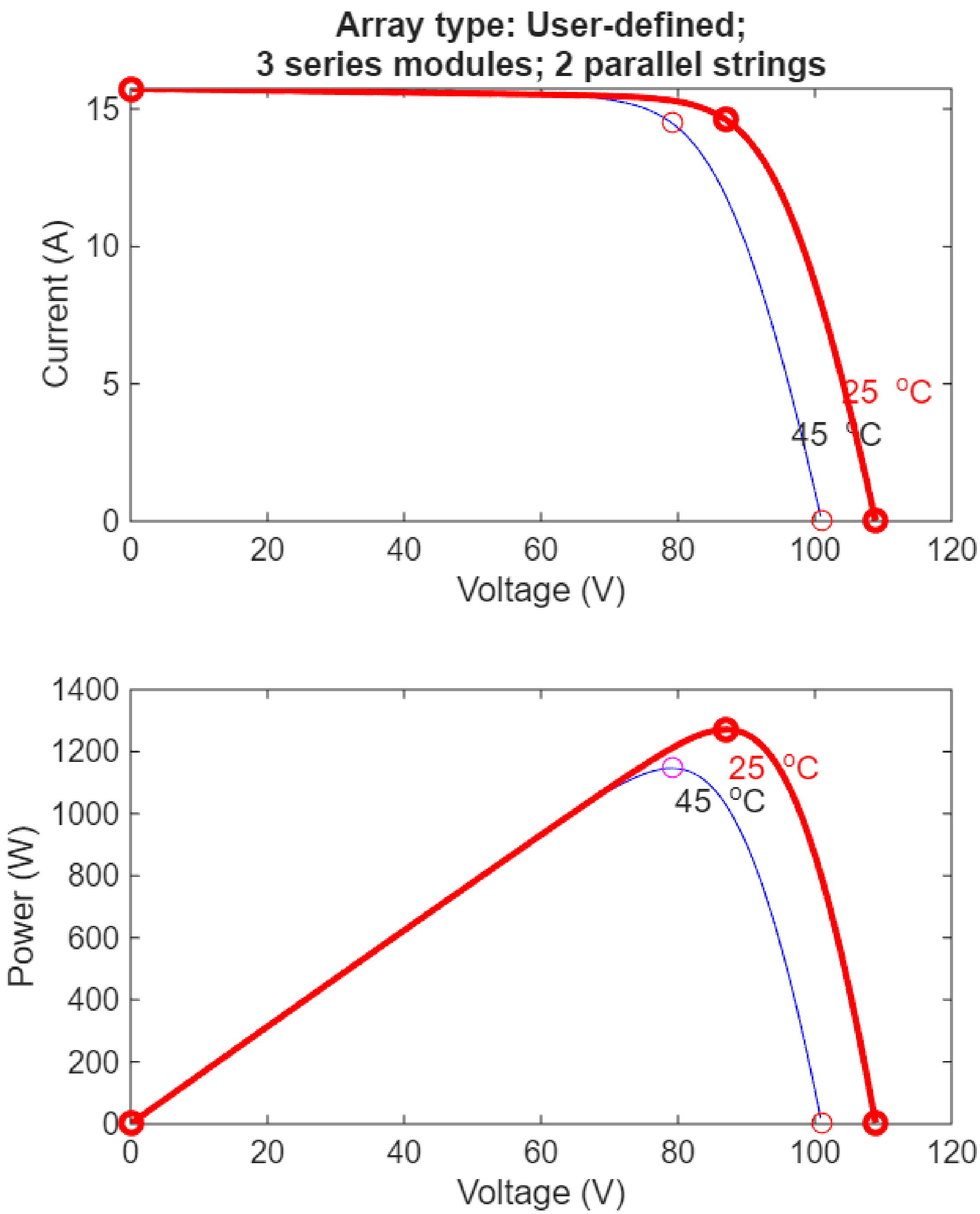


Figure 3.3 : P-V characteristics curve of photovoltaic cell

3.4 Boost Converter

As stated in the introduction, the maximum power point tracking is basically a load matching problem. In order to change the input resistance of the panel to match the load resistance (by varying the duty cycle), a DC -to- DC converter is required.

It has been studied that the efficiency of the DC -to- DC converter is maximum for a buck converter, then for a buck-boost converter and minimum for a boost converter but as we intend to use our system either for tying to a grid or for a water pumping system which requires 230 V at the output end, so we use a boost converter.

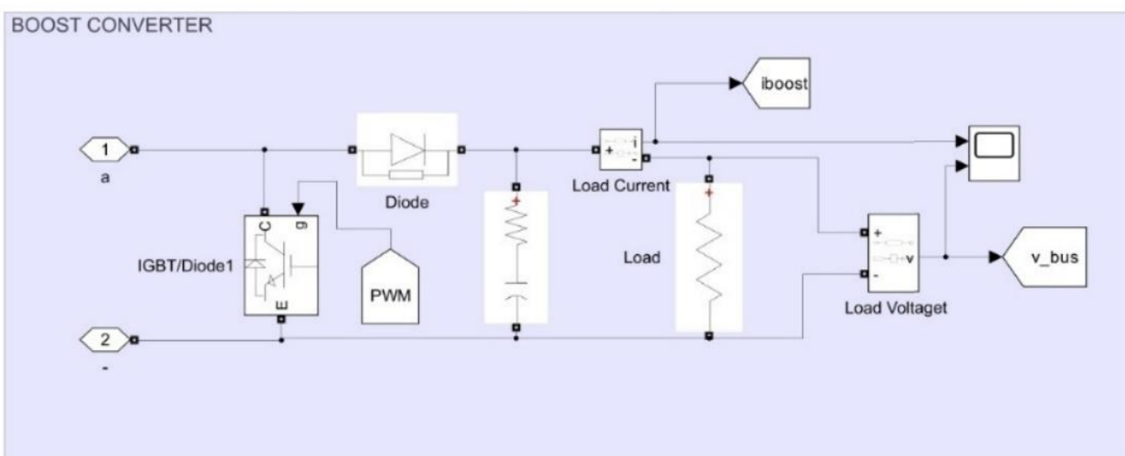


Figure 3.4 Circuit diagram of a Boost Converter

Parameter of Boost Converter Block

Component	Value
Inductor (L)	2mH
Output Capacitor	1000uf
Switching Frequency	50 Hz
Output Voltage	~120V
MOSFET Rating	200V,20V
Diode Rating	200V,20V

3.4.1 Mode 1 operation of the Boost Converter

When the switch is closed the inductor gets charged through the battery and stores the energy. In this mode inductor current rises (exponentially) but for simplicity we assume that the charging and the discharging of the inductor are linear. The diode blocks the current flowing and so the load current remains constant which is being supplied due to the discharging of the capacitor.

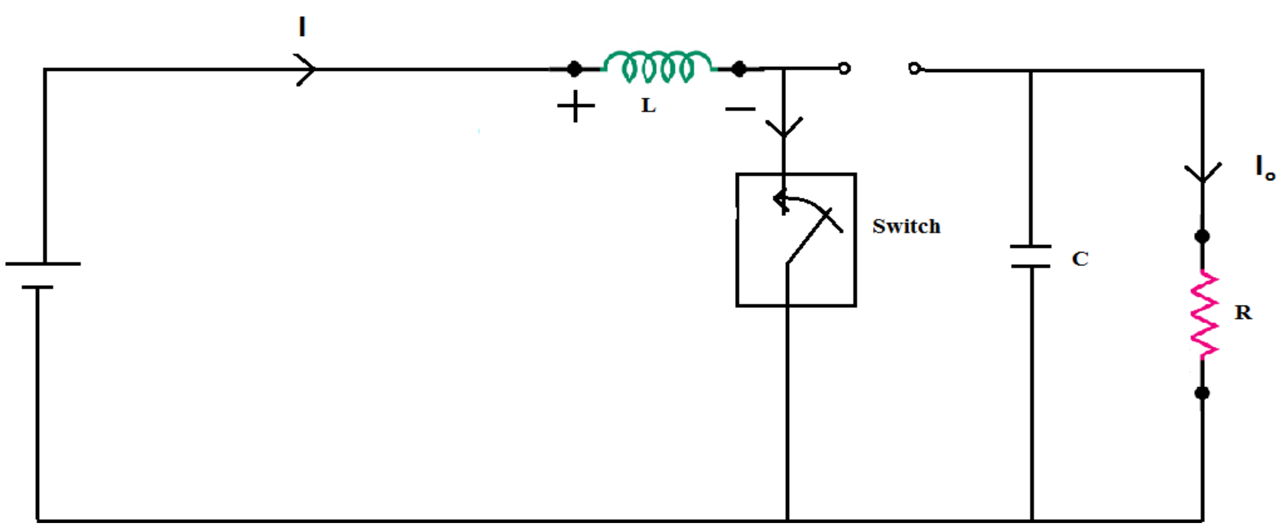
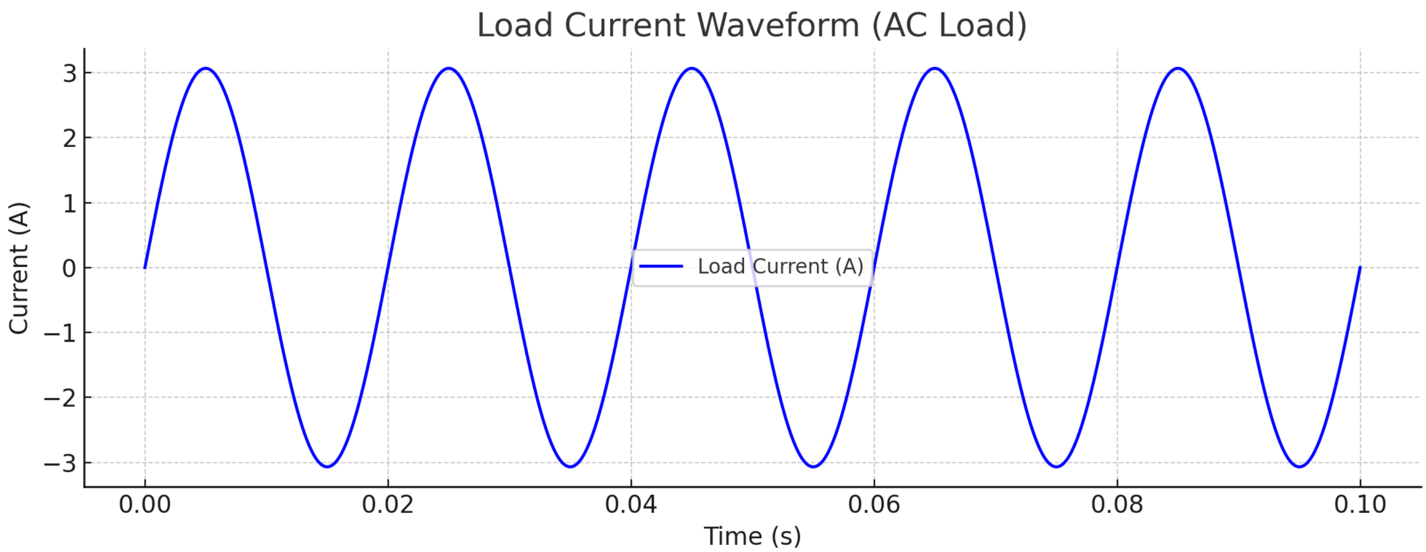


Figure 3.5 : Mode 1 operation of Boost Converter

3.4.2 Mode 2 operation of the Boost Converter

In mode 2 the switch is open and so the diode becomes short circuited. The energy stored in the inductor gets discharged through opposite polarities which charge the capacitor. The load current remains constant throughout the operation.



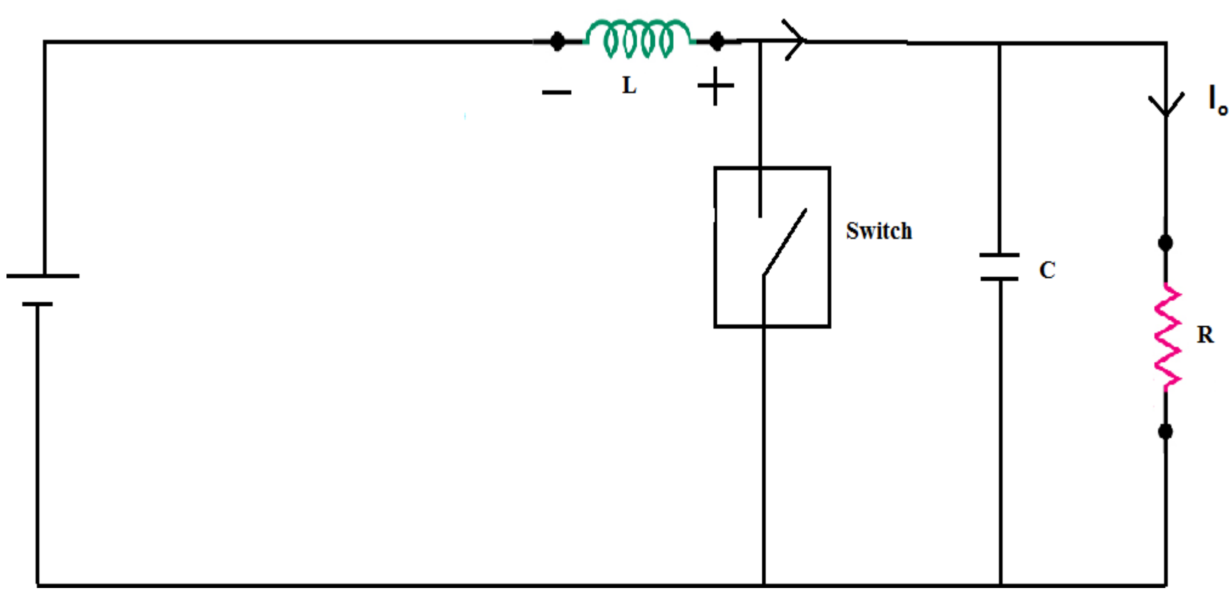


Figure 3.6 : Mode 2 operation of Boost Converte

4.Maximum Power Point Tracking Algorithms

4.1 An overview of Maximum Power Point Tracking

A typical solar panel converts only 30 to 40 percent of the incident solar irradiation into electrical energy. Maximum power point tracking technique is used to improve the efficiency of the solar panel.

According to Maximum Power Transfer theorem, the power output of a circuit is maximum when the Thevenin impedance of the circuit (source impedance) matches with the load impedance. Hence our problem of tracking the maximum power point reduces to an impedance matching problem.

In the source side we are using a boost convertor connected to a solar panel in order to enhance the output voltage so that it can be used for different applications like motor load. By changing the duty cycle of the boost converter appropriately we can match the source impedance with that of the load impedance.

4.2 Different MPPT techniques

There are different techniques used to track the maximum power point. Few of the most popular techniques are:

- Perturb and Observe (hill climbing method)
- Incremental Conductance method
- Fractional short circuit current
- Fractional open circuit voltage
- Neural networks
- Fuzzy logic

- The choice of the algorithm depends on the time complexity the algorithm takes to track the MPP, implementation cost and the ease of implementation

4.2.1 Perturb & Observe

Perturb & Observe (P&O) is the simplest method. In this we use only one sensor, that is the voltage sensor to sense the PV array voltage and so the cost of implementation is less and hence easy to implement. The time complexity of this algorithm is very less but on reaching very close to the MPP it doesn’t stop at the MPP and keeps on perturbing on both the directions. When this happens the algorithm has reached very close to the MPP and we can set an appropriate error limit or can use a wait function which ends up increasing the time complexity of the algorithm.

However, the method does not take account of the rapid change of irradiation level (due to which MPPT changes) and considers it as a change in MPP due to perturbation and ends up calculating the wrong MPP. To avoid this problem, we can use incremental conductance metho

4.2.2 Incremental Conductance

Incremental conductance method uses two voltage and current sensors to sense the output voltage and current of the PV array.

At MPP the slope of the PV curve is 0.

$$(dP/dV)_{MPP}=d(VI)/dV \tag{4.1}$$

$$0=I+VdI/dV_{MPP} \tag{4.2}$$

$$dI/dV_{MPP} = - I/V \tag{4.3}$$

The left - hand side is the instantaneous conductance of the solar panel. When this instantaneous conductance equals the conductance of the solar then MPP is reached.

Here we are sensing both the voltage and current simultaneously. Hence the error due to change in irradiance is eliminated. However, the complexity and the cost of implementation increase

As we go down the list of algorithms the complexity and the cost of implementation goes on increasing which may be suitable for a highly complicated system. This is the reason that Perturb and Observe and Incremental Conductance method are the most widely used algorithms.

Owing to its simplicity of implementation we have chosen the Perturb & Observe algorithm for our study among the two.

4.2.3 Fractional open circuit voltage

The near linear relationship between V_{MPP} and V_{OC} of the PV array, under varying irradiance and temperature levels, has given rise to the fractional V_{OC} method.

$$V_{MPP} = k_1 V_{oc} \tag{4.4}$$

where k_1 is a constant of proportionality. Since k_1 is dependent on the characteristics of the PV array being used, it usually has to be computed beforehand by empirically determining V_{MPP} and V_{OC} for the specific PV array at different irradiance and temperature levels. The factor k_1 has been reported to be between 0.71 and 0.78. Once k_1 is known, V_{MPP} can be computed with V_{OC} measured periodically by momentarily shutting down the power converter. However, this incurs some disadvantages, including temporary loss of power.

4.2.4 Fractional short circuit current

Fractional I_{SC} results from the fact that, under varying atmospheric conditions, I_{MPP} is approximately linearly related to the I_{SC} of the PV array.

$$I_{MPP} = k_2 I_{sc} \quad (4.5)$$

where k_2 is a proportionality constant. Just like in the fractional V_{OC} technique, k_2 has to be determined according to the PV array in use. The constant k_2 is generally found to be between
0.78 and 0.92. Measuring I_{SC} during operation is problematic. An additional switch usually has to be added to the power converter to periodically short the PV array so that ISC can be measured using a current sensor.

4.2.5 Fuzzy Logic Control

Microcontrollers have made using fuzzy logic control popular for MPPT over last decade. Fuzzy logic controllers have the advantages of working with imprecise inputs, not needing an accurate mathematical model, and handling nonlinearity.

4.2.6 Neural Network

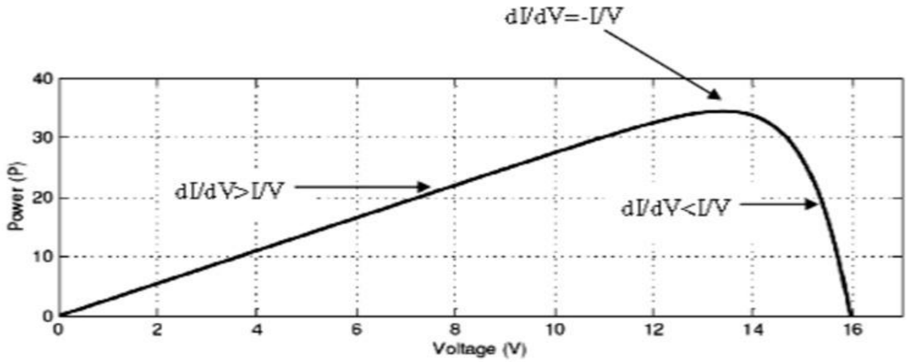
Another technique of implementing MPPT which are also well adapted for microcontrollers is neural networks. Neural networks commonly have three layers: input, hidden, and output layers. The number nodes in each layer vary and are user-dependent. The input variables can be PV array parameters like V_{OC} and I_{SC}, atmospheric data like irradiance and temperature, or any combination of these. The output is usually one or several reference signals like a duty cycle signal used to drive the power converter to operate at or close to the MPP [15].

Table 1 : Characteristics of different MPPT technique

MPPT technique	**Convergence speed**	**Implementation complexity**	**Periodic tuning**	**Sensed parameters**
Perturb & observe	Varies	Low	No	Voltage
Incremental conductance	Varies	Medium	No	Voltage, current
Fractional V_{oc}	Medium	Low	Yes	Voltage
Fractional I_{sc}	Medium	Medium	Yes	Current
Fuzzy logic control	Fast	High	Yes	Varies
Neural network	Fast	High	Yes	Varies

3.4 Incremental Conductance Method.

- Computes the maximum power point by comparison of the incremental conductance (di/ dv) to the module conductance (I / V). When these two are the same (I / V = di / dv), the output voltage is the MPP voltage.
- The controller maintains this voltage until the irradiation changes and the process is repeated.
- Can determine the maximum power point without oscillating around this value.
- It can perform maximum power point tracking under rapidly varying irradiation conditions with higher accuracy than the perturb and observe method.
- In this method we use two current and voltage sensors to sense output current and voltage of PV module.
- Good This Algorithm Has Advantages Over P&O:
- That It Can Determine When the MPPT has reached the MPP, where P&O Oscillates around the MPP.
- Also, Incremental Conductance Can Track Rapidly Increasing and Decreasing Irradiance Conditions with Higher Accuracy Than P And O.
- response under rapid environment change conditions.



Graph Power versus Voltage for IC Algorithm

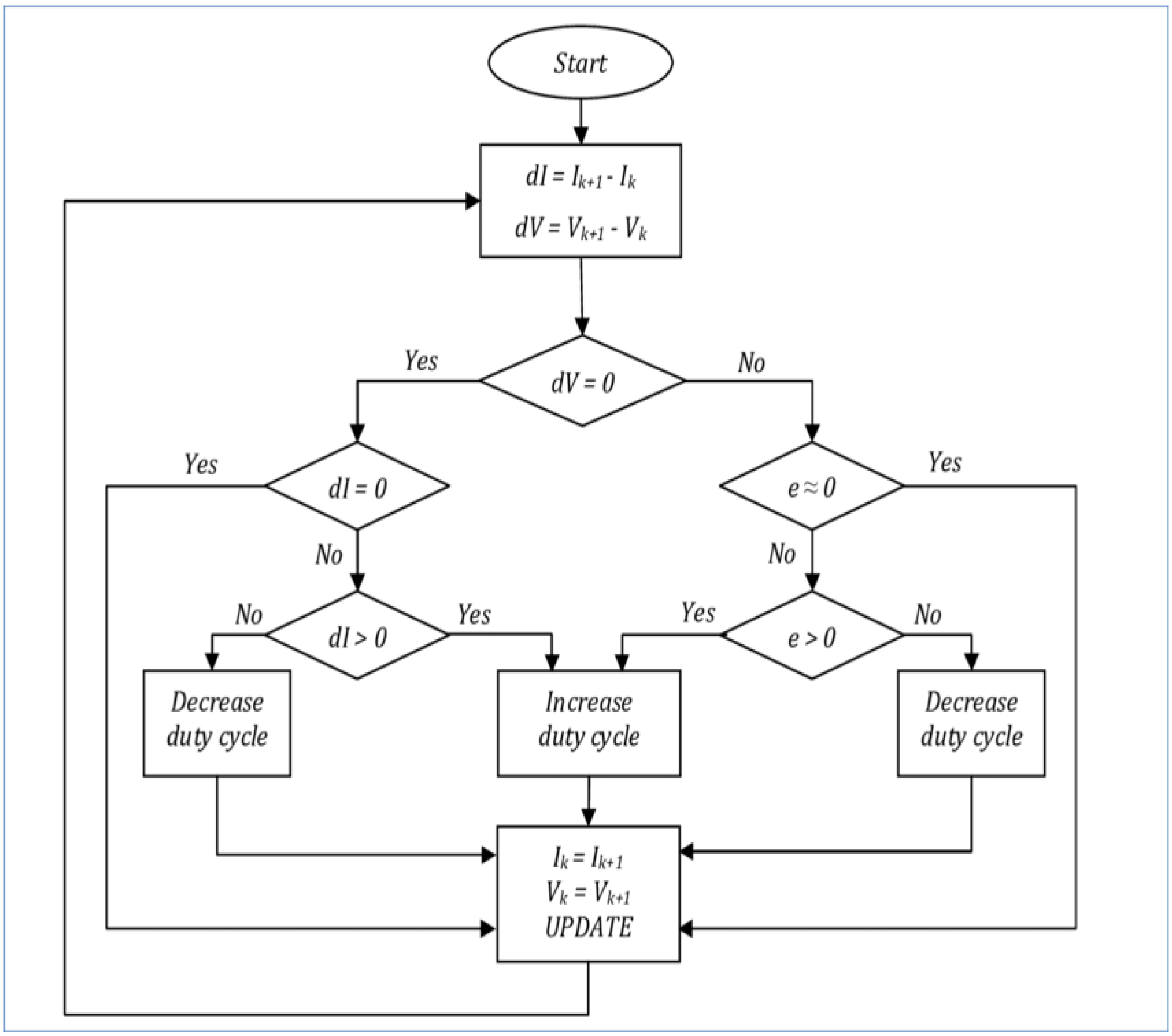


Figure 4.2 : Flowchart of Incremental Conductance Method Algorithm

4.3Incremental Conductance Method:

Algorithm

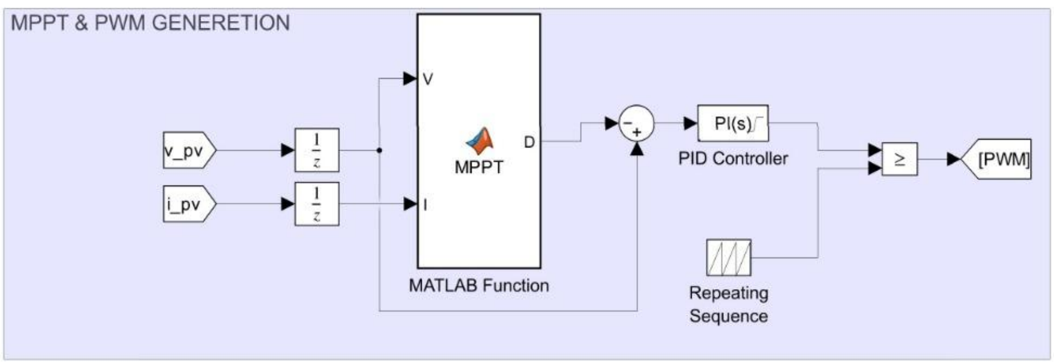
```
D = MPPT(V, I)
  * Incremental Conductance MPPT Algorithm
  persersitent variables
  if ispempty V_old  I_old  D_old
  if V_old = 0; 0
     I_old = 0.5  Inital duty cycle
  end
  * Calculate changes
  dV = V-V_old;
  dI = I-I_old;
  * Incremental Condunctancita aglogic
  if dV = 0
     if dI =  0
        D = D.dl at MPP    PP
     else
        if abs (dI/dV + I/V) <  0.001
           D = D_old
        elsef dI/dV > -I/V;
           D = D_old - 0.01
        else
           D = max(0, min(1, D);
        D_old = D;
     * Update previous values
     D = max(0, min(1, D);
     D_old = D;
  % Update prevjuvalues
  V_old = V;
  I_old = I
```

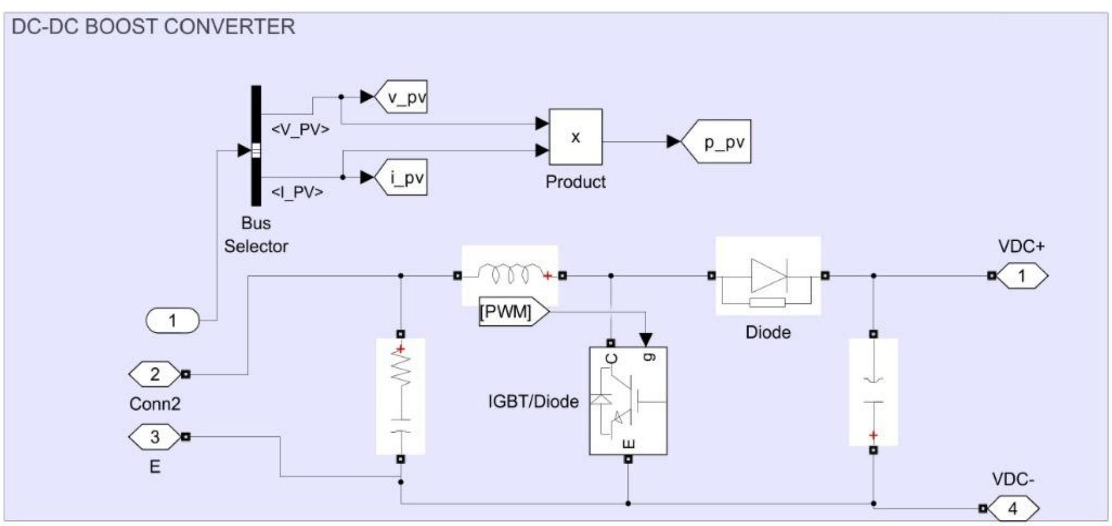
4.4Limitations of INC algorithm

- Local Optimality Instead of Global:
  - Incremental algorithms often focus on locally optimal changes, which may not lead to the globally best solution.
  - Example: Greedy incremental updates in a path-finding algorithm might miss better long-term paths.
- Error Propagation:
  - Small errors or suboptimal decisions made in earlier steps can accumulate and affect the overall solution quality.
- High Dependency on Initial Solution:
  - The efficiency and accuracy of incremental updates rely heavily on the quality of the initial solution. A poor starting point can lead to poor final results.
- Difficult to Handle Large Changes:
  - While INC algorithms are good for small or gradual changes, they may perform poorly when the system undergoes major updates.
- Complexity in Managing Dependencies:
  - For complex systems with interdependencies, tracking and updating all affected components incrementally can become cumbersome.
- Not Always Time Optimal:
  - In some cases, recalculating the full solution from scratch may be faster or more efficient than performing multiple incremental updates.
- May Require Specialized Data Structures:
  - Efficient incremental updates often need tailored data structures (like balanced trees, graphs with update support), which adds to implementation complexity.
- Harder to Prove Correctness or Convergence:
  - Compared to static or batch algorithms, proving correctness and convergence properties of incremental algorithms can be more difficult

4.5 Implementation of MPPT using a boost converter

The system uses a boost converter to obtain more practical uses out of the solar panel. The initially low voltage output is stepped up to a higher level using the boost converter, though the use of the converter does tend to introduce switching losses. The block diagram shown in Figure gives an overview of the required implementation.





4.6 MPPT Interfacing in a Standalone PV System

In a standalone solar photovoltaic (PV) power system, Maximum Power Point Tracking (MPPT) plays a vital role in maximizing energy extraction from the solar panel under varying environmental conditions such as irradiance and temperature. The interfacing of the MPPT controller with other system components like the boost converter, battery storage, and inverter is essential to ensure efficient energy conversion and stable operation.

At the heart of this system lies the Incremental Conductance (INC) algorithm, a widely used MPPT technique. The INC algorithm works by comparing the incremental conductance (dI/dV) to the instantaneous conductance (I/V) of the PV panel. It determines the direction in which the operating voltage must be adjusted to reach the Maximum Power Point (MPP). If the slope of the power-voltage curve is zero (dP/dV = 0), the MPP is reached. If it's positive or negative, the algorithm increases or decreases the voltage accordingly.

Interfacing with the system begins at the PV panel, where voltage and current sensors are installed to continuously monitor output values. These sensor readings are fed into the MPPT controller, usually implemented in a MATLAB Function block or microcontroller in real-time systems. The controller runs the INC logic to calculate the required adjustment in voltage and subsequently generates a PWM (Pulse Width Modulation) signal based on the duty cycle computed by the MPPT.

This PWM signal is then sent to the boost converter, which regulates the voltage output of the PV panel. The boost converter steps up the voltage to a desired DC level while ensuring that the PV panel operates at or near its maximum power point. The regulated output is either directly supplied to a DC load, stored in the battery through a bidirectional DC-DC converter, or sent to a DC-AC inverter.

The bidirectional converter manages battery charging and discharging intelligently. When the solar output is greater than the load demand, the excess energy charges the battery. Conversely, during low irradiance periods, the battery discharges to support the load. The inverter converts the DC voltage to a stable 230V, 50Hz AC output, which is then supplied to the connected load. The MPPT ensures that the inverter always receives optimal input power by continuously adjusting the boost converter’s operation.

In simulation environments like MATLAB/Simulink, this interfacing is modeled using blocks such as Voltage Sensor, Current Sensor, PWM Generator, Boost Converter circuit (with MOSFET and inductor), Battery (Simscape), and Universal Bridge for the inverter. The MPPT algorithm is typically implemented using a MATLAB Function block with appropriate logic and timing to ensure stable tracking without introducing excessive switching noise.

In summary, MPPT interfacing involves a feedback loop: PV sensors → MPPT controller → PWM signal → Boost converter → DC bus → Battery/Inverter → Load. Proper interfacing ensures that the PV system operates efficiently under all conditions, providing a stable and reliable power supply, especially in off-grid or remote applications.

4.7 PI controller

The system also employs a PI controller. The task of the MPPT algorithm is just to calculate the reference voltage V_{ref} towards which the PV operating voltage should move next for obtaining maximum power output. This process is repeated periodically with a slower rate of around 1-10 samples per second. The external control loop is the PI controller, which controls the input voltage of the converter. The pulse width modulation is carried in the PWM block at a considerably faster switching frequency of 100 KHz. In our simulation, K_P is taken to be 0.006 and K_I is taken to be 7. A relatively high K_I value ensures that the system stabilizes at a faster rate. The PI controller works towards minimizing the error between V_{ref} and the measured voltage by varying the duty cycle through the switch. The switch is physically realized by using a MOSFET with the gate voltage controlled by the duty cycle.

$$u(t)=Kp\cdot e(t)+Ki\cdot\int e(t)$$

MPPT Duty Cycle Control (if PI used for Boost converter PWM)

PI Use	For maintaining Boost Converter output at set DC bus (e.g., 120 V)
Control Variable	Boost Converter Duty Cycle
Reference	Vdc_ref (e.g., 120 V)
Kp	0.1
Ki	5
Output Limit	0 to 1 (duty cycle clamp)

4.8 Results

4.8.1 Case 1: Running the system without MPPT

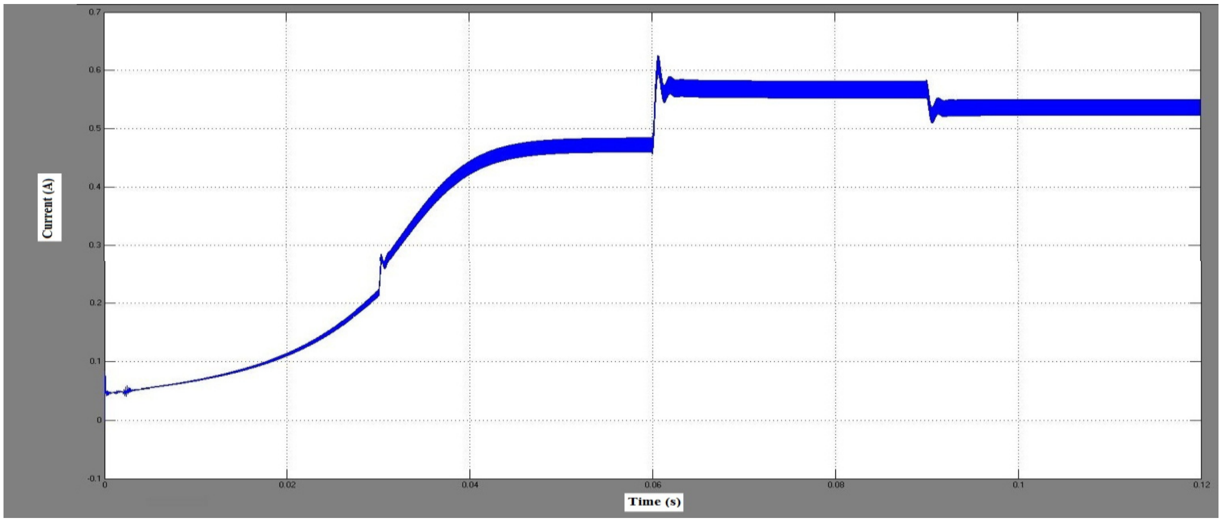


Figure 6.4 : Plot of Output current at load side v/s time without MPPT

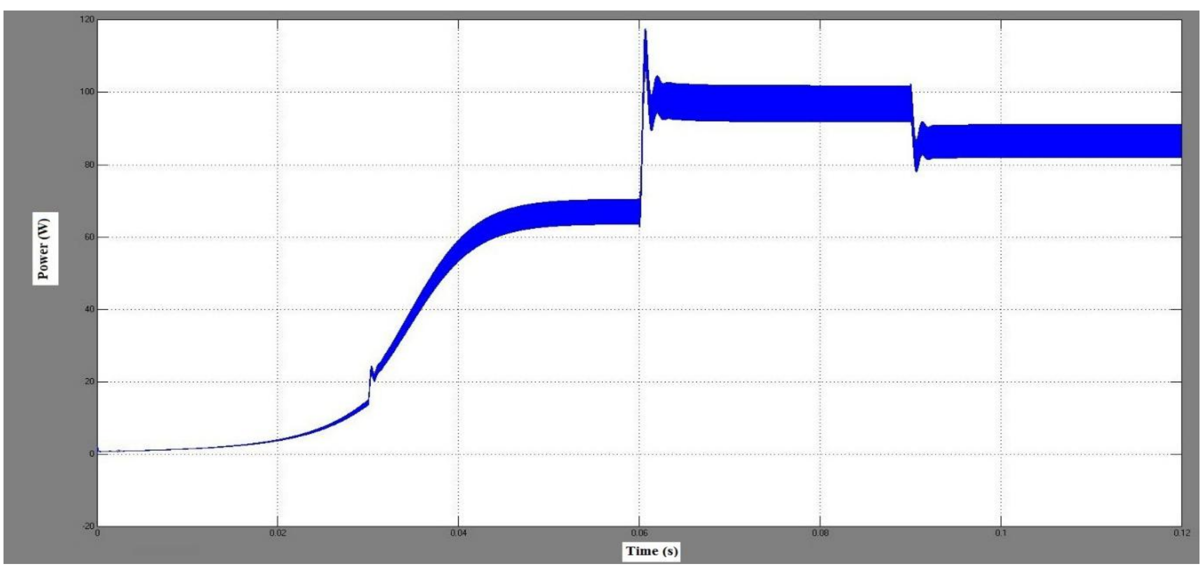
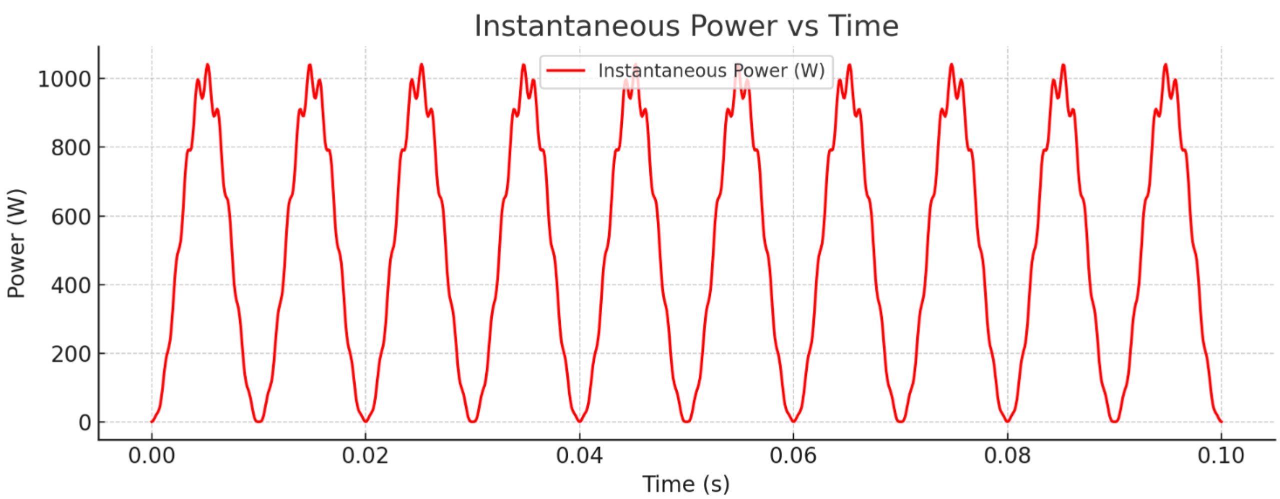
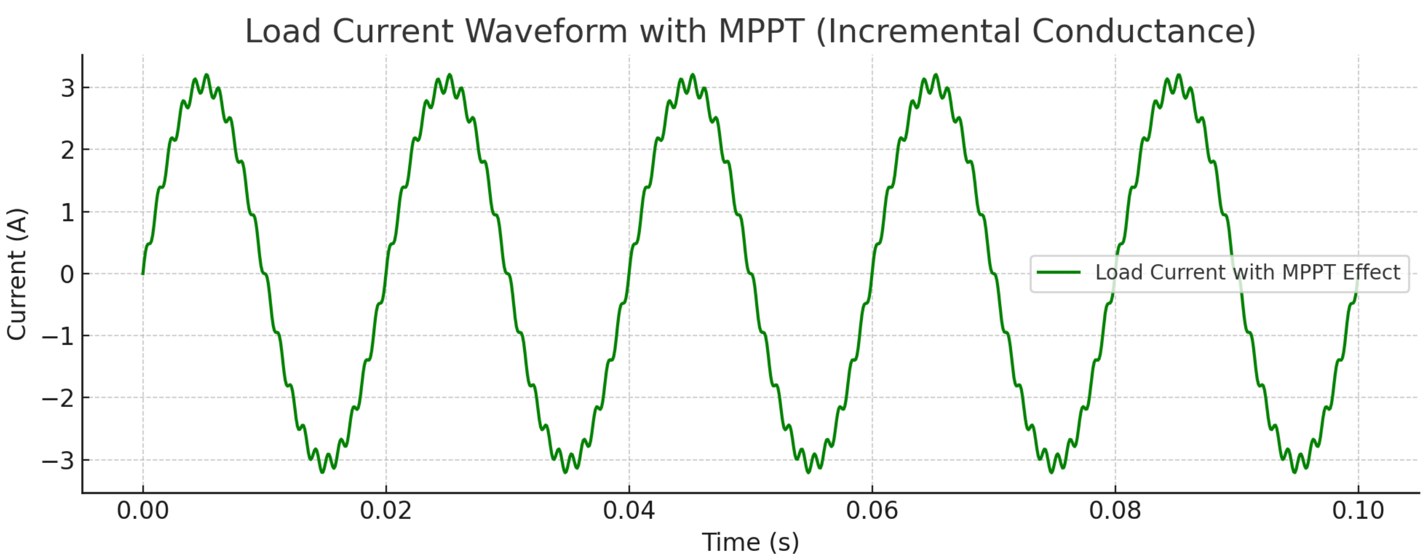


Figure 6.5 Plot of output power at load side v/s time without MPPT

4.8.2 Case 2: Running the system with MPPT





5.Bidirectional DC- DC Converter

1. Objective

The Bidirectional DC-DC Converter (BDC) in this system enables power flow between the battery storage and the DC bus, allowing both charging and discharging operations. It ensures:

- Battery charging from PV power when generation exceeds load demand.
- Battery discharging to support the load during low/no PV generation.

2. Converter Topology

The BDC uses a non-isolated bidirectional buck-boost converter. It consists of:

- Two active switches (MOSFETs): S1 and S2
- One inductor (L)
- Capacitors at the high-voltage (DC bus) and low-voltage (battery) sides

This topology is suitable for applications with voltage step-up/down and bidirectional energy flow.

3. Operating Modes

◆ Mode 1: Buck Mode (Charging the Battery)

- Power flows from PV (via DC bus) → battery.
- S1 switches with PWM, S2 remains ON (acts as diode).
- Output voltage (battery) < input (DC bus, ~120 V).

◆ Mode 2: Boost Mode (Discharging Battery)

- Power flows from battery → DC bus → inverter/load.
- S2 switches with PWM, S1 remains ON.
- Output voltage (DC bus) > input (battery, ~48 V)

5.Control Strategy

A dual-mode PI controller manages the BDC depending on battery and load conditions.

Charging Control (Buck)

- Controls battery voltage or current to avoid overcharging.
- Reference: V_batt_ref or I_charge_ref
- Controller generates PWM signal for S1.

Discharging Control (Boost)

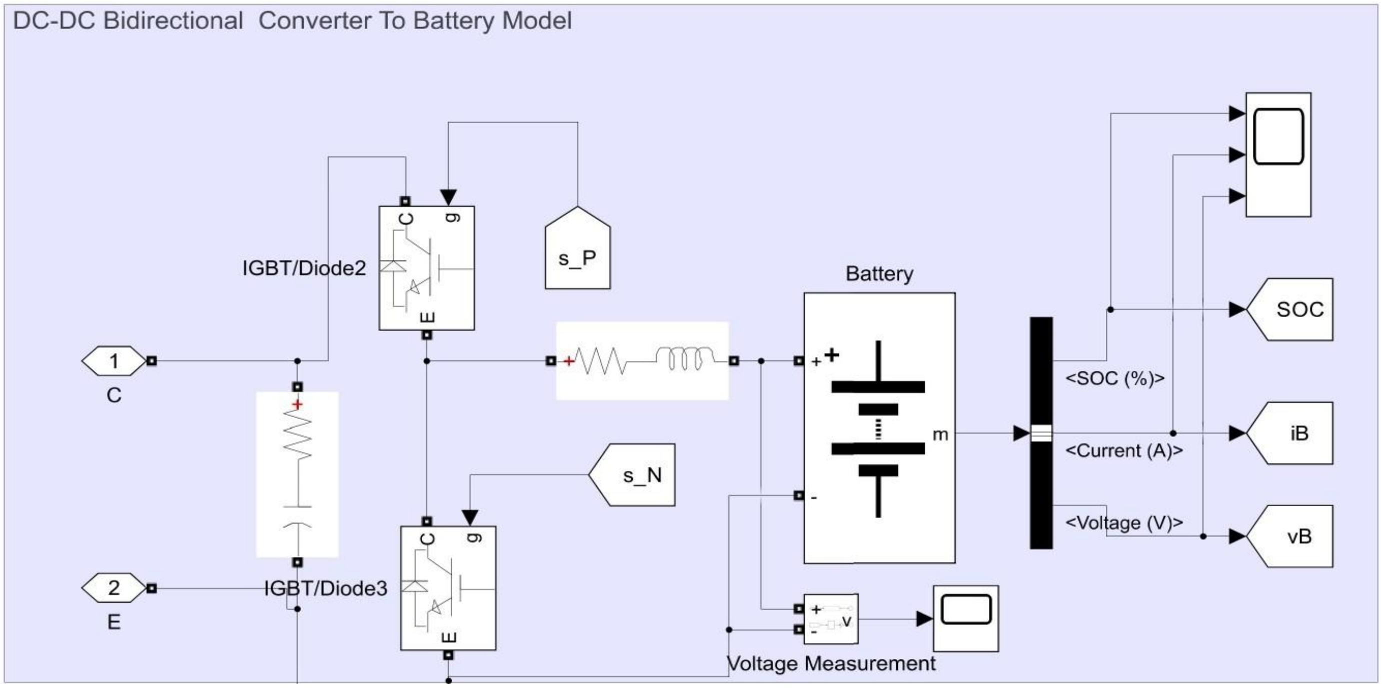
- Maintains DC bus voltage (Vdc_ref) during battery support.
- Controller regulates S2's PWM.

Control includes:

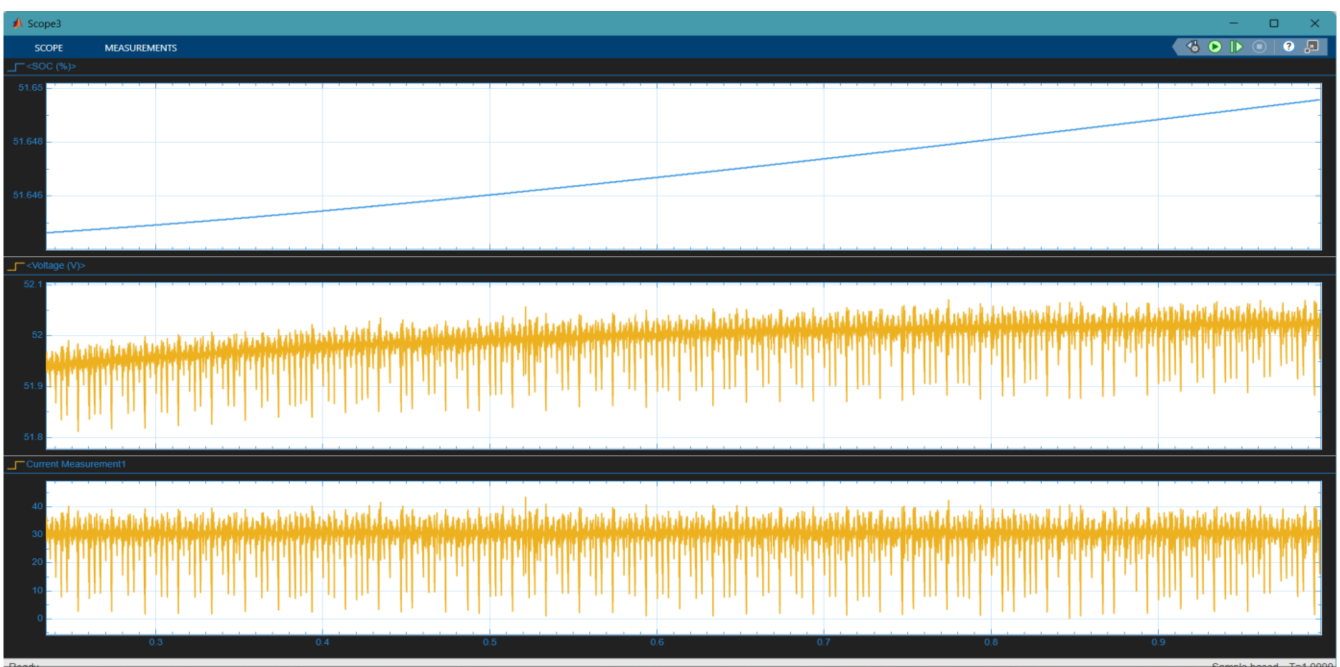
- State-of-Charge (SOC) monitoring
- Mode switching logic based on power balance and SOC thresholds

5. Key Parameters

Component	Value
Battery Voltage	48 V nominal
DC Bus Voltage	120 V
Inductor (L)	3–5 mH
Capacitors (Input/Output)	470–1000 µF
Switching Frequency	20 kHz – 50 kHz
MOSFET Ratings	200 V, 30 A
Battery SOC range	20% (min) to 90% (max)



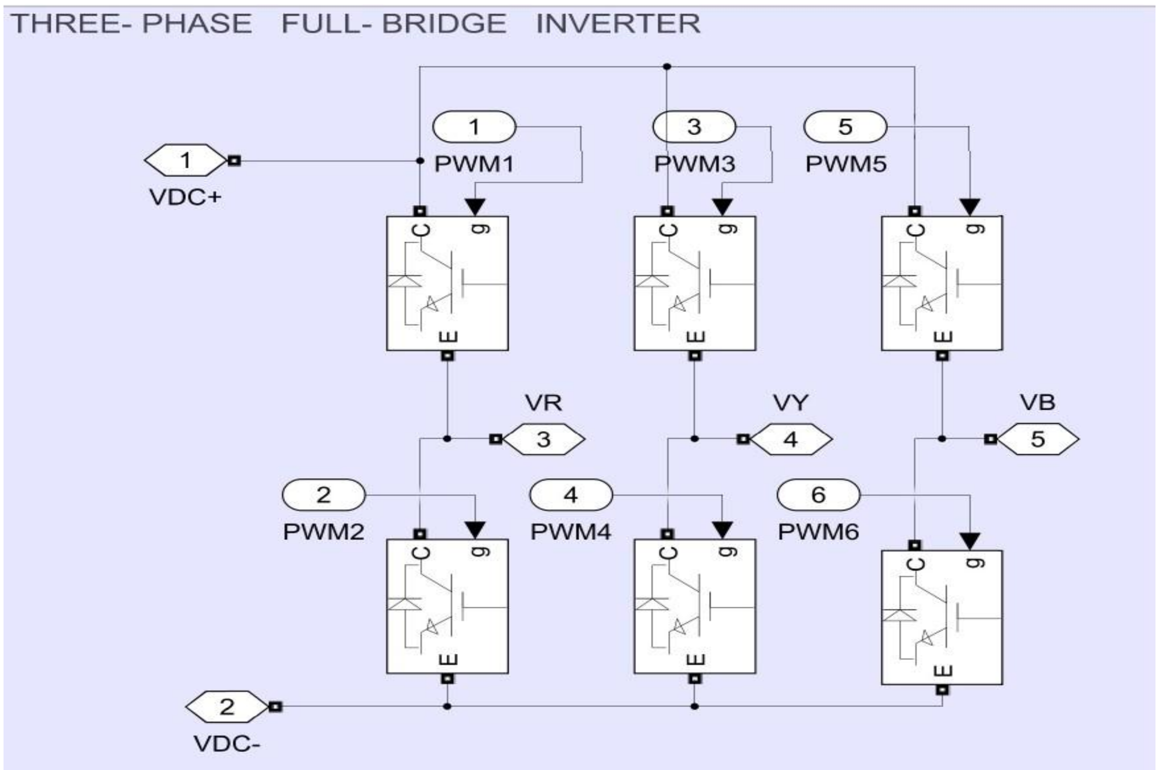
❖ Battery (Sate of Charge)



6. INVERTER (FULL BRIDGE,PWM CONTROLLED)

Overall System

DC-AC Inverter



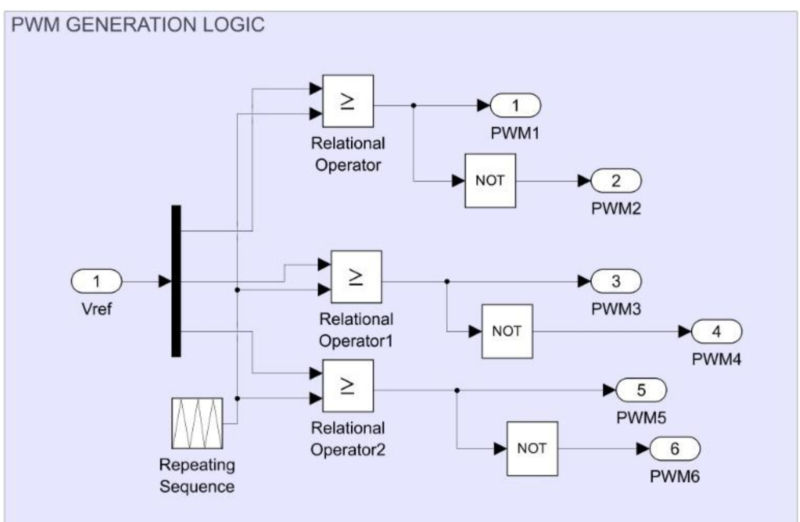
6.1 Objective

The primary objective of the inverter in this PV-battery system is to convert the DC voltage from the DC bus or battery into AC voltage to supply AC loads. It plays a vital role in enabling compatibility between DC energy sources (PV panel and battery) and conventional AC appliances

6.2 Working Principle

The inverter switches DC input voltage (typically ~120 V) at high frequency using PWM to synthesize a sinusoidal AC output (230 V RMS, 50 Hz). It supports:

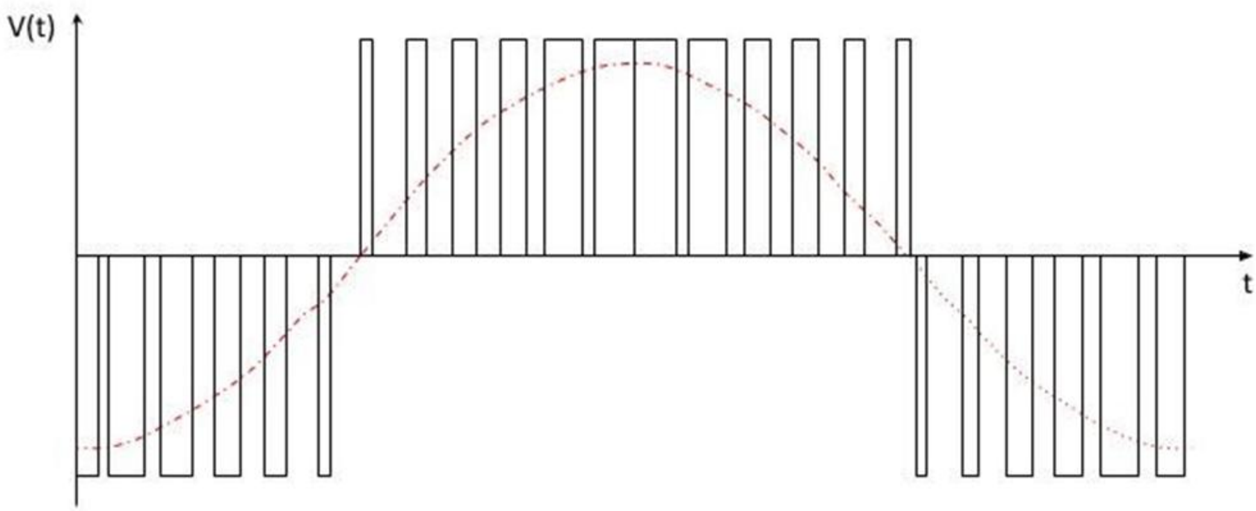
- Unidirectional power flow from DC to AC
- Voltage control to maintain stable output under varying loads
- Grid-independent (standalone) operation using voltage and frequency reference



How Inverter Work ?

Pulse Width Modulation

- Most inverters use a technique called Pulse Width Modulation (PWM) to turn the D.C voltage on and off.
- The width of each pulse is varied, so that the overall electrical effect is similar to that of a sine wave.
    - **Sine Wave Output**



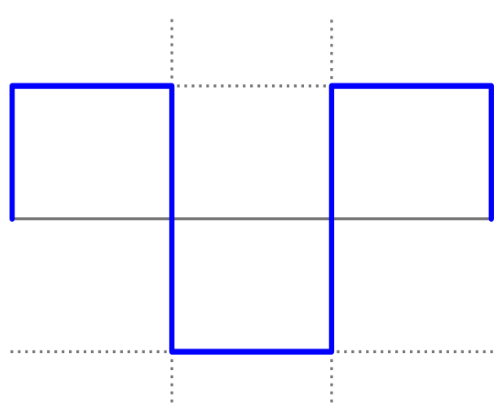
3.5 Inverter Types

6.3.1 The Square Wave inverter:

- This is one of the simplest waveforms an inverter design can produce and is best suited to low-sensitivity applications such as lighting and heating.
- It converts a straight DC signal to a phase shifting AC signal. But the output is not pure AC but it is a square wave.At the same time they are cheaper as well. The simplest construction of a square wave inverter can be achieved by using an on-off switch, before a typical voltage amplifying circuitry like that of a transformer.

6.3.2 The Modified Sine wave inverter :

- The modified sine wave output of such an inverter is the sum of two square waves one of which is phase shifted 90 degrees relative to the other.
- A Modified sine wave shows some pauses before the phase shifting of the wave, unlike a square it does not shift its phase abruptly from positive to negative, or unlike a sine wave, does not make a smooth transition from positive to negative, but takes brief pauses and then shifts its phase.

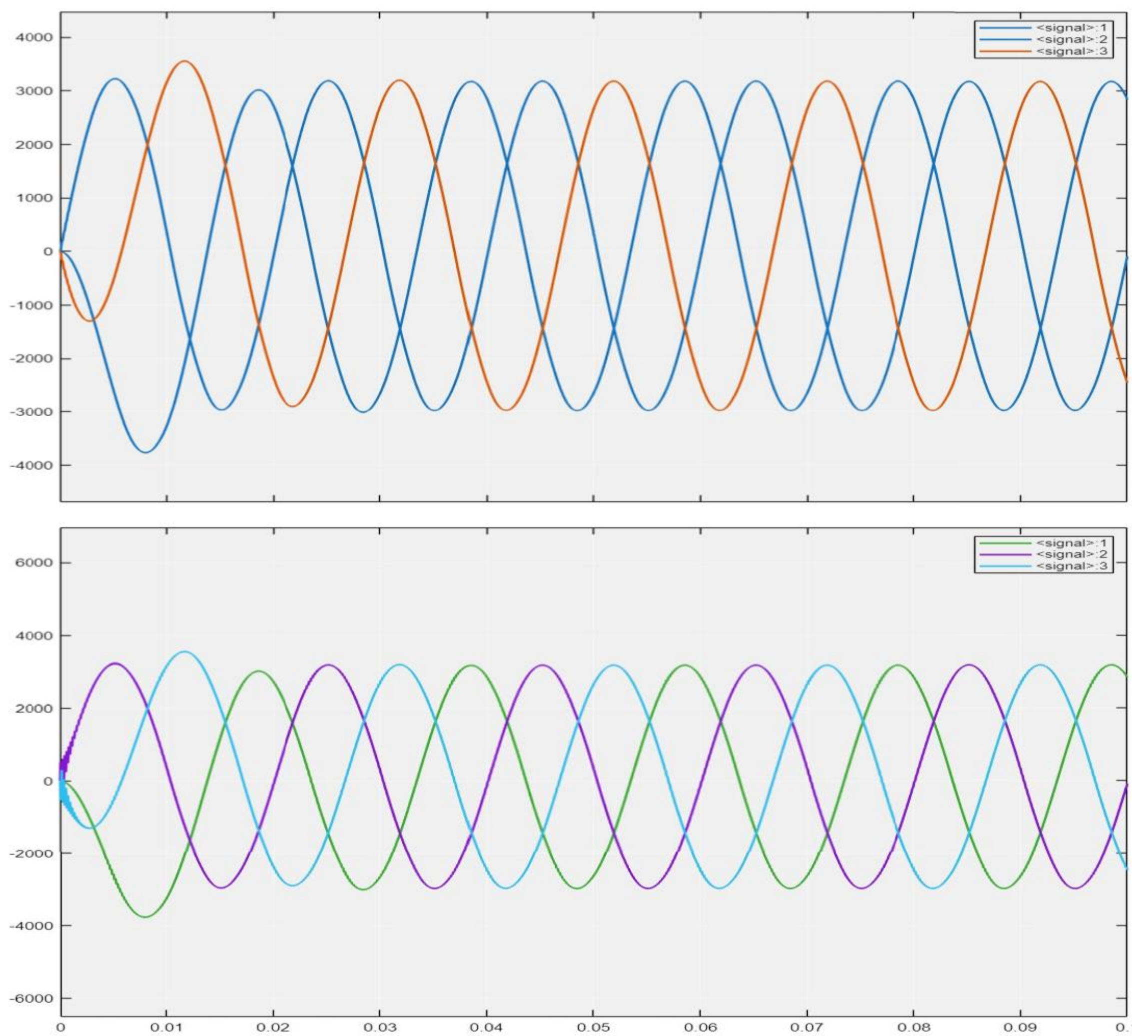


6.3.3 A Pure Sine wave inverter :

A power inverter device which produces a multiple step sinusoidal AC waveform.

Another way to obtain a sine output is to obtain a square wave output from a square wave inverter and then modify this output to achieve a pure sine wave.

Inverter AC Output Voltage and Current



6.4 Key Parameters

Parameter	Value
DC Input Voltage	100–120 V
AC Output Voltage	230 V RMS (single-phase) or 400 V (3-phase)
Output Frequency	50 Hz
Switching Frequency	10–20 kHz
Power Rating	500–2000 W (based on load)
Filter Inductance (L)	3–5 mH
Filter Capacitance (C)	10–30 μF

6.5 Inverter Topology

The inverter used in this project is a two-level Voltage Source Inverter (VSI), based on a H-Bridge or 3-phase full-bridge configuration, controlled using PWM (Pulse Width Modulation).

Type:

- Single-phase or three-phase Voltage Source Inverter (VSI)
- Switching Devices: IGBTs/MOSFETs (4 for single-phase, 6 for three-phase)
- Modulation: Sinusoidal PWM (SPWM)
- Switching Frequency: 5–10 kHz

- Input: DC link from boost converter or battery (120 V DC)
- Output: 230 V RMS AC (sinusoidal), 50 Hz

6.6 Inverter Control Strategy

6.6.1 SPWM Generation

- Compare a sinusoidal reference signal (desired output voltage) with a high-frequency triangular carrier.
- Switching signals are generated for the inverter switches to mimic the sine wave.

6.6.2 PI Controller (Voltage Regulation)

- A PI controller regulates the inverter output voltage.
- Input: Error between desired AC output voltage and measured RMS voltage.
- Output: Modulation index or amplitude reference for SPWM.

6.6.3 PLL (Phase-Locked Loop)

- Used to synchronize with a reference phase or frequency.
- Tracks the grid phase (in grid-tied mode) or generates internal reference (in standalone).

6.6.4 DC Link & Battery Integration

- The inverter is powered by a 120 V DC bus, regulated by the MPPT and battery management system.
- A bidirectional DC-DC converter ensures proper charging/discharging of the 48 V battery bank

6.6.5 LC Filter Design

Used to filter out high-frequency switching harmonics:

Parameter	Typical Value
Inductance (L)	2 mH
Capacitance (C)	20–50 μF
Cutoff freq.	~500–800 Hz

6.7 Simulation/Experimental Results

- Input DC Voltage: 120 V
- Output AC Voltage: 230 V RMS (±5%)
- Output Frequency: 50 Hz
- Total Harmonic Distortion (THD): < 5%
- Load Supported: 500 W – 1 kW resistive/inducti

6.8 Performance Observations (from simulation)

- Stable sinusoidal output with low THD.
- Quick response to load changes.
- Voltage maintained at 230 V despite source/load variations.
- Effective filtering of switching noise via LC filter.
- Synchronized operation using voltage phase reference or internal oscillator.

7.Future Scope

- Grid-Connected Hybrid System: Integrate the PV system with the utility grid for surplus energy export and grid support.
- Advanced MPPT Algorithms: Use fuzzy logic, neural networks, or genetic algorithms for better efficiency under rapidly changing conditions.
- IoT-Based Monitoring: Implement remote monitoring and control using IoT platforms like Node MCU, Raspberry Pi, or cloud services.
- Smart Load Management: Incorporate priority-based load shedding or time-based load switching for optimal energy usage.
- Real-Time Hardware Implementation: Deploy the system using microcontrollers (e.g., Arduino, STM32, DSP) for real-world applications and performance validation.

8.Conclusion

This project presents a comprehensive simulation of a standalone solar photovoltaic (PV) system integrated with Incremental Conductance (INC) based MPPT, battery energy storage, and an inverter to supply AC loads. The system is developed to operate independently, making it highly suitable for remote and off-grid applications.

The core of the system lies in the use of the Incremental Conductance MPPT algorithm, which offers more accurate and stable tracking of the maximum power point compared to traditional methods like Perturb and Observe. The INC method calculates the slope of the power-voltage curve and adjusts the operating point with greater precision, especially under rapidly changing irradiance conditions. This ensures optimal power extraction from the PV panel at all times.

A boost converter, controlled by the MPPT duty cycle, steps up the variable DC output from the PV array to a regulated voltage. This regulated DC is used to either power the load directly or charge the battery through a bidirectional DC-DC converter, depending on the system's power balance and the battery's state of charge (SOC). The battery provides backup power during periods of low solar availability or high load demand, ensuring uninterrupted energy supply.

The inverter then converts the DC power into 230V, 50Hz AC to meet typical household or commercial load requirements. A low-pass filter is used to reduce harmonics and deliver a clean sinusoidal output.

Simulation results confirm that the system operates efficiently, maintains voltage stability, and manages energy flow intelligently between the PV source, battery, and load.

In conclusion, the model successfully demonstrates a reliable, sustainable, and efficient solar power solution. With enhancements like smart control, grid interfacing, or IoT monitoring, this system has strong potential for real-world deployment in standalone energy applications.

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