INVESTIGATION ON EFFICIENCY IMPROVEMENT METHODOLOGIES FOR SOLAR PHOTOVOLTAIC SYSTEM FOR RENEWABLE ENERGY APPLICATIONS

Thesis

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in

Mechanical Engineering

By

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DECLARATION BY THE SCHOLAR

I hereby declare that the work presented in this thesis entitled “Investigation on Efficiency Improvement Methodologies for Solar Photovoltaic System for Renewable Energy Applications " in fulfillment of the requirements for the award of Degree of Doctor of Philosophy, submitted in the Maharishi School of Engineering & Technology Maharishi University of Information Technology, Lucknow is an authentic record of my own research work carried out under the supervision of Dr. Ashok Kumar Srivastava . I also declare that the work embodied in the present thesis-

i) is my original work and has not been copied from any journal/ thesis/ book; and
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This is to certify that **Mr. Naval Kishore Jain** has completed the necessary academic turn and the swirl presented by him/her is a faithful record is a bonfire original work under my guidance and supervision. He/She has worked on the topic **“Investigation on Efficiency Improvement Methodologies for Solar Photovoltaic System for Renewable Energy Applications”** under the Maharishi School of Engineering & Technology Maharishi University of Information Technology, Lucknow.

Dr. Ashok Kumar Srivastava

Date:

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ABSTRACT

As their name suggests, renewable energy sources are ones that can be replenished through time; as a result, they are resources that will never run out. Some of the most common renewable energy sources are water, biomass, solar power, geothermal heat, and wind. As fossil fuel and oil stocks continue to be depleted, there is a significant need for renewable energy sources. In addition, the increased atmospheric carbon dioxide levels caused by these nonrenewable resources pose a hazard to the ecosystem. According to many, solar power offers the most promise of any renewable energy source now in existence, making it an ideal replacement for more traditional energy sources. In the last 10 years, solar power has become increasingly popular throughout the globe. There have been a plethora of studies aimed at maximizing energy extraction in this most famous field. Solar power is becoming increasingly popular due to its many advantages, such as being cost-effective, environmentally friendly, and requiring little in the way of upkeep. For various manufacturing technologies and locations, this research aims to conduct the numerical model of a 1MWp and 100 kWp solar power plant. A model of the plant, studies of losses, and a demonstration of the planned power station were all made possible with the help of the PV-Syst programming tool. In order to conduct the techno-economic analysis of the system, several assembly techniques and unique guiding plans have been employed. Implementing a maximum power point tracking system enhanced with a solar photovoltaic system is another goal of the project.

As part of this experiment, we also tested how cooling affected the efficiency of the solar photovoltaic system and how thermal instability affected its power production. A variety of cooling systems have been designed and studied to evaluate the efficiency and effectiveness of solar photovoltaic systems in terms of power production and operation. In order to improve the operational output of solar photovoltaic systems, this study has been expanded to include the use

of maximum power point tracking systems. Combining photovoltaic and solar thermal components results in a hybrid system known as PV/T. An integrated system, the solar PV/T generates both electricity and thermal energy. A photovoltaic (PV) module, an absorber plate, and tubes are the components of a PV/T collector. It is the job of the absorber to soak up the heat that the PV module produces and then reduce it. This enhances its power and allows for the secondary collection of the thermal energy it produces. In this study, we examine and contrast the efficiency of solar photovoltaic systems with that of PV/T hybrid water collectors. The efficiency of electric and photovoltaic conversion was attempted to be evaluated. Regarding the energy and exergy of a solar PV/T system, the first two laws of thermodynamics are applicable. Energy exergy is a form of low-quality energy that can be transformed into high-grade energy inside a system. One way to think about measuring energy quality is by comparing the exergy to energy ratio of a material. Various mass flow rates ranging from 0.002 to 0.004 kg/sec were tested in the Jaipur environment. A range of 5% to 8% was determined for the average electrical efficiency. Typical thermal efficiencies ranged from fifty percent to sixty-two percent. The total efficiency ranged from 56% to 68% on average. Efficiency varied from 5% to 8% on average, with 13% being the highest possible. The results shown that when the mass flow rate of water increases, electrical efficiency declines and thermal efficiency rises. Enhanced performance, dependability, reduced maintenance, and stability of solar cells' current-voltage characteristics are further advantages of the hybrid idea, as are reductions in thermal stresses, which prolong the life of the PV module.

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
AC	Alternating Current
BOS	Balance of Systems
CPVT	Center for Photovoltaic/Thermal
DC	Direct Current
FOCV	Fractional Open Circuit Voltage
FSCC	Fractional Short Circuit Current
FLC	Fuzzy Logic Controller
GA	Global Horizontal Irradiance
G	Irradiance
I	Current
I_old	Old Current
I_new	New Current
INC	Incremental Conductance
Impp	Maximum Power Point Current
ISC	Short Circuit Current
Isc_ref	Reference Short Circuit Current
k1	Constant Ratio for VOC
k2	Constant Ratio for ISC
MPPT	Maximum Power Point Tracking
MPP	Maximum Power Point
P	Power
P_old	Old Power
P_new	New Power
P&O	Perturb and Observe
PCU	Power Conditioning Unit
PV	Photovoltaic
PVT	Photovoltaic Thermal
SPV	Solar Photovoltaic
STC	Standard Test Conditions
T	Temperature
T_c	Cell Temperature
V	Voltage
V_old	Old Voltage
V_new	New Voltage
Vmpp	Maximum Power Point Voltage
VOC	Open Circuit Voltage
ΔI	Change in Current
ΔV	Change in Voltage
ΔT	Change in Temperature
ηe	Electrical Efficiency
μsc	Temperature Coefficient of Short Circuit
Vmp	Maximum Power Point Voltage
Ipv	Photo Current
ID	Diode Current
Io	Reverse Saturation Current
n	Ideality Factor

kB	Boltzmann Constant
Tc	Cell Temperature
VT	Thermal Voltage
Q	Electron Charge
C1	First Planck Constant
C2	Second Planck Constant
FF	Fill Factor
η	Efficiency
Pmax	Maximum Power
PV/T	Photovoltaic/Thermal
KIPV	Irradiance Multiplier of Photo Current

CHAPTER 1

INTRODUCTION

1.1 Background

Actually, the majority of the world's fuel comes from fossil fuels. The demand for fossil fuels is rising steadily alongside the economic expansion of both industrialized and emerging nations. Worldwide energy consumption is predicted to increase at a pace of 1.6% per year between 2006 and 2030, resulting in a 45% increase.

Massive economic expansion is already in the works for the next decade, propelling India's economy to the position of ninth biggest in the world. The combination of cheap labor costs and high manufacturing efficiency makes India an attractive location for investors from around the world. Jobs and economic growth in the main cities have been boosted by these initiatives. The majority of people have it at extremely low levels, and it only accounts for a tiny fraction of the overall population.

A renewable energy source is one that can be replenished. Renewable energy sources abound, including wind, sun, hydropower, biomass, and more. Considering the negative impact on the environment and the impracticality of using even trace amounts of fossil fuel, renewable energy sources will be crucial in meeting world demand in the next decades. One way to mitigate climate change and reduce emissions of greenhouse gases is to make use of our renewable energy sources.

An increase in energy demand can be met with reasonable fossil fuel consumption, but at a risk of hazardous levels of atmospheric greenhouse gas emissions. According to climate change mitigation efforts, emissions of greenhouse gases, including carbon dioxide (CO2), have increased by 1.9% per year from fossil fuels over the last 30 years. The Fourth Intergovernmental Panel Assessment Report 2007 on Climate Change found that rising sea levels are in line with the phenomenon of global warming. The Arctic Sea's snow and ice levels have increased due to the effects of climate change. There has been a rise in the sea level. The Indian Ministry of Power provided Figure 1.1, which depicts the country's energy map. A solution to the problem of climate change and the increasing need for renewable energy sources like solar, wind, hydropower, and biofuels are the main goals of this proposal. Demand for fossil fuels is expected to decline as the renewable energy sector experiences growth. Another way to lessen the impact of climate change is for renewable energy to gradually supplant fossil fuels. The sun's rays reach Earth's surface at a rate of over 80,000 TW, which is 10,000 times the world's energy consumption, making solar power one of the most potential renewable energy sources.

All renewable energy sources get their power from sunlight. A tremendous quantity of solar energy is being released into the solar system by the sun. Even though Earth only absorbs a fraction of the sun's rays, even if they were to strike the surface for just one hour, all of that energy could be converted into usable energy. Energy generated by the sun mostly finds use in solar thermal and photovoltaic (PV) systems. Photovoltaic is a method that converts sunlight directly into usable power. There is zero fuel use and zero greenhouse gas emissions from PV technology. Solar cells, however, are not cheap. So far, the goal of photovoltaic (PV) research and development has been to create affordable solar cells and PV systems that are both effective and efficient. Solar energy has the greatest potential among renewable power sources. The presence of water in plants is a result of the solar fuel cycle and photosynthesis. There is 1017 W of solar energy in the atmosphere. There is 1016 W of solar energy reaching Earth's surface. One thousand times the power that we use is required to meet the global demand for energy, which is 1013 W. Photovoltaic solar cells produced by the solar energy sector could provide the global need for power fifty times over if just five percent of that energy were to be utilized. A solar photovoltaic cell converts sunlight directly into usable energy. The most important and modest power demands in India are met by solar panels, which also power irrigation pump systems, water and rural electricity supplies, hospital freezers, and other similar devices. Almost 300 days of the year in India are sunny.

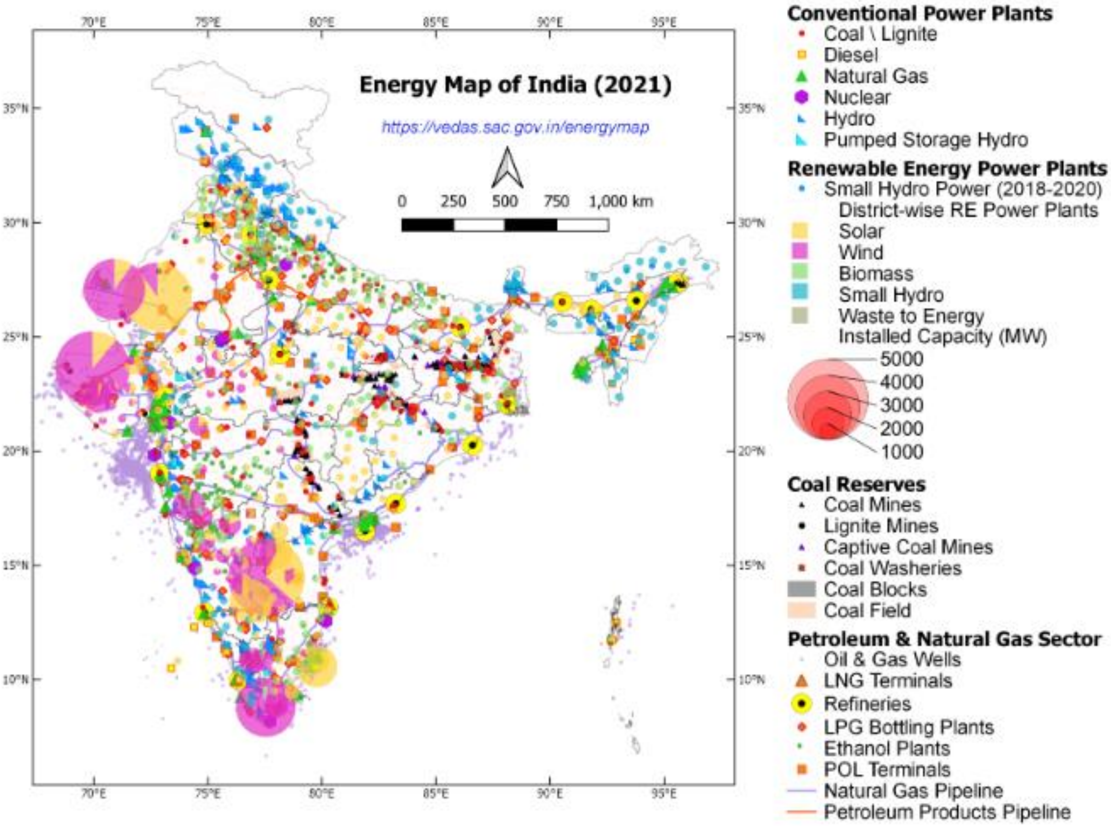

Figure 1.1 India's Energy Map (Source: Indian Ministry of Power)

1.2 Solar Energy

1.2.1 Basic

This is the surface temperature of the sun, which is 5800 K. The sun's energy comes from nuclear fusion events that take place at temperatures greater than 15 million K in the sun's core. According to the Planck radiation rule for blackbodies, the solar constant is around 1368 W/m2. The amount of energy that the sun generates and stores per square meter of surface area is called the solar constant. There were many uses for solar heat collectors and solar photovoltaic cells, which converted the sun's abundant energy into usable heat and electricity.

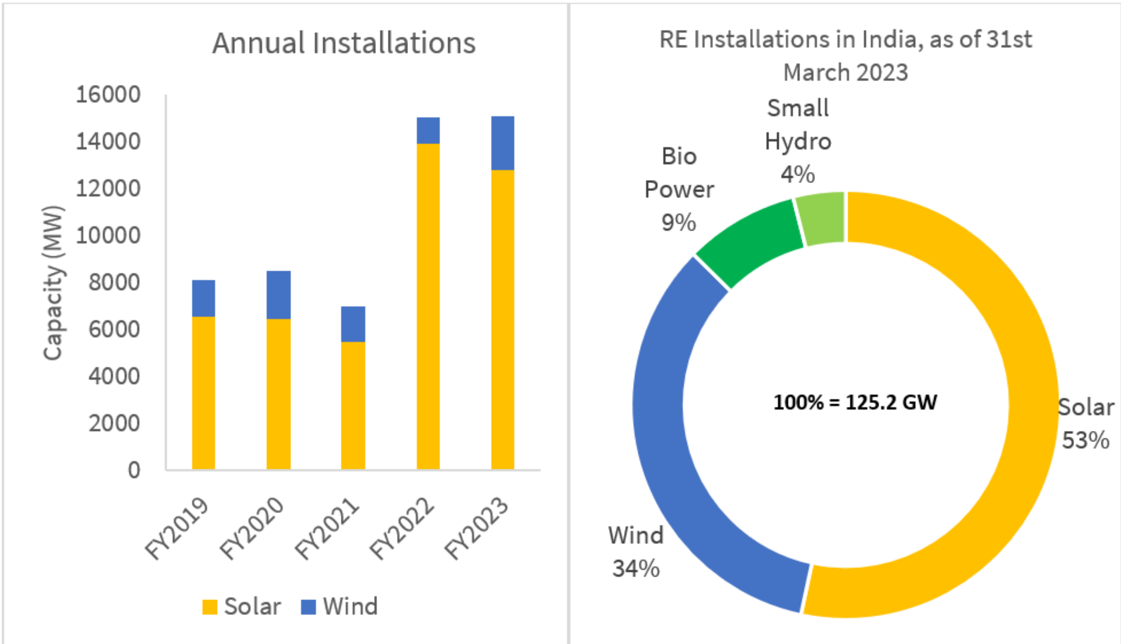

Figure 1.2 Additions of Solar PV Installations (Source: Indian Ministry of Power)

1.2.2 Solar Radiation

The average incident solar flux on a unit area perpendicular to the beam outside the atmosphere is a constant. According to the World Radiation Center, the solar constant is 1367 W/m2. The irradiance of a surface is the amount of electromagnetic radiation that hits it in a given region and time. The amount of solar radiation that strikes a horizontal surface unit at any given location on Earth is called insolation. The sun's rays that reach Earth's surface, including both direct and indirect sources. Since air molecules, water vapor, and harmful particles scatter sunlight throughout the atmosphere, over 30% of it is deflected before reaching Earth's surface. Heat, water vapor, and carbon dioxide are the substances that absorb ozone. After dispersal, absorption, and radiation to space, the sun's radiance value—approximately 1000 W/m^2 at midnight on a clear sky day—reaches the Earth's surface at sea level.

1.2.3 Solar Constant

The energy received from the Sun at Earth's middle sun distance and at the top of the atmosphere, perpendicular to a surface area perpendicular to the direction of radiation propagation, is called the solar constant. Time and the distance between the Sun and Earth both affect the amount of solar radiation. At the World Radiation Centre, the solar constant was measured at 1367 W/m2.

1.2.4 Extraterrestrial and Terrestrial Solar Radiation

The emissive power density of the blackbody is given according to Planck's radiation law

$$\mathrm{E}_{\mathrm{b},\lambda}(\lambda T) = \frac{C_1}{\lambda^5\left[\exp(C_2/\lambda T) - 1\right]}\left[W(m^2.\mu m)\right] \qquad (1.1)$$

The spectral emissive density, denoted as $\mathrm{E}_{\mathrm{b},\lambda}$ is measured in W/(μm.m2) units, and the first and second Planck ray constants are $\mathrm{C}_1 = 3.743\times10^8\left[W.\mu m^4/m^2)\right]$ and $\mathrm{C}_2 = 1.439\times10^4\left[\mu.K\right]$ respectively. As a solar beam travels through the atmosphere, its trajectory length is proportional to the vertical trip length minus the journey length through the atmosphere that actually crosses the solar beam to the ground. Thus, when the sun is directly overhead, the air mass is at a unity. In the context of a solar orientation, the air mass is proportional to the square of 2. The air mass can be calculated as the reciprocal of the cosine of the angle θ. Sunlight on Earth differs greatly from that outside the atmosphere in terms of both intensity and composition. Spectral radiation data collected from coastal and mountainous areas allowed scientists to determine the extraterrestrial radiation's dispersion spectrum. Air, water, CO_2, and O_2 molecules absorb, disperse, and reflect light at various rates and wavelengths, rendering these results invalid. This is a challenging calculation since the air in the lower atmosphere changes as a result of cloud cover.

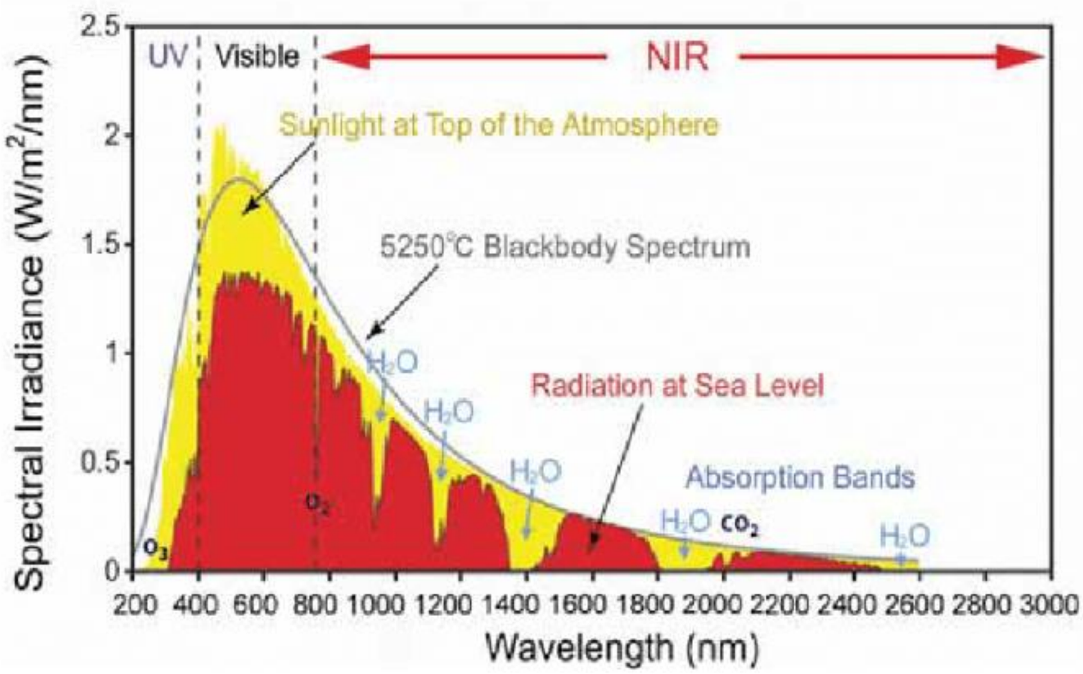

Figure 1.3 Solar Radiation Spectrums [21]

1.2.5 Solar PV Cell

One way that sunlight may be converted into direct power is by the use of photovoltaic cells, which are made of semi-conductor materials. Constructed by bus bars and fingers with their contact grid, a solar cell is a monocentric silicon wafer.

A photovoltaic cell can only function with these essential components:

• The creation of electron holes and the absorption of photons separated charge carriers.

• How various charge carriers move across the external circuit.

When photovoltaic crystalline cells are struck by electron-hole pairs with wavelengths less than 1100 nm, the electrical field causes the electrons to move from a p-silicon type to an n-silicon type and the holes from the n-type back to the p-silicon type. Because of electrical neutrality, the photovoltaic effect is interrupted. An external weight must be applied in order to fix the imbalance. The current route that allows electrons to move from n-type to silicone-type is provided by the external charge; when the electrons reach p-type silicon, they recombine with the hole. The image current is generated when an electron travels through an external load.

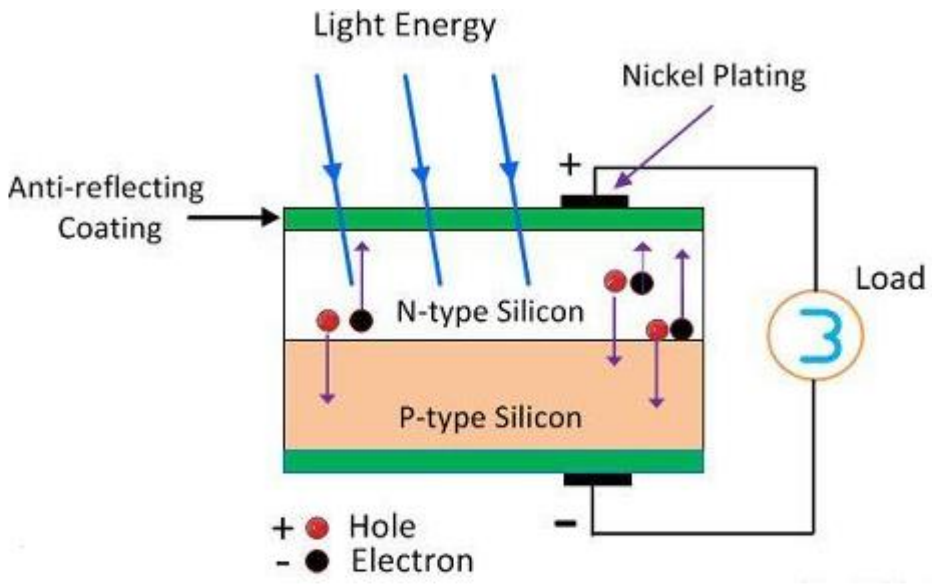

Figure 1.4 PV Cell [23]

In the actual diode equation called the Shockley equation, the dark I-V current voltage curve of the ideal p-n junction is given:

$$I = I_o[\exp(qV/nkT) - 1] \quad (1.2)$$

Where I_o is dark saturation current, V voltages are added, q is electric charge, k constant Boltzmann, T is cell temperature and n is the factor of ideality. The current output is given under sunlight light,

$$I = I_L - I_o[\exp(qV \times qV/nkT) - 1] \quad (1.3)$$

Where I_L is a current created by light.

1.2.6 Structures of Solar Cells

In order to maximize efficiency and minimize costs, solar cells are made from a wide range of materials and semiconductor designs utilizing a number of production techniques. A variety of amorphous semiconductor cells, including silicon, with multiple forms and functions make up solar cells. Thin film solar cells constructed of poly-crystalline materials are commonly used in materials such as copper-indium dieseline (CIS), cadmium telluride (CdTe), and thin film silicone. One crystalline thin film (GaAs) may be produced by using high-efficiency materials like gallium arsenide. Different configurations of the four basic structures of solar cells—the homojunction, heterojunction, p-i-p, n-i-p, and multi-connection-are possible.

1.2.7 Photovoltaic Module

A photovoltaic module's foundation is a set of solar cells. Solar cells can be linked in parallel or series to high voltage, current, and power levels. The solar system's fundamental component is the photovoltaic module, which is essentially a circuit board with photovoltaic cells enclosed in a laminate. A PV series may include a variety of modules and panels. To preserve the front surface's surface while maintaining a high degree of transmissibility, the modules are constructed of laminates with a back plate and a low-iron glass cover. Under standard test circumstances (STC), PV modules and arrays are typically rated at their maximum DC power. Under typical testing circumstances, the module's (cell's) operating temperature is 25°C, the incident solar radiation is 1000 W/m^2, and the air mass is 1.5.

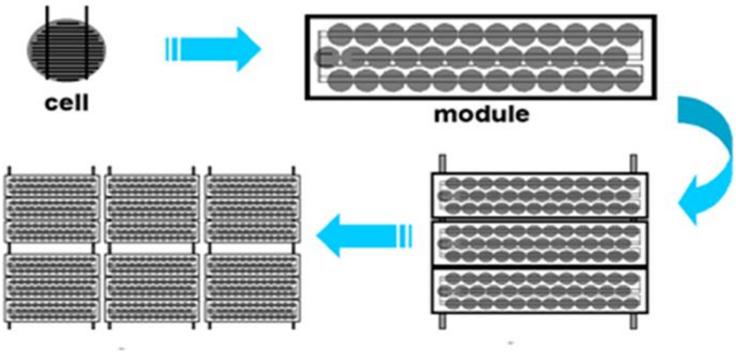

Figure 1.5 Cell, Module, Column and Array

1.2.8 Features and Efficiency of the PV Module

The output of a photovoltaic module is represented by a current voltage curve. Module current and voltage, as well as the I-V curves, are defined by the load variance. Under typical research settings, this is accomplished. At low levels of load resistance, the voltage surrounding the module is almost zero and the current is at its maximum. What we term "short-circuit current" (I_{sc}) is the output current when the voltage is zero. The module's short circuit is analogous to this. Additionally, the solar level has a direct correlation with the current in the short circuit. Until the module is able to avoid retaining the current and reaches zero, the current drops dramatically with increasing load. There is no load on the voltage in the zero current module, which is called the open-circuit voltage (V_{oc}). Solar radiation only has a little effect on the open circuit voltage. The voltage output of a solar module is proportional to the number of cells linked in series.

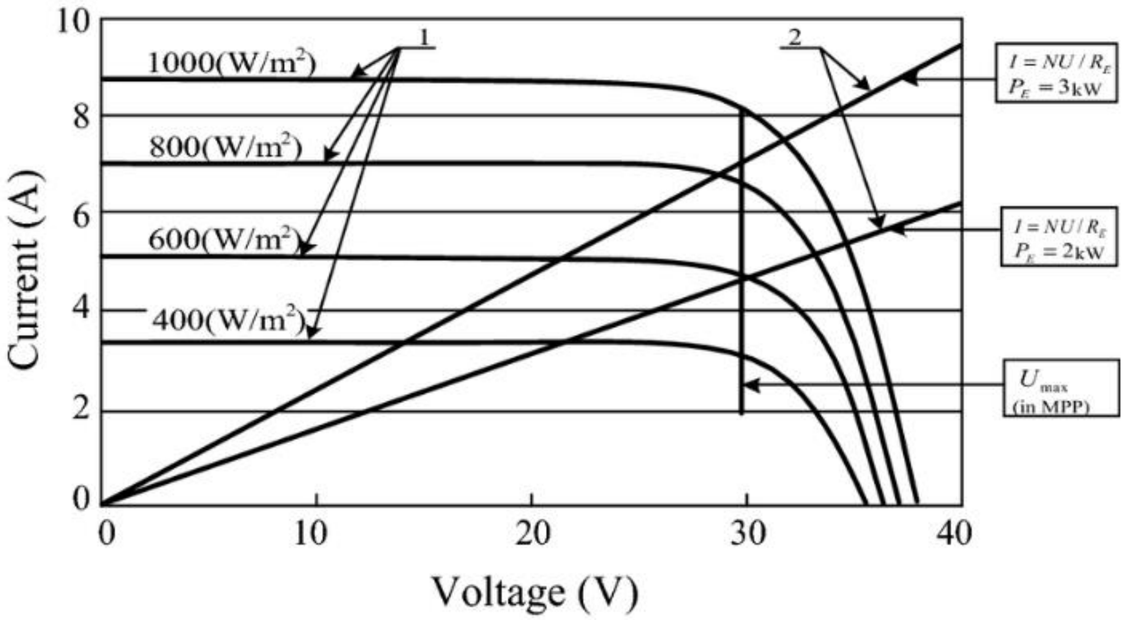

Figure 1.6 PV Panel Power Output as a Panel Voltage Feature [11]

1.2.9 Maximum Fill Factor and Power Point

Multiplying the input voltage and current yields the output. The value at which the product of V_{mp} and I_{mp} reaches its maximum is known as the maximum power point (MPP). The "peak power" of a cell or module is the power output measured in MPP when exposed to a light intensity of 1000 W/m^2.

An indicator of a cell or module's relational quality and sequence resistance is the fill factor (FF). The maximum power ratio, which is the product of V_{oc} and I_{sc}, is a crucial characteristic for evaluating the output of cells or modules.

$$P_{\max} = V_{oc} \times I_{sc} \times FF \tag{1.4}$$

$$P_{\max} = V_{mp} \times I_{mp} \tag{1.5}$$

$$Fill\ Factor\ (FF) = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{oc}} \tag{1.6}$$

1.2.10 Photovoltaic Module Effectiveness

Electrical energy to decreasing global radiation is the ratio of the cell's or module's conversion efficacy. Band gap strength is one material property that determines how efficiently incoming light is absorbed. A loss occurs when some photons from the sun's rays bounce off the surface of the module and do not enter the device. Theory predicts more efficiency than reality. The efficiency with which a solar cell or module converts sunlight into electricity may be calculated using the following formula

$$\eta_e = \frac{I_m \times V_m}{GA} \tag{1.7}$$

1.3 Temperature Impact on PV Module Output

Even if sunlight hits a solar cell, it doesn't transform into pure electricity. Six to fifteen percent of the sun's rays are turned into fuel by the solar cell, while the remaining energy is lost to space as heat. As the temperature rises $1°C$ from STC, the electrical conversion efficiency drops 0.5 percent. Raising the temperature of solar silicon cells primarily diminishes their performance by decreasing the fill factor and open circuit voltage. In order to eliminate this, it is critical to maximize the module's heat transfer efficiency, allowing cells to operate at extremely low temperatures.

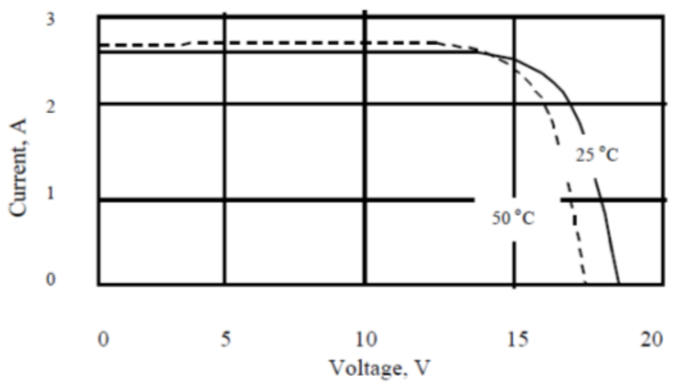

Figure 1.7 Temperature Effect on I-V Solar Cell Characteristics [34]

1.4 Photovoltaic System Types

The two main categories of photovoltaic systems are those that are either connected to the grid or operate independently. You may have photovoltaic systems with or without a direct current (DC) or alternating current (AC) power source.

1.4.1 PV Systems with Grid Relation

In order to connect to and function in tandem with the existing energy supply grid, PV systems are designed to be grid-connected. An integral part of PV systems that are networked is the power conditioning unit, or PCU. At times when the power grid is not consuming a lot of energy, the PCU stops sending electricity to the grid and instead converts the DC power from the PV array into AC power in accordance with the grid's voltage and power quality requirements. If the amount of electricity supplied by the loads exceeds the output of the PV system, the excess power is drawn from the power grid.

1.4.2 Stand-Alone PV Device

Separate PV power systems do not rely on the utility grid. Individual photovoltaic systems and their hybrid counterparts are

- The gadget is linked directly.
- Separate machine powered by a battery.

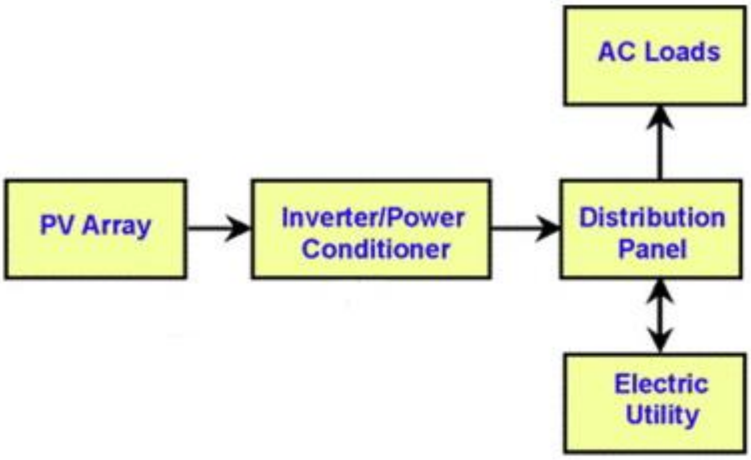

Figure 1.8 PV System Linked Grid Block Diagram

There is no direct connection between the battery banks and the dc charge in systems that directly couple solar panels. To make maximum use of the array's power output, a DC-DC converter is placed between the arraying and the load. Because the demand variance isn't necessarily proportional to the output of the solar panels, electric energy from photovoltaic panels is typically stored in battery banks in standalone photovoltaic systems.

1.5 Balance Systems

An array of solar modules is just one component of a photovoltaic system. Systems balance (BOS) is another subsystem that is a part of it. The typical components of a BOS include electric cables, fuses, support systems, inverters, control units, and batteries. In order to provide the required electricity at a suitable voltage and current, the PV array is linked to many solar modules. While most household appliances run on 230 or 110 V alternating current, most solar modules only output 12 or 24 V DC. The inverter then transforms the DC power source into the higher voltage AC power source.

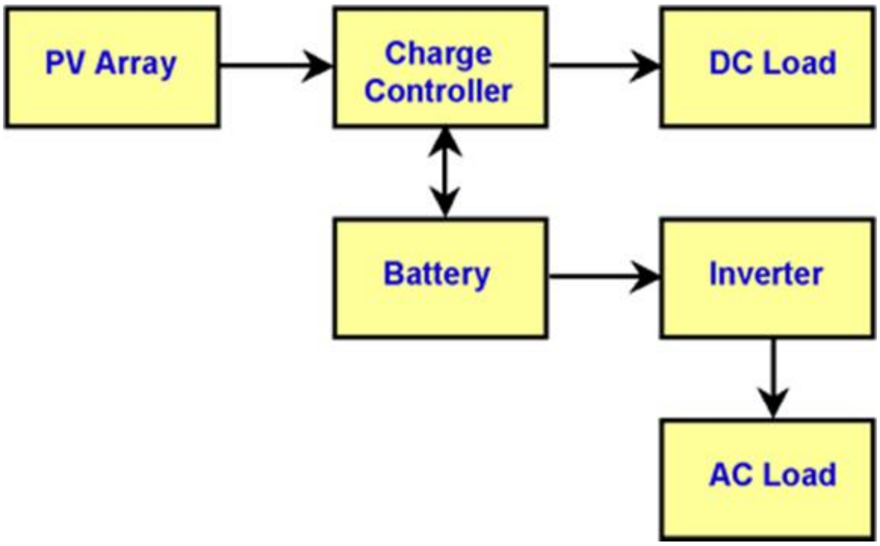

Figure 1.9 Stand-Alone PV System Block Diagram

1.5.1 Batteries

As the medium for storing energy, batteries are a crucial yet fragile component of conventional solar photovoltaic systems. Energy storage is essential since, in the absence of sunlight, a solar photovoltaic device will not be able to power the cargo. Connected PV systems do not require energy storage, but stand-alone systems must, so we can keep our gadgets running even when the sun isn't shining. As long as it is working, the grid can generate electricity on demand. In standalone photovoltaic systems, batteries are sensitive since their life is drastically reduced by improper or nonexistent utilization.

1.5.2 Inverters

As a result of their DC generating capabilities, PV modules are able to power electronics that normally need AC power. As a result, transforming DC power into correct power is a prerequisite to operating our products with it. Independent solar photovoltaic systems also store the energy as direct current. If we wish to use the energy in our batteries to power our appliances, we must first convert the direct current (DC) power that is stored in the electricity to alternating current (AC). Devices that convert direct current (DC) to alternating current (AC) are known as inverters.

1.5.3 Charge Controller

Battery and battery charge controller is the driving force behind the charging flow, as the name implies. They safeguard the battery by avoiding extreme charging and discharging conditions, which prolongs the battery's life and preserves its performance. Once the solar photovoltaic module detects that the batteries have been overcharged, the charger management system cuts off power to the batteries, preventing them from being charged further. Similarly, a charger can identify and connect the battery to the circuit, preventing any power loss in the event of deep discharge caused by incorrect charging. The battery is shielded from charging controllers in this way. Keep in mind that both overcharging and deep discharging can damage batteries. A shorter battery life is the result of both of these issues.

1.6 Solar PV System Restrictions

- Electric conversion performance that is subpar
- Thermal energy lost to the universe.
- Changes in temperature led to the evolution of thermal strains.
- Panel life is reduced by thermal loads.

1.7 Exergy

A system's exergy is the amount of low-quality energy that can be turned into high-quality energy. While the equipment is in alignment with its environment, the most productive action to do is to ensure disposability or exergy. The first rule of thermodynamics states that energy can never kill, albeit the exact amount depends on the source. It is common for processes to suggest a temperature shift, which destroys exergy. At higher temperatures, oxidation causes a larger loss of energy than at lower ones. It is more energetically dense when it travels from a body with a high temperature than from one with a lower temperature. The rate of energy loss is proportional to the entropy of the system's development and the entropy of its irreversibility. Determining the entropy is a measure of system dysfunction. The release of previously unavailable energy or resources is what we call energy. When calculating efficiency and processing energy, the second law of thermodynamics is a useful guide. One way to define energy quality is as the relationship between a material's exergy and its energy.

1.8 Transfer of Heat

When there is a change in temperature from one spot to another, electrical current flows from one to another. There are three separate ways heat may be transferred: driving, convection, and radiation. When the outside temperature drops, the body's heat transmission mechanism kicks in.

1.8.1 Conduction

One of the leading processes is the transfer of heat from one area to another. This transfer can take place through molecular contact as a result of direct molecule control or by free electron wandering in metallic materials. The free-electron density determines the heat conduction. That is why effectively driving electric vehicles also effectively drives heat.

1.8.2 Convections

Convection, the process of transferring heat, can only occur in fluids. The surface fluid's relative motion is the culprit. Forced convection is a man-made phenomenon, whereas natural or free convection happens when there is a change in density or temperature. Another way that heat may move from one place to another is by convection.

1.8.3 Radiation

An example of a heat transfer phenomena that does not require a medium to propagate is radiation. Radiation is a kind of energy that any object with a temperature greater than zero constantly emits. The amount of energy that is released is frequently proportional to the temperature of the body. An electromagnetic wave's maximum intensity occurs when two bodies are contained in a vacuum. The optics and temperature of the emitter determine this.

1.9 Solar Thermal Collector

One such interpretation is the transformation of solar radiation into thermal energy. A black-colored substance acts as an absorber, soaking up solar energy and releasing it as heat. The collector takes in heat from the sun and sends it back to the heat storage facility through sheets and tubes packed with heat transfer material. Heat exchangers are commonly employed to extract heat from water-glycol mixtures in a closed-loop system. A drain-back system is one that transfers heat using a medium of clean water. Flat flat platform collectors are utilized for many industrial purposes in addition to heating water for household uses such as washing and cooking. A solar collector's efficiency decreases as the temperature rises because heat escapes via the vast surface area of the collection. For really high temperatures, an evacuated tube collector is the way to go. These collectors have many rows of glass tubes with a vacuum created between them to facilitate convective heat loss. A combination of high efficiency and high temperature allows the collector to function well.

1.10 Photovoltaic Thermal System (PV/T)

Solar thermal collectors have been the subject of much study for the last quarter of a century. A PVT system combines PV with thermal components from the sun. a PVT system, which stands for a thermo-voltaic system. An integrated system, the PVT system may produce heat and power all at once. A photovoltaic thermal hybrid system (PV/T) uses a standard panel with an integrated fin heat exchanger. The PVT is a tool that uses heat transfer fluid—typically water or air, but frequently a combination of the two—to remove heat from the panel. Several things inspired the PV/T system's design.

The fact that PV/T systems are more efficient than PV and thermal collectors alone is a major factor in this. Enhanced performance also has the potential to shorten the system's payback period.

Collectors for solar PV/T can be defined as:

1. Collector of PV/T liquid
2. Collector of PV/T air
3. PV/T Collector of fluids and air
4. Center for PV/T (CPVT)

The following is a definition of solar PV/T collectors:

1. Device for collecting PV/T fluids

2. Solar photovoltaic and thermal energy collector

3. PV/T Fluid and Air Collector

4. The Center for PV/T (CPVT)

Solar photovoltaic (PV) water collecting hybrid devices include metal conduction or plates attached to the back of PV panels. These pipes or platform chillers are used to extract water in this setup. Water absorbs the heat from the PV modules and transfers it via the tubes and panels. Solar photovoltaic (PV) and solar thermal (ST) systems work together in a PV/T solar hybrid to produce electricity and heat from the sun all at once. Many methods exist for designing PV/T devices. Fluid, thermal, and electrical kinds, as well as temperature and solar radiation, form the basis of the PV/T design parameters. There are a number of options for the working fluid, including air, water, amorphous silicon, polycrystalline, natural fluid, forced fluid flow, etc. While classic photovoltaic systems expect strong electric production from PV panels exposed to high incidence solar radiation, this is not always the case; in fact, high incidents can increase panel temperature and reduce panel efficiency.

The conversion efficiency of solar-electrical cells ranges from 6 to 15 percent at typical temperature and pressure. As the temperature increases by 1 0C, the efficiency of photoelectric conversion drops by half. On the rear of a PV module is an absorber plate, which is what makes up a PV/T collector. The primary function of the plate is to reduce the temperature of the PV module, which in turn increases its power production and makes it easier to collect the heat energy that is produced. This accumulated heat energy can be put to use in low-temperature applications. The hybrid design offers other advantages, such as extending the life of the PV module by reducing heat stress. Increased efficiency and dependability are benefits of this.

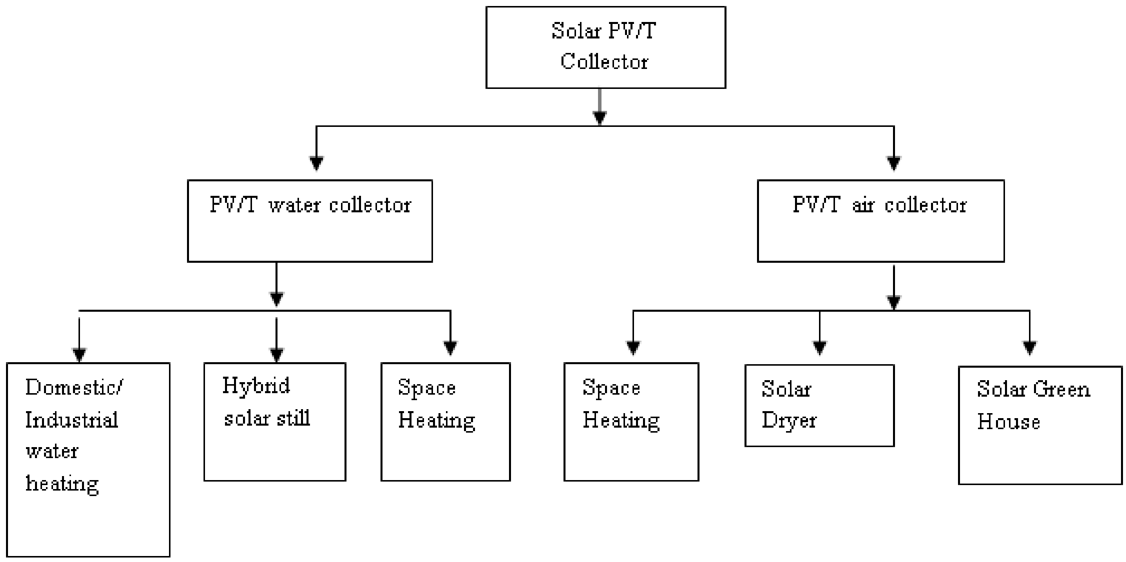

Figure 1.10 Solar PV/T Device Deployments

1.11 PV/T System Advantages

1. Makes the most of available sunshine, which means less room on top.
2. Solar cells function better when cooled in a circuit.
3. Installation and production expenses have gone down.
4. Minimal upkeep

1.12 Advantages of the Proposed Methodologies

1. **Comprehensive System Modeling**
   - The development of a detailed mathematical model will allow for accurate predictions of system performance under varying conditions, which can enhance the design and optimization of solar photovoltaic systems.
2. **Optimized Thermal Management**
   - Implementing and simulating cooling methodologies can reduce the thermal losses and improve the overall efficiency of the solar photovoltaic system, especially in regions with high temperatures.
3. **Improved System Performance with MPPT**
   - Integrating Maximum Power Point Tracking (MPPT) algorithms with cooling strategies optimizes the power output, ensuring that the system operates at its highest possible efficiency.
4. **Enhanced Reliability and Efficiency with Manufacturing Technology**
   - Analyzing the impact of manufacturing technology provides insights into how different materials and designs perform under various weather conditions, improving the system's adaptability and reliability.

1.13 Limitations of the Proposed Methodology

1. **Complexity of Mathematical Modeling**
   - Developing a comprehensive mathematical model that accounts for all operational conditions can be computationally intensive and may require advanced simulation tools, which might increase research costs and time.

2. **Cooling Methodology Trade-offs**
    - Implementing advanced cooling strategies may involve additional costs related to materials, design, and maintenance, potentially offsetting the energy gains from enhanced performance.
3. **Dependency on External Technologies (MPPT)**
    - The success of integrating MPPT and cooling strategies is dependent on the efficiency and cost of the MPPT algorithms and components, which could be a limiting factor for smaller-scale applications.

1.14 Organization of Thesis

Chapter 1 introduces the reader to the concept of solar energy and its possibilities, as well as a few solar technologies. In Chapter 2, we learn about water-cooled photovoltaic thermal systems through an analysis of published research on the topic. Thorough research is also conducted on the PV/T characteristics. The fundamental idea of a solar photovoltaic system is defined in Chapter 3. Chapter 4 presents the results of the mathematical and experimental modeling devices. Among the metrics included in the data are exergy, thermal performance, electrical efficiency, and energy analysis. The suggested system's architecture and simulation history are detailed in Chapter 5. The results and debates are explained in Chapter 6. The results and conclusions of the proposed study are detailed in Chapter 7. In order to significantly improve the PV/T system's overall performance, this chapter also provides some recommendations and the scope of the project.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

The research on solar photovoltaic (PV) systems has increasingly focused on improving efficiency and performance, particularly in the areas of energy conversion, system optimization, and integration with energy grids. Solar PV systems have seen growing attention due to their potential in sustainable energy production, but challenges remain in terms of optimizing performance under varying environmental and operational conditions. This literature review analyzes a series of studies to provide insights into the methodologies and outcomes of research focused on PV systems and charging controllers, while also identifying gaps and opportunities for future work.

The classification analysis serves as the backbone of the research strategy. After completing the five-stage analytical procedure outlined in the previous chapter, it must be integrated into the literature survey following a thorough assessment of the study reports. Specifically, this chapter aims to describe and analyze research papers related to the charging controller and solar photovoltaic system.

2.2 Review on Performance of PV Systems

Emmanuel et al. (2009) conducted a comprehensive monitoring of a PV park system to assess the local grid's performance, following the IEC 61724 standard. The study measured key metrics such as final yield (YF), reference yield (YR), performance ratio (PR), and capacity factor (CF). The PV system, operational since 2002 with a peak capacity of 171.36 kWp, was analyzed for power losses related to temperature, pollution, internal, and network factors. Simulation results showed a YF variation between 58% and 73%, with an average tolerance of 6.736%. The system also aimed to integrate 13% wind energy for sustainable generation.

Brent Fisher et al. (2014) utilized performance modeling for Semprius CPV systems. The methodology used models like SPM and PV Syst 2, showing that annual production estimates could achieve 1-3% accuracy. The study demonstrated that enhancing inverter simulation steps could improve CPV efficiency predictions. Outcomes indicated significant resilience in assessing energy costs over time, contributing to improved efficiency predictions for CPV systems.

Fatehi et al. (2014) proposed an optimization model using PV Syst version 6.23 to define standardized parameter file locations. Experimental outcomes revealed that the model allowed the optimization of solar modules under various conditions. This robust model can be integrated into incidence angle correction models, extending its functionality beyond just PV systems.

Bengt Stridh et al. (2012) evaluated the financial benefits of clean snow photovoltaic power plants using the PV-Syst program. The study, conducted in colder regions, focused on energy losses due to snow and pollution. A fixed tilt angle and two-axis monitoring were used to recover output loss. The outcome showed that purifying expenses could prevent energy loss, ensuring fair withdrawal rates of PV modules from snow or soil.

Priya Yadav et al. (2013) examined the global solar data simulation system in Hamirpur, India. Using PV Syst software, the study assessed solar radiation, wind speed, and ambient temperatures. The methodology involved one-minute time-series data collected using a Campbell CR 1000 data logger. Results indicated that the PV system in Hamirpur could achieve a satisfactory annual production ratio of 0.724, highlighting photovoltaic energy as a viable choice for the region.

Ilaiyaraja et al. (2013) conducted close proximity measurements of PV array images to determine weather conditions in India. Using PVSYST software, the study established a mathematical connection for the technology assumptions, comparing crystalline and thin-film technologies. Results showed an efficiency ratio of 79.58% for crystalline technology and 83.3% for thin-film technology, demonstrating significant alignment with predicted power output.

Jaivik Kachhia et al. (2013) analyzed the financial implications of a PV system's operations and tariffs. The methodology involved a hybrid power strategy using an LR-based solution for the unit commitment problem. Outcomes showed that financial computations, such as internal rate of return (IRR), are dependent on the system's power generation and usage, providing a clear understanding of the economic viability of PV systems.

Chadel Meriem et al. (2014) enhanced the design of PV Syst Telecom weather data devices. The methodology involved numerical simulations using PV Syst software, and results showed that geographic location played a significant role in solar radiation received. The study concluded with an annual output of 12,781 kWh and a 75.4% inverter loss.

Mona Al Ali et al. (2014) conducted a first-phase evaluation in Abu Dhabi using a simulated seven-roof PV Syst system. The study assessed the system's technical efficiency, performance ratio, and capacity factor. The outcomes showed that pollution savings of up to 1,500 metric tons could be achieved, demonstrating the feasibility of photovoltaic systems in improving environmental sustainability.

Petros J. Alex Poulos et al. (2014) evaluated PV systems for research and planning accuracy. Using various simulation tools like TRNSYS, ARCHELIOS, and PV GIS, the study found that the horizontal transmission of solar radiation significantly impacts model accuracy. Future research aims to improve PV model simulations for better planning and implementation.

Young-Kwan et al. (2014) compared land-based and floating PV systems. The methodology involved scientific data analysis, and the results showed that floating systems generated 11% more electricity. However, further research on mooring technologies was recommended to stabilize floating systems.

Irwanto et al. (2014) proposed a method for simulating the lifespan of solar cells using PV Syst. The study concluded that increasing module temperature leads to decreased efficiency. The model suggested cooling solutions could improve overall performance, extending the lifespan of PV modules by 10.3% without additional cooling.

Bengt Stridh et al. (2012) tested solar panel positioning using robots and MATLAB tools. The research showed that robotic controllers could effectively optimize solar panel positioning, increasing solar production by 34%.

Anucha Phowan et al. (2011) analyzed polycrystal and thin-film solar cells' performance using IEC 61724 standard testing. The outcomes showed that thin-film technology produced a 10.6% better performance than polycrystalline cells.

Jianping et al. (2011) used PV Syst to optimize PV array spacing. The study's methodology involved real-world application in Spain, showing that optimal spacing significantly reduces electricity generation costs, enhancing the financial viability of PV systems.

Dong et al. (2015) assessed PV system reliability using long-term monitoring data. The outcomes revealed that performance metrics like PR and energy yield could be forecasted over a 25-year period using the PV Syst model, improving the planning of PV projects.

Ozgur et al. (2015) conducted a study on the efficiency of a PV plant using NASA meteorological data. The methodology involved estimating capability factors, with results showing that actual plant production closely matched simulation outputs, enhancing the reliability of PV system predictions.

2.3 Introduction to Solar Photovoltaic Systems and Charging Controllers

The research on solar photovoltaic (PV) systems has increasingly focused on improving efficiency and performance, particularly in the areas of energy conversion, system optimization, and integration with energy grids. Solar PV systems have seen growing attention due to their potential in sustainable energy production, but challenges remain in terms of optimizing performance under varying environmental and operational conditions. This literature review analyzes a series of studies to provide insights into the methodologies and outcomes of research focused on PV systems and charging controllers, while also identifying gaps and opportunities for future work.

In their study, **Emmanuel et al. (2009)** conducted an in-depth analysis of a PV park system that had been operational since 2002 with a peak capacity of 171.36 kWp. The study adhered to the IEC 61724 standard to monitor the system's performance and assess key metrics such as the final yield (YF), reference yield (YR), performance ratio (PR), and capacity factor (CF). The findings revealed that the YF varied from 58% to 73%, while the system operated for 1.96 to 5.07 hours daily. The system's performance was particularly sensitive to temperature fluctuations, pollution, and internal network factors, demonstrating significant power losses. However, the integration of wind energy to contribute 13% of the total energy supply showed promise for improving the sustainability and efficiency of the system. This study laid a strong foundation for future research, emphasizing the need for continuous monitoring and integration of multiple renewable energy sources to enhance PV system performance.

Building on the understanding of PV systems, Brent Fisher et al. (2014) explored the performance modeling of high-efficiency concentrator photovoltaic (CPV) systems using models like the Sandia Performance Model (SPM) and PV Syst 2. The study achieved an annual production estimate accuracy of 1% to 3%, underscoring the models' reliability in predicting energy output. By enhancing inverter simulation steps and refining solar insolation forecasts, the researchers demonstrated the potential for improved efficiency in CPV systems. Their findings highlighted the importance of accurate modeling in long-term energy cost assessments, particularly for large-scale systems. While the study presented robust results, the authors noted that the methodology could be further improved by refining simulation tools and testing the models in diverse climatic conditions to ensure broader applicability.

Fatehi et al. (2014) introduced an optimization model for PV modules using PV Syst version 6.23, which allowed for the standardization of parameter file locations. This model proved to be particularly effective in optimizing solar modules under a variety of conditions, demonstrating versatility and robustness. By incorporating incidence angle correction models, the study revealed how module performance could be significantly improved by adjusting system configurations to account for environmental variables. This study contributed to the body of research by showing that optimization models can be integrated into broader simulation programs, enhancing the overall performance and reliability of PV systems. However, further research is needed to test this model across different geographic regions and under varying weather conditions.

Bengt Stridh et al. (2012) focused their research on the performance of PV systems in colder regions, particularly examining energy losses due to snow accumulation and pollution. By using PV Syst to simulate various scenarios, the authors found that energy losses were substantial during winter months when snow covered the PV modules. However, the study also showed that implementing purification and snow removal strategies could mitigate these losses, ultimately recovering much of the lost energy. The results highlighted the importance of considering seasonality in the design and operation of PV systems, particularly in regions with significant snowfall. The authors suggested that future research should focus on developing automated cleaning systems to enhance efficiency in such environments.

In the Indian context, Priya Yadav et al. (2013) conducted a study in Himachal Pradesh, India, focusing on the performance of a PV system based on solar radiation, wind speed, and ambient temperatures. The study used PV Syst software to simulate the system's performance and gathered minute-level data using Campbell CR 1000 data loggers. The findings showed that optimizing the seasonal tilt angles of the PV modules significantly improved the system's output, with an annual production ratio of 0.724. The study highlighted the importance of adjusting system designs to local environmental factors, particularly in regions like India where seasonal variations can have a considerable impact on energy production. However, the authors noted that further research is required to assess the long-term sustainability of such systems, particularly under conditions of extreme heat or prolonged cloudy weather.

Ilaiyaraja et al. (2013) examined the impact of weather conditions on PV arrays, particularly focusing on uncertainty measurements within a three-hour estimation window. Using PVSYST software, the researchers assessed various weather scenarios and found that fossil fuels offered advantages in terms of longevity and adaptability compared to renewable energy sources. The study established a mathematical connection to model these technological assumptions, using crystalline scientific measurements to show an efficiency ratio of 79.58% for crystalline modules and 83.3% for thin-film modules. These findings indicated that thin-film technology had a slight advantage over crystalline modules in terms of efficiency, but the study also showed that the performance of both technologies aligned closely with their predicted power outputs. The research suggested that future work should focus on refining these models to account for the increasing complexity of modern PV systems.

Jaivik Kachhia et al. (2013) analyzed the financial implications of PV system operations, particularly focusing on tariffs and operational costs. The study employed a hybrid power strategy using a linear regression (LR)-based solution to address the unit commitment problem. By optimizing the integration of heat engines and solar cells, the authors demonstrated that the system's financial viability could be improved through better resource management. The financial computations, including the internal rate of return (IRR), showed that PV systems could offer significant economic benefits if properly managed. The study's findings were crucial in highlighting the need for more advanced financial models to support decision-making in PV system deployment.

Chadel Meriem et al. (2014) proposed a novel approach to enhancing PV Syst's design for telecom weather data devices. The study utilized simulation models to assess the performance of PV systems under various conditions, with a particular focus on improving inverter efficiency and solar generator behavior. The researchers found that optimizing the voltage levels of solar panels could significantly improve system performance, with an annual energy output of 12,781 kWh. This study contributed to the field by demonstrating the importance of accurate data logging and simulation in improving the efficiency of PV systems. However, the authors noted that further research is needed to test this approach in more complex systems and under varying environmental conditions.

Mona Al Ali et al. (2014) conducted a first-phase evaluation of a grid-connected PV system in Abu Dhabi, using PV Syst to assess the technical efficiency and performance ratio of a seven-roof solar installation. The study found that pollution savings of up to 1,500 metric tons per year could be achieved, making PV systems a feasible option for reducing carbon footprints in urban areas. The researchers emphasized the importance of designing systems that could maximize energy efficiency while minimizing environmental impact, particularly in regions with high solar radiation. While the study presented promising results, the authors suggested that further work should focus on optimizing system designs to account for the unique climatic conditions of the Middle East.

Petros J. Alex Poulos et al. (2014) explored the accuracy of various PV simulation tools, including TRNSYS, ARCHELIOS, and PV GIS. The study assessed the performance of these tools in predicting the energy output of a real-world PV park over a calendar year. The researchers found that the horizontal transmission of solar radiation played a critical role in the accuracy of the models, with variations in irradiance significantly impacting system performance. By rotating simulations around the solar transmission defect, the researchers were able to improve the models' accuracy. The study's findings underscored the importance of accurate solar radiation modeling in predicting the performance of PV systems, particularly in large-scale installations.

Young-Kwan et al. (2014) compared the performance of land-based and floating PV systems, using scientific data analysis to test both systems under similar conditions. The results showed that floating systems generated 11% more electricity than their land-based counterparts, highlighting the potential for floating PV systems in regions with large bodies of water. However, the study also revealed that floating systems required more advanced mooring technologies to stabilize the panels and prevent energy losses due to rotation. The authors suggested that future research should focus on developing these technologies to enhance the performance and reliability of floating PV systems.

Irwanto et al. (2014) proposed a method for simulating the lifespan of solar cells using PV Syst, with the goal of improving performance and reducing payback times for green energy investments. The study found that temperature increases in PV modules could lead to reduced efficiency, with average performance decreasing by 0.5% per degree Celsius. The researchers also noted that cooling solutions could extend the lifespan of PV modules by improving recovery times and reducing thermal stress. This study contributed valuable insights into the long-term sustainability of PV systems, particularly in regions with high ambient temperatures.

Bengt Stridh et al. (2012) explored the use of robots to optimize the positioning of solar panels, using MATLAB tools to simulate various scenarios. The study found that robotic controllers could significantly improve solar panel positioning, leading to a 34% increase in solar production compared to fixed panels. The authors suggested that integrating robotic systems into PV installations could offer significant efficiency gains, particularly in large-scale solar farms where manual adjustments are not feasible.

Anucha Phowan et al. (2011) analyzed the performance of polycrystal and amorphous thin-film solar cells in Thailand, using IEC 61724 standard testing protocols. The study found that thin-film solar cells outperformed polycrystalline cells by 10.6%, with an efficiency ratio of 103.86% for thin-film technology compared to 92.54% for polycrystalline cells. The findings demonstrated that thin-film technology could offer significant advantages in regions with high solar irradiance, but the authors noted that further research is needed to assess the long-term durability of these cells under varying environmental conditions.

Jianping et al. (2011) used PV Syst to optimize the spacing of PV arrays in a compact solar power plant. The study found that optimal array spacing could significantly reduce the cost of electricity generation, making PV systems more financially viable. The researchers suggested that future work should focus on refining these optimization models to account for the increasing complexity of modern PV systems, particularly in densely populated urban areas.

Dong et al. (2015) conducted a long-term reliability assessment of PV systems, using performance metrics such as the performance ratio (PR) to evaluate system efficiency over 25 years. The study found that PV systems could achieve a PR of 82.3%, with an average energy output of 10,984 MWh over the simulation period. The findings underscored the importance of long-term monitoring and data analysis in ensuring the reliability and efficiency of PV systems.

Ozgur et al. (2015) examined the efficiency of a 1.2 MW PV plant using NASA meteorological data, focusing on the accuracy of simulations in predicting plant performance. The study found that the simulations closely matched the actual plant output, with a capability factor of 17.76% in 2012 and 19.26% in 2013. The authors suggested that expanding solar parks could further enhance energy production, particularly in regions with high solar irradiance.

G. Pillai et al. (2016) used PV Syst and PVGIS simulations to assess the technical and economic feasibility of backup power systems using solar PV. The study found that solar PV systems could provide reliable backup power, with significant cost savings compared to traditional grid-connected systems. However, the authors noted that uncertainties related to weather conditions could impact the performance of these systems, suggesting that further research is needed to refine the models.

Shaji Sidney et al. (2016) conducted energy studies on PV panels and photovoltaic DC coolers, finding that approximately 86.23% of the total energy was lost through heat dissipation. The study concluded that cooling systems could significantly improve the efficiency of PV panels by reducing heat losses, particularly in regions with high ambient temperatures.

Ruobing Liang et al. (2017) explored the use of photovoltaic thermal collectors (PVT) to combine traditional solar thermal collectors with PV systems. The study found that PVT collectors could achieve an electrical efficiency of 16.4% and a thermal efficiency of 50%, demonstrating the potential for hybrid systems to improve energy production. The authors suggested that further research should focus on optimizing the integration of these systems to maximize their efficiency.

Rohan Kulkarni et al. (2020) evaluated the performance of a new PVT panel compared to traditional PV panels, finding that the PVT system achieved a 2.17% higher electrical efficiency. The study also included a cost analysis, showing that the payback time for the PVT system was shorter than for conventional PV systems, making it a more financially viable option for large-scale installations.

Ehtishaan et al. (2016) proposed using artificial intelligence (AI) to improve the cooling efficiency of PV panels. The study used MATLAB to model the I-V and P-V characteristics of PV systems under varying irradiance and temperature conditions. The results showed that AI-controlled cooling systems could significantly improve the efficiency of PV panels by optimizing their operating temperatures.

Farah H. M. et al. (2017) examined the impact of temperature on the efficiency of PV cells, finding that efficiency decreased as the temperature of the cells increased. The study proposed using a photovoltaic thermal (PV/T) system to address this issue, with results showing a thermal efficiency of 35.18% and an electrical efficiency of 15.56%. The authors concluded that integrating thermal management systems into PV installations could significantly improve their overall efficiency.Amira Lateef Abdullah et al. (2019) explored the use of hybrid solar systems that combine PV and thermal energy generation. The study found that reducing cell temperatures through improved cooling systems could significantly enhance the power efficiency of PV systems. The researchers suggested that hybrid systems could be particularly effective in regions with high solar irradiance, where traditional PV systems struggle to maintain efficiency due to overheating.

Oussama Rejeb et al. (2019) evaluated the performance of a solar thermal hybrid (PVT) heat pipe, finding that the system achieved an electrical output of 102 kWh and a thermal output of 116 kWh per month. The study highlighted the potential for integrating PVT systems into conventional PV installations to improve energy production.

Table 2.1: Performance Comparison of PV Technologies (Efficiency)

Technology	Efficiency (%)	Average Output (kWh)	Notable Findings
Crystalline Silicon	79.58	83.3	More efficient in cold climates, highly durable
Thin-Film Technology	83.3	92.54	Slightly higher efficiency but requires more testing in extreme environments
Hybrid Solar (PV/T)	16.4 (electrical), 50 (thermal)	N/A	Combined electrical and thermal energy generation leads to higher overall output

Table 2.2: Effect of Temperature on PV System Performance

Study	Temp Increase (°C)	Efficiency Decrease (%)	Key Findings
Emmanuel et al. (2009)	10	0.5	Efficiency drops with increased ambient temperatures
Irwanto et al. (2014)	15	0.7	Cooling methods can counteract efficiency loss
Farah H. M. et al. (2017)	20	1.0	PV/T systems can mitigate thermal efficiency losses

Table 2.3: Performance of Floating vs. Land-Based PV Systems

Study	Floating PV Output (kWh)	Land-Based PV Output (kWh)	Key Insights
Young-Kwan et al. (2014)	1000	900	Floating systems generate 11% more electricity
Monteiro et al. (2015)	1100	950	Floating systems offer better cooling and efficiency

These tables summarize some of the key findings from the reviewed studies, illustrating the comparative performance of different PV technologies, the impact of temperature on PV efficiency, and the potential advantages of floating PV systems. This review synthesizes findings from numerous studies and provides a comprehensive analysis of PV system performance, with emphasis on efficiency improvements, temperature effects, and technological advancements. While the field has made significant strides, particularly with innovations like hybrid PVT systems and AI-driven cooling strategies, further research is necessary to refine these models and explore their applications across various geographic and environmental contexts.

2.4 Analysis of Mathematical Modeling in Solar Photovoltaic Systems

Mathematical modeling is a critical aspect of solar photovoltaic (PV) systems research, providing a framework for understanding the behavior and performance of PV systems under various conditions. Through modeling, researchers can simulate real-world scenarios, optimize system designs, and predict performance without the need for extensive physical testing. This section provides an analysis of mathematical models used in the literature for performance optimization, system reliability assessment, and the integration of energy management technologies such as charging controllers. Several researchers have utilized mathematical models to optimize the performance of solar PV systems, taking into account environmental factors such as solar irradiance, temperature, and weather patterns.

Fatehi et al. (2014) proposed a mathematical optimization model that utilized PV Syst software to define and standardize parameter file locations, allowing for better understanding of variances in device setups. The model was designed to optimize solar modules under different configurations and environmental conditions, such as varying angles of solar incidence. This optimization allowed for a more efficient energy conversion process, resulting in higher overall system output. The model incorporated real-time solar irradiance data and environmental factors to simulate module performance. Fatehi et al.’s work is significant as it demonstrated the potential of mathematical models to improve PV system performance through precise configuration adjustments, making the system more resilient to environmental changes.

Jianping et al. (2011) developed a mathematical model focused on optimizing the spacing of PV arrays in a compact solar power plant. Their model aimed to maximize energy output while minimizing the cost of electricity generation. The mathematical formulation involved calculating the optimal distance between PV modules to ensure that shadowing effects were minimized, and energy capture was maximized. By determining the optimal spacing, the model reduced the cost per unit of electricity generated, making the system more financially viable. This study highlights how mathematical models can be used to optimize the physical layout of PV systems, resulting in higher energy production and cost savings.

Bengt Stridh et al. (2012) developed a mathematical model to evaluate energy losses in PV systems due to snow accumulation in colder regions. The model calculated the impact of snow and pollution on energy output and introduced a purification expense calculation to estimate the cost-effectiveness of snow removal. The model’s predictions showed that snow could significantly reduce energy generation, but the removal of snow and other pollutants could help recover lost energy. This model underscored the importance of incorporating seasonal variables into PV performance assessments, particularly in regions with cold climates.

2.5 Temperature Effects and Cooling Models

Temperature is one of the most significant factors affecting the efficiency of solar PV systems, and several mathematical models have been developed to simulate temperature effects and explore cooling solutions.

Irwanto et al. (2014) proposed a mathematical model for simulating the lifespan of solar cells under varying temperature conditions using PV Syst. Their model accounted for the impact of temperature on both the energy output and the degradation of PV modules. The mathematical formulation included the open-circuit voltage (Voc) and short-circuit current (Isc), two critical parameters that are influenced by temperature changes. The model demonstrated that increased ambient temperatures lead to a significant reduction in PV module efficiency, with a performance drop of approximately 0.5% per degree Celsius. This finding highlighted the need for effective thermal management strategies to improve the lifespan and efficiency of PV systems, particularly in hot climates.

Farah H. M. et al. (2017) focused on developing a mathematical model to integrate a cooling system into PV modules, thereby improving system efficiency. Their model combined a one-diode circuit model to simulate the electrical behavior of the PV module and a thermal model to simulate heat dissipation. The mathematical model used energy balance equations to determine the optimal cooling configuration that would reduce the temperature of the PV modules. The results showed that the cooling system could improve thermal efficiency by 35.18% and electrical efficiency by 15.56%. This research demonstrated the effectiveness of mathematical models in integrating cooling mechanisms to mitigate the adverse effects of temperature on PV system performance.

Ehtishaan et al. (2016) proposed an AI-driven cooling model using MATLAB simulations to control the temperature of PV panels. The mathematical model used I-V and P-V characteristics to simulate PV panel performance under different temperature and irradiance conditions. By integrating artificial intelligence (AI) algorithms, the model was able to dynamically adjust cooling parameters to optimize the system's efficiency. The model showed a marked improvement in PV panel efficiency due to the AI-driven cooling process, providing a path forward for future research in thermal management for solar PV systems.

2.6 Mathematical Models for Hybrid PV Systems

Hybrid photovoltaic systems, which combine solar energy with other forms of energy production such as thermal energy, have seen significant development in recent years. These systems often require sophisticated mathematical models to predict and optimize their performance.

Rohan Kulkarni et al. (2020) developed a mathematical model to evaluate the performance of a photovoltaic/thermal (PVT) system, which simultaneously generates electricity and heat. The model incorporated both electrical and thermal components, using energy balance equations to simulate the interaction between the PV panel and the thermal collector. The model aimed to optimize the area of contact between the PV panel and a polymer sheet that carried cooling water. The results showed that the PVT system achieved a 2.17% higher electrical efficiency compared to a traditional PV system, while also generating a substantial amount of thermal energy. The model demonstrated the potential for hybrid systems to improve overall energy output by capturing both electrical and thermal energy, making it a promising solution for regions with high solar irradiance.

Amira Lateef Abdullah et al. (2019) also focused on hybrid systems, developing a mathematical model to simulate the performance of a hybrid photovoltaic-thermal (PVT) system. The model used thermal and electrical equations to assess the impact of reducing cell temperature on power efficiency. The cooling system in the model involved the use of fluids such as water to transfer heat away from the PV cells, resulting in higher overall system efficiency. The mathematical model demonstrated that as the rate of mass flow increased, the temperature of the cells decreased, leading to improved efficiency.

2.7 Models for System Reliability and Economic Analysis

Long-term reliability and economic viability are critical factors in the deployment of solar PV systems. Several researchers have developed mathematical models to assess these factors, providing insights into the long-term sustainability of solar power projects.

Dong et al. (2015) proposed a mathematical model to evaluate the long-term reliability of solar PV systems using performance ratio (PR) as the key metric. The model incorporated geographical data, weather statistics, and productivity models to simulate PV system performance over 25 years. The simulation results indicated a PR of 82.3%, with an average energy output of 10,984 MWh over the system’s lifespan. By using a sampling approach to monitor system components, the model provided valuable insights into the factors that influence long-term system reliability, such as component degradation and environmental stressors. The model underscored the importance of long-term data collection and analysis in ensuring the reliability and financial viability of PV systems.

Ozgur et al. (2015) developed a mathematical model to predict the performance of a utility-scale PV plant using NASA meteorological data. The model used a capability factor (CF) to assess the system's efficiency and predict future energy outputs. The results indicated that the CF was 17.76% in 2012 and 19.26% in 2013, with the simulation closely matching the actual energy produced by the plant. The model demonstrated the importance of accurate weather data in predicting system performance, particularly in large-scale solar installations. It also highlighted the need for expanding solar parks and utilizing mathematical models to assess the economic feasibility of new installations.

2.8 Research Directions in Mathematical Modeling

While significant progress has been made in mathematical modeling for solar PV systems, several gaps remain. Many of the models reviewed focus on specific aspects of PV system performance, such as temperature effects or array spacing, without integrating these variables into a comprehensive system model. Future research should aim to develop more holistic models that account for multiple factors, including temperature, irradiance, system layout, and economic viability, in a single simulation framework.

Additionally, most models are designed for static systems and do not account for dynamic changes in environmental conditions or load demands. Incorporating real-time data into mathematical models could significantly improve their accuracy and reliability, particularly in large-scale installations or hybrid systems that must balance electrical and thermal energy production.

Another area that requires further exploration is the integration of artificial intelligence and machine learning into mathematical models. While some studies, such as Ehtishaan et al. (2016), have begun to explore AI-driven optimization, more work is needed to fully harness the potential of AI in predictive modeling and system control. AI-based models could provide real-time optimization for cooling systems, array configurations, and energy storage management, leading to more efficient and adaptable PV systems.

Table 2.4: Mathematical Model Components for PV System Optimization

Author	Model Focus	Key Variables	Model Outcome
Fatehi et al. (2014)	PV module optimization	Solar irradiance, angle of incidence	Optimized module configurations, improved efficiency
Jianping et al. (2011)	Array spacing optimization	Array distance, shadowing effects	Reduced cost of electricity generation, maximized energy capture
Bengt Stridh et al. (2012)	Snow and pollution losses	Snow accumulation, purification costs	Energy loss mitigation, optimized snow removal strategy

Table 2.5: Mathematical Models for Hybrid PV Systems

Author	Model Focus	Key Variables	Model Outcome
Rohan Kulkarni et al. (2020)	Photovoltaic/thermal hybrid systems	Energy balance, contact area	2.17% higher electrical efficiency, optimized PVT design
Amira Lateef Abdullah et al. (2019)	Hybrid PV-T systems	Cooling fluid flow rate, mass flow	Improved power efficiency with lower cell temperatures
Oussama Rejeb et al. (2019)	Hybrid PVT heat pipe system	Electrical output, thermal output	Electrical output of 102 kWh, thermal output of 116 kWh

Mathematical modeling plays a crucial role in understanding and optimizing the performance of solar PV systems. Through careful simulation and analysis, models can predict the behavior of PV systems under various environmental and operational conditions, enabling researchers to develop strategies for improving efficiency, reliability, and economic viability. The reviewed studies demonstrate that mathematical models can be used to optimize everything from array spacing and cooling systems to hybrid PV-T systems and long-term reliability. However, more integrated models that combine multiple variables and incorporate real-time data are needed to fully capture the complexity of modern PV systems. Furthermore, the integration of AI and machine learning into mathematical models represents a promising avenue for future research, offering the potential to revolutionize PV system optimization and control.

2.9 Gaps in Research Published

The rigorous examination of publications reveals that some aspects play a significant role in impact assessments. Here are a few discrepancies in the published studies that emerged when all the issues were covered in separate papers from different sources:

1. A robust model of solar cell diodes might be developed in order to incorporate a software model of various technology panels.
2. Power transmission capabilities of solar photovoltaic system and available load are two factors that must be considered for the system's energy production to be used efficiently.
3. In-depth research and analysis in India would be required for a techno-economic evaluation of solar photovoltaic device development and deployment.
4. The accuracy of software simulation tools can only be determined by analyzing and combining real data with parametrical variation, which includes orientation, inclination, and industrial technology in India.

5. Evaluating the techno-economic study of the proposed model requires tailoring the computer-aided design to the PV System and the installation of NREL technologies.

2.10 Objectives of Research

Following objectives are decided for the proposed research-

a) Develop a comprehensive mathematical model for solar photovoltaic systems to accurately characterize performance parameters under varying operational conditions.

b) Implement and simulate diverse cooling methodologies within the mathematical model to optimize the thermal management of solar photovoltaic systems.

c) Investigate optimal accessory configurations, integrating Maximum Power Point Tracking (MPPT) algorithms and cooling strategies, to enhance overall system performance.

d) Analyze the impact of manufacturing technology on system performance in relation to varying weather conditions, facilitating a deeper understanding of system reliability and efficiency.

e) Conduct a thorough technical and economic feasibility analysis of the proposed solar photovoltaic system, considering factors such as installation costs, energy output, maintenance requirements, and potential return on investment.

This chapter delves into the study topic, the specific problem addressed, and the scope of work with methods through a thorough literature analysis of recent works. Results from this literature study inspired me to pursue research into solar photovoltaic system performance forecasts and yield analysis for techno-economic simulation in the Indian context.

CHAPTER 3

INTRODUCTION TO SOLAR PV SYSTEM

3.1 Introduction to Solar Cell

Solar cells, also known as photovoltaic (PV) cells, work by converting sunlight into electrical energy through the photovoltaic effect. The efficiency of a solar cell refers to its ability to convert sunlight into usable electricity, measured as the ratio of output electrical energy to input solar energy. Solar cells are typically made using semiconductors that form a p-n junction, which is doped to facilitate the conversion of solar energy into direct current (DC).

The single-diode model is commonly used to represent the behavior of a solar cell due to its simplicity and effectiveness. In this model, solar cells are either connected in series or parallel to achieve the desired voltage and current. Series connections increase the output voltage, while parallel connections increase the output current. The equivalent circuit of a single-diode photovoltaic cell consists of a current source, a diode, and both series and parallel resistances. The single diode type is a popular choice because of its simplicity and accuracy. In order to produce the appropriate voltage and current, the cells are linked in series or parallel. When the cells are connected in series, the output voltage is high, and when they are connected in parallel, the output current is enormous.

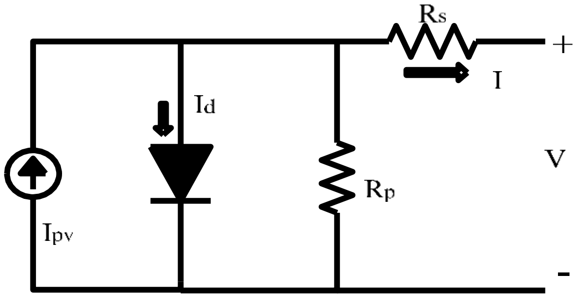

Figure 3.1: Equivalent Circuit of a Single Diode Solar Cell

Figure 3.1 shows the PV equivalent circuit. A voltage that changes linearly with solar insolation is produced when light hits photovoltaic cells, which causes a potential difference. It is feasible to model an ideal solar cell as a source of current. Rp, the shunt resistance, gives the current leakage as a function of the terminal voltage of the solar cells. Series resistance (Rs) is a measure of the contact losses in semiconductors and metals. By connecting diodes in series, we can model the p-n junctions of photovoltaic cells and determine the amount of current that flows through them when light hits them.The solar cell's behavior is given by the following equation. Following is a definition of the PV cell model based on the I-V relationship of the PV system [49]. Equation (3.1) describes the overall I-V characteristics of the solar cell, incorporating series and parallel resistances and temperature effects.Equation (3.2) calculates the photocurrent, which depends on the irradiance and temperature variations from standard test conditions (STC).Equation (3.3) gives the reverse saturation current, critical for determining the behavior of the p-n junction in the PV cell.Equations (3.4) to (3.15) further refine the relationship between current, voltage, and temperature under various environmental conditions.

$$I = I_{pv} - I_S\left(\exp\left[\frac{q(V+R_S I)}{N_s kTa}\right] - 1\right) - \frac{V+R_S I}{R_p} \tag{3.1}$$

$$I_{pv} = \left(I_{pv,n} + K_I \Delta T\right)\frac{G}{G_n} \tag{3.2}$$

$$I_S = \frac{I_{SC,n}+K_I\Delta T}{\exp\left(V_{OC,n}+K_V\Delta T\right)/a(N_s kT/q)-1} \tag{3.3}$$

$$I_{PV} = I_{Ph} - I_D - I_P \tag{3.4}$$

$$I_p = \frac{\left(V_p+R_S I\right)}{R_p} \tag{3.5}$$

I_p - Photo current, I_D - Diode current

$$I_D = I_0\left[\exp\frac{\left((V_p+R_S I\right)}{(nK_B T))-1}\right] \tag{3.6}$$

Now substituting the value of I_D

$$I_{PV} = I_{Ph} - I_0 \left[\exp \frac{(V_p + R_s I)}{(nK_B T) - 1}\right] - I_P \tag{3.7}$$

$$I_{PV} = I_{Ph} - I_0 \left[\exp \frac{(V_p + R_s I)}{(nK_B T)} - 1\right] - \frac{(V_p + R_s I)}{R_p} \tag{3.8}$$

$$V_T = \frac{(K_B T_c)}{q_e} \tag{3.9}$$

$$I_a = \frac{n_s A_f K_B T_c}{q} = nAV_T \tag{3.10}$$

$$I_{PV} = I_{Ph\,\mathrm{ref}} - I_{0\,\mathrm{ref}} \left[\exp\left(\frac{(V_p)}{a_{\mathrm{ref}}}\right) - 1\right] \tag{3.11}$$

$$I_{sc.ref} = I_{\mathrm{Ph.ref}} - I_{0.ref} \left[\exp\left(\frac{(0)}{a_{ref}}\right) - 1\right] = I_{\mathrm{Phref}} \tag{3.12}$$

The photo current depends on both irradiance and temperature and relationship given by

$$I_{pv} = \frac{G}{G_{\mathbb{R}\mathrm{ef}}}\left(I_{ph.ref} + \mu_{sc} \cdot \Delta T\right) \tag{3.13}$$

Where,

G-Irradiance W/m^2

G_{ref} - Irradiance at STC $(1000\mathrm{W/m^2})$

$$\Delta \mathrm{T} = T_c - T_{c,ref} \tag{3.14}$$

μ_{sc}-Coefficient temperature of Short circuit and I_0 is given by the

$$\mathrm{I_0} = \mathrm{I_{sc}} \exp\left(\frac{-\mathrm{V_{oc.rff}}}{\mathrm{a}}\right)\left(\frac{\mathrm{T_c}}{\mathrm{T_{c.ref}}}\right)^3 \mathrm{Xexp}\left[\left(\frac{\mathrm{q}\in\mathrm{G}}{\mathrm{A \cdot K}}\right)\left(\frac{1}{\mathrm{T_{c.ref}}} - \frac{1}{\mathrm{T_c}}\right)\right] \tag{3.15}$$

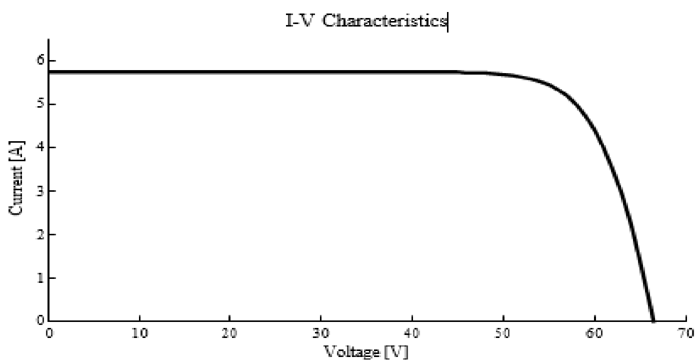

Figure 3.2: V-I Characteristics of Solar Cell at Fixed Temperature and Irradiation

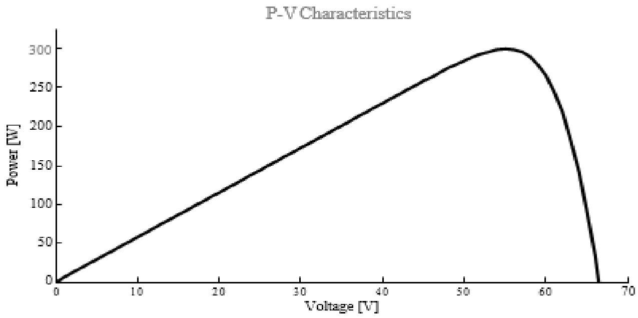

Figure 3.3: P-V Characteristics of Solar Cell at Fixed Temperature and Irradiation

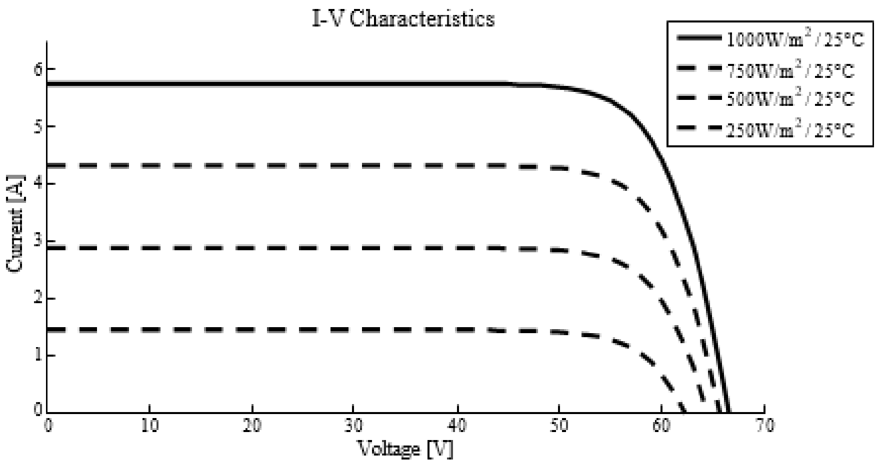

Figure 3.4: V-I Characteristics of Solar Cell at Variable Temperature and Irradiation [23]

Figure 3.2 shows the V-I characteristics of a solar cell at constant irradiance and temperature. The Power-Voltage (P-V) and Voltage-Current (V-I) properties of a photovoltaic cell are shown in Figure 3.3 and Figure 3.4, respectively. It shows how the rate of light insulation and temperature affect IV characteristics. An increase in the PV cell's insulation causes the current flow to increase. When the power-voltage characteristics curve reaches its highest point, it indicates that the device is operating at full power. Figures 3.5 and 3.6 depict the features of PV modules and the effects of MPPT, respectively [50].

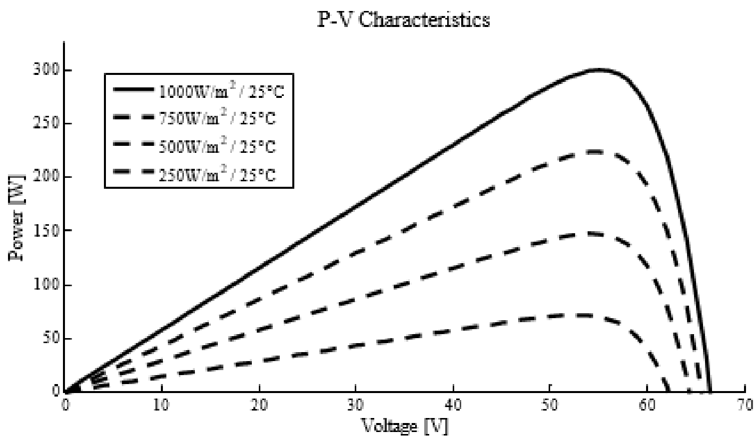

Figure 3.5: P-V Characteristics of Solar Cell at Variable Temperature and Irradiation

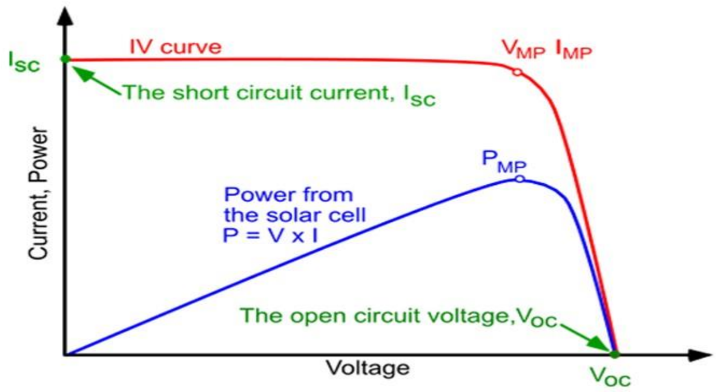

Figure 3.6: Significance of Maximum Power Point [23]

3.2 Impact of Shading on Characteristic of Solar PV System

Solar PV modules are often connected in series-parallel combinations to form arrays. The overall output of a PV array is the cumulative output of the individual modules. However, shading can have a significant impact on the performance of the entire system. When shading occurs, even in a small area of a single module, it affects the output of the entire series string, potentially forcing the shaded module to operate in reverse bias, where it acts as a load rather than a power source.

Figure 3.7: Impact of Shading on Characteristics of PV System illustrates how shading shifts the operational current of the PV array. This shift can cause "hot spots" where the module heats up due to increased current flow through the shaded area. These

hot spots can lead to permanent damage, including thermal or second breakdown, where reverse-biased cells reach dangerously high temperatures. This is depicted in **Figure 3.9**, which shows the P-V characteristics of a PV system under partial shading conditions.

To mitigate these effects, bypass diodes are typically installed across PV modules. **Figure 3.8: Connection of Bypass Diode in PV System** illustrates how bypass diodes allow current to flow around shaded or malfunctioning cells, thus preventing reverse bias and potential damage. Bypass diodes can protect the PV system by redirecting current, but they must be carefully designed to ensure that they engage only under shaded conditions.

Key outcomes of shading impact include:

- **Reduced overall system efficiency** due to shaded cells acting as resistive loads.
- **Increased heat generation** in shaded areas, potentially leading to permanent damage.
- **Bypass diode utilization** can protect cells but may lead to lower output as some cells are bypassed.

Series-parallel combination PV modules are used to construct PV arrays. The overall power output of the PV array is equal to the sum of all the modules' powers. So, even a little change in one PV module might affect the whole system and maybe even cause problems with other PV modules. Figure 3.7 shows that in a changeable light environment, PV modules will be compelled to move to a reverse biased area and act as a load instead of a power source if the operational current of the PV array is I_K [50].

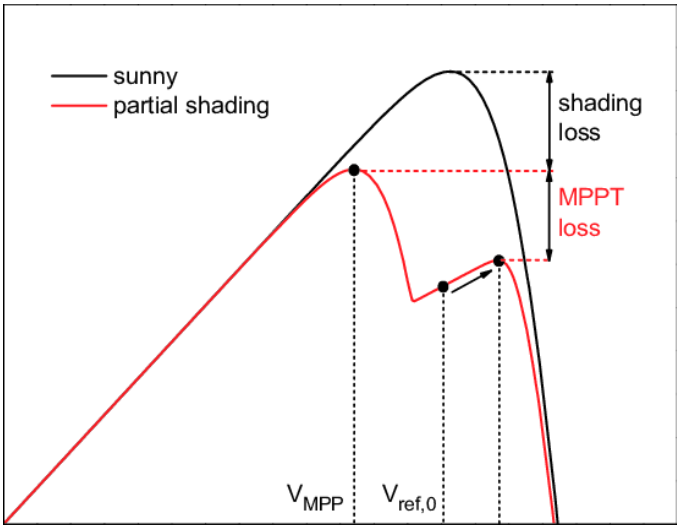

Figure 3.7: Impact of Shading on Characteristics of PV System [22]

Other reasons for hot spots include manufacturing defects and PV cell degradation. In the event that the cell temperature increases to a point where thermal breakdown or second breakdown occurs, the panel might suffer permanent damage. The second breakdown phenomenon happens when the temperature of a reverse biased cell goes over a certain degree; this causes the reverse voltage to be smaller and the cell current to be larger. The P-N junction temperature increases dramatically under these conditions, leading to irreversible cell damage. In the event of a shading effect, the connectivity of modules is illustrated in Figure 3.8 [51].

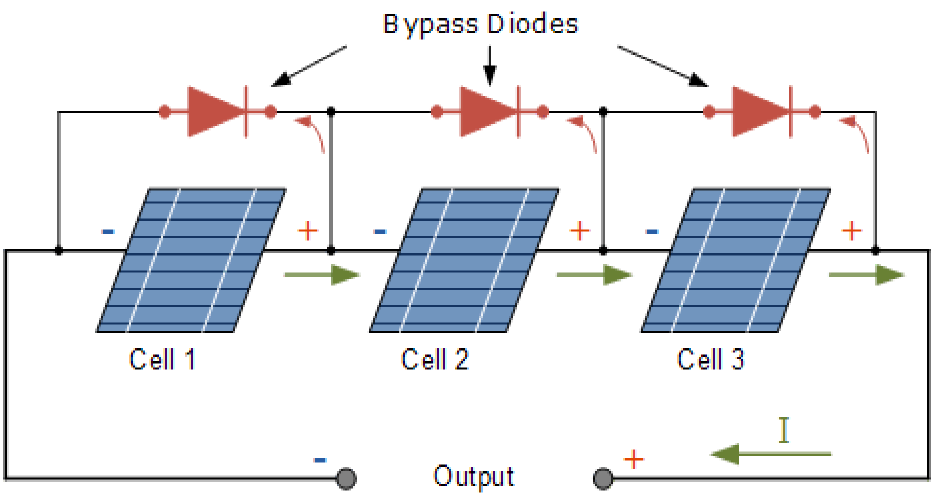

Figure 3.8: Connection of Bypass Diode in PV System [51]

The voltage is generated by PV modules that are assembled in a PV array using a series-parallel-combination configuration. Because modules lose heat instead of generating power under typical lighting conditions, this scenario must be carefully considered. When exposed to typical illumination, the diode's reverse bias has no effect. To protect the module, nevertheless, the diode will be forward biased when the light levels fluctuate. Bypass diodes provide these outcomes:

•The current that cells normally get when exposed to light goes via this bypass diode.

• Bypass diodes enable cells to use some of the energy generated by cells in different light settings to power cells in a more consistent light environment.

•With fewer cells equipped with bypass diodes, the break-through voltage will not be achieved.

•As the number of cells with bypass diodes increases, the break-through voltage is reached more quickly.

Besides using regular bypass diodes, there are other ways to avoid hot spotting.

• The cells' power loss is proportional when utilizing a PV panel with a low reverse-breakdown voltage.

•Reduced power loss from PV panels is possible with a low reverse breakdown voltage.

•Nevertheless, the effectiveness of this method hinges on its ability to protect cells against degradation. When exposed to hot areas, this PV cell loses about 20 times its maximum power output (MPPT).

• Active Hot Spot Detection and Protection: This method uses sensors to identify PV cell mismatch by looking for open circuits in the PV panel using relay switches. Bypass diodes are used in the PV system; they have no effect on the current flowing through cells that are unaffected. Also, with the use of bypass diodes, cells can have some of the power they produce when the light is changing transferred to them when the light is constant. When the cells are shaded (under normal light circumstances), the current flow via the bypass diode is shown by the power-voltage characteristics curves displayed in Figure 3.9 [52].

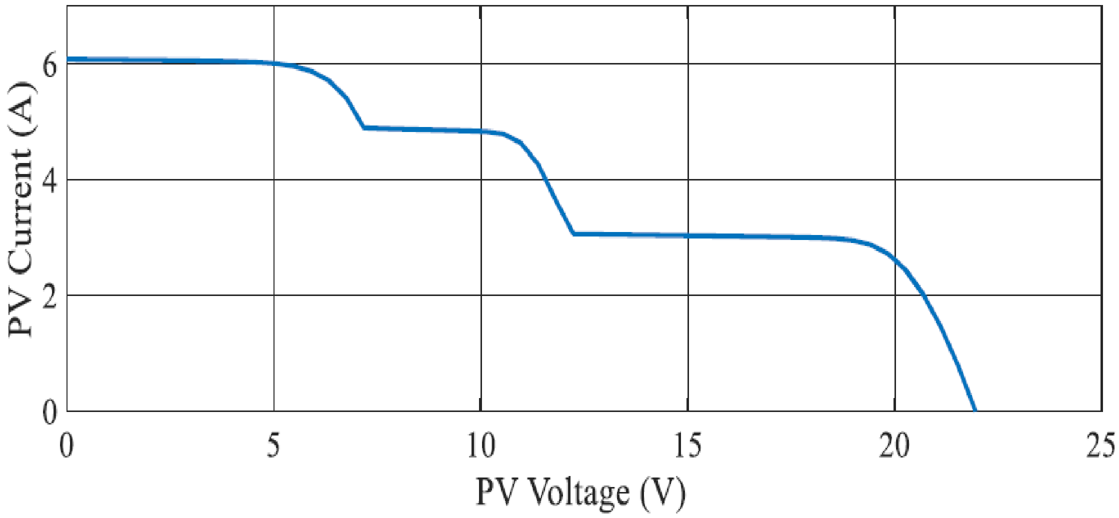

Figure 3.9: P-V Characteristics of PV System under Partial Shading

3.3 System Structure and Operational Modes

3.3.1 Inverter Mode

Figure 3.10 shows the organization's PV system topology. Terminals link solar panels, batteries, loads, and inverters. Table 3.1 shows the results of comparing various PV system types.

Table 3.1: Comparison between different types of solar cell

Solar Cell Type	Efficiency	Advantages	Shortcomings
Monocrystalline Si	16-20%	1. Highly stable efficiency	High material complexity in fabrication
Polycrystalline Si	14-17%	1. Cost-effective efficiency	Sensitive to impurities
Amorphous Si	5-7% (single) / 8-11% (tandem)	1. Good efficiency at low light levels	1. Low overall efficiency

		2. Low energy and material requirements for production	2. Initial degradation and long-term stability issues
GaAs	33% (lab)	High resistance at elevated temperatures	1. Toxicity of materials
			2. Limited material availability
CdTe	11%	Low production cost	1. Material toxicity
			2. Limited availability of raw materials
CIS (CuInSe2)	13%	High stability	1. Limited material availability
			2. Material toxicity

There are two modes of operation in the system that correspond to the various states of the solar plates, batteries, and power supply that are deployed. The inverter will enter inverter mode and the relay will transfer power to the battery in the event that the AC power goes out.

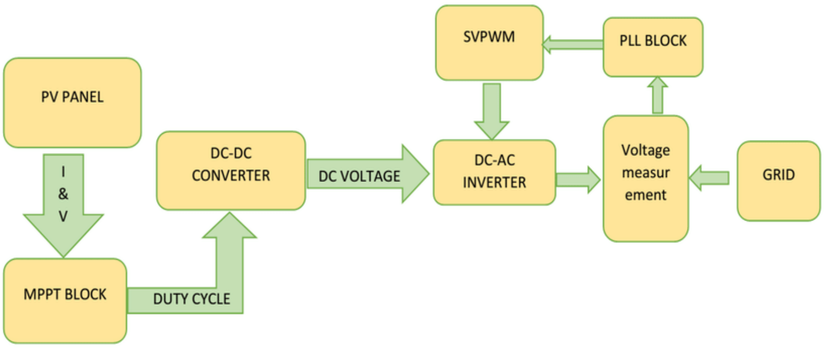

Figure 3.10: Block Diagram of Solar PV System

Both the device and the battery enter charging mode the moment they are connected to the power source. The inverter will enter inverter mode and the relay will transfer power to the battery in the event that the AC power goes out. Both the device and the battery enter charging mode the moment they are connected to the power source [53].

3.3.2 Charging Mode

If there is an available source of AC power, solar power, or both, the gadget will operate in a charging mode. The machine detects the AC power source and communicates with the triac driver to track the gate's pulse. A thyristor's output voltage and the amount of current going into the battery are both controlled by the gate pulse. A diode connected to the anode of the panel and the anode of the battery supplies current to the battery. The battery's response to the solar charging package is prevented from happening because the diode is in reverse. This allows the solar energy to fully charge the battery. When this mode is on, the load draws no power from the grid and is instead fueled solely by the battery [54].

3.4 Classification of Solar Photovoltaic System

There are three main types of solar photovoltaic systems: those that are completely self-sufficient, those that are connected to the grid, and those that are dispersed.

3.4.1 off Grid PV Systems

"Photovoltaic system off-grid" refers to an automated facility that generates power from solar radiation. Solar panels, control devices, and batteries make up the bulk of it. If you plan on using an AC load, you might also consider purchasing an AC inverter. The self-operated photovoltaic power station incorporates a variety of photovoltaic producing systems, including those for distant settlement power, signal communications power, cathodic safety, sun lighting, and others. Figures 3.11 and 3.12 illustrate the system diagrams of PV systems that are linked to the grid and those that are off the grid, respectively [55].

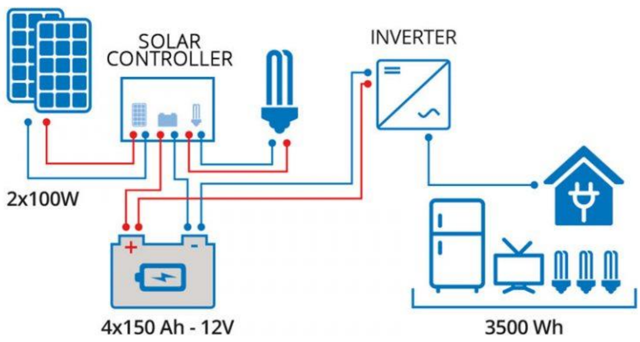

Figure 3.11: off grid PV system [56]

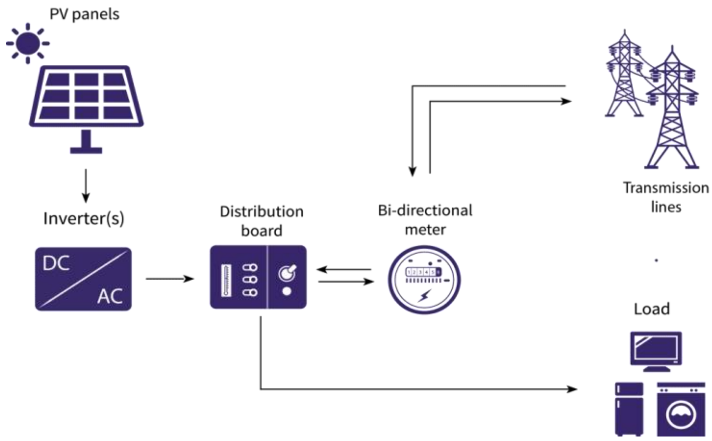

Figure 3.12: Grid Connected Photovoltaic system [56]

3.4.2 Grid-Connected PV System

The networked photovoltaic system is linked directly to the community grid once solar modules generate DC current, and then it undergoes transformation energy into alternating current (AC) power that satisfies utility standards via the grid. Depending on whether or not they contain batteries, grid-connected solar systems may be classified into two distinct types. Depending on the situation, grid-connected battery photovoltaic systems can be set up either on or off the grid. You may also use it as a backup power source in case there is an issue with the grid. However, neither battery can be planned for use in grid-connected PV systems and will not serve as backup power sources [56].

This chapter discusses the characteristics of PV arrays when exposed to different light levels. In this study, we utilize the MATLAB Simulink software to analyze how PV modules react to different lighting scenarios. In this chapter, we will go over the mathematical modelling and simulation of PV arrays in detail. We will also cover the characteristics of PV modules in both cases, including how they react to different lighting conditions. Develop a generic PV module using the MATLAB/Simulink platform [57].

3.5 Summary

This chapter delves into the fundamental concepts and operational characteristics of solar photovoltaic (PV) systems, focusing on their structure, behavior under various conditions, and the mathematical models that describe their performance.

The chapter begins by introducing the basic operation of solar cells, which convert sunlight into electrical energy through the photovoltaic effect. The efficiency of a solar cell, influenced by temperature and irradiance, is explained using the single-diode model. This model is commonly used to simulate solar cell performance due to its simplicity and accuracy. Equations governing the relationship between current, voltage, and resistance (both series and parallel) are presented, along with explanations of how these parameters influence overall system efficiency. Key figures illustrating current-voltage (I-V) and power-voltage (P-V) characteristics under different environmental conditions are discussed to highlight how temperature and light affect system output.The impact of shading on solar PV systems is also analyzed in detail. Shading can cause significant drops in system efficiency and lead to hot spots that may damage the cells. Bypass diodes are introduced as a solution to mitigate these effects by allowing current to bypass shaded or malfunctioning cells, thereby protecting the system. Figures showing the behavior of PV systems under partial shading and the role of bypass diodes are included to enhance understanding.

The chapter then examines the operational modes of solar PV systems, particularly inverter mode and charging mode, which are critical for energy management in both off-grid and grid-connected systems. Off-grid systems rely solely on solar energy and storage, while grid-connected systems interface with the utility grid, providing backup power when needed.Lastly, a classification of solar PV systems is provided, covering off-grid, grid-connected, and hybrid systems. The differences in operation, efficiency, and application between these systems are discussed. Through a combination of mathematical modeling and practical system analysis, the chapter lays the foundation for understanding the design and optimization of solar PV systems under various environmental and operational conditions.

In summary, this chapter provides a comprehensive overview of the solar PV system's functioning, from basic cell operation to the effects of shading and system configurations, supported by detailed mathematical models and graphical representations.

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CHAPTER 4

MATHEMATICAL MODELING OF SOLAR PHOTOVOLTAIC SYSTEM

4.1 Introduction

In this section, we will provide a comprehensive mathematical model of Maximum Power Point Tracking (MPPT) techniques used in solar photovoltaic (PV) systems. These models will cover the different aspects of the PV system's electrical characteristics, the role of converters, and how MPPT techniques such as Perturb and Observe (P&O), Incremental Conductance (IncCond), and Fractional Short Circuit Current (FSCC) help optimize the system's performance. This mathematical model will also include the integration of boost converters used to achieve optimal power output.

Light sources with varying energy levels, such as optical and thermoelectric transmission, are often included in standard applications, though the primary focus remains on solar energy. Numerous photovoltaic (PV) solar network designs are available, each featuring distinct configurations connecting inverters, external grids, battery systems, and other electrical loads. The core challenge that Maximum Power Point Tracking (MPPT) addresses is optimizing energy transfer from solar cells by considering key factors: the intensity of sunlight, the temperature of the solar panels, and the thermal state of the plates.

The performance of the energy transfer process depends on the electric load characteristics, which fluctuate with changes in sunlight and panel temperature. MPPT ensures that the system operates at maximum efficiency by continuously adjusting to these variations. This technology detects and maintains the optimal load characteristic known as the Maximum Power Point (MPP). MPPT resolves the issue of selecting the appropriate charge for the battery and enables circuits to manage loads applied to the solar cells. These circuits convert voltage, current, or frequency to suit various systems or equipment.

The nonlinear efficiency of solar cells can be analyzed using an IV curve, which illustrates the relationship between temperature and total power output. MPPT samples the PV cell output and dynamically adjusts the load resistor to ensure the system achieves maximum power under different environmental conditions. This approach is commonly applied in systems that convert, filter, and regulate voltage or current for various loads, such as grids, batteries, or motors. Some solar inverters include the MPPT feature, allowing them to convert DC power to AC by sampling output power and adjusting the resistance accordingly.

The total power of an MPPT system is the product of its maximum power point voltage (Vmpp) and current (Impp). A solar panel's operational efficiency depends on the impedance of the plate. By adjusting the apparent impedance of the solar plate, the system can drive the operational point to the MPP. This impedance matching between the source (the solar panel) and the load is handled by a DC-DC converter integrated into the system, which alters the service cycle to optimize energy transfer.

Solar panels typically convert only 30-40% of sunlight into electricity. However, by using MPPT technology, the efficiency can be significantly improved. The Thevenin impedance matching theorem ensures that the circuit operates at maximum efficiency when the source impedance aligns perfectly with the load impedance. By monitoring the MPP, the system can continuously adjust the boost converter's service cycle to match the load impedance with the source, maximizing the output voltage for various applications, including motor loading.

In summary, MPPT optimizes solar energy systems by adjusting the impedance through a boost converter, ensuring that solar panels operate at their highest possible efficiency across a wide range of conditions. [59].

4.2 Introduction to Mathematical Modeling of MPPT

The behavior of a photovoltaic cell can be represented by its I-V characteristics, and the general equation governing the current output of a PV' cell is given by:

$$I = I_{ph} - I_0 \left(\exp\left(\frac{q(V+IR_s)}{nKT} \right) - 1 \right) - \frac{V+IR_s}{R_p} \tag{4.1}$$

Where:

- I_{ph} is the photocurrent generated by sunlight (proportional to irradiance)
- I_0 is the diode saturation current,
- q is the electron charge $(1.6 \times 10^{\circ} - 19\mathrm{Cl})$
- V is the terminal valtage of the PV cell,
- R_n is the series resistance of the PV cell.
- R_p is the parallel (shumt) resistance,
- n is the diode ideality factor,
- K is the Bolitmann constant $(1.38 \times 10^{\wedge} - 23\ \mathrm{J/K})$.
- T is the temperature of the PV cell in Kelvin.

The photocurrent I_{ph}, which is dependent on irradiance and temperature, can be modeled as:

$$I_{ph} = \left(I_{ph-n/} + \mu_m \cdot \Delta T \right) \cdot \frac{G}{G_{rn/}} \tag{4.2}$$

Where:

- $I_{\mathrm{mi\_}nj}j$ is the photocurrent at reference temperature and irradiance,
- μ_{mn} is the temperature coefficient of the short-circuit current,
- $\Delta T = T - T_{rs}$ is the change in temperature,
- G is the irradiance,
- G_{ref} is the irradiance at standard test concitions (STC, $1000\ \mathrm{W/m^2}$)

The open-circuit voltage V_{ox} of the PV cell can be modeled as:

$$V_{\mathrm{ox}} = \frac{nKT}{q} \ln\left(\frac{I_{\mathrm{s}}}{I_0} + 1\right) \tag{4.3}$$

The maximum power point (MPP) is determined by finding the point on the $1 - \mathrm{V}$ curve where the product of current and voltage is maximized. Mathematically, this condition can be expressed as:

$$\frac{dP}{dV} = 0 \tag{4.4}$$

Where P is the power output of the PV cell.

$$P = V \cdot I \tag{4.5}$$

By substituting the $1 - \mathrm{V}$ characteristic (Equation 4.1) into this equation, one can find the maximum power point voltage V_{mip} and current I_{mip} .

A boost converter is commonly used to step up the voltage from the PV module to the required level, ensuring the system operates at the maximum pawer point. The mathematical model of the boost converter is given by:

$$V_{\text{out}} = \frac{V_{\text{m}}}{1-D} \quad (4.6)$$

Where:

- V_{out} is the output voltage,
- V_{m} is the input valtage from the PV panel
- D is the duty cycle of the boost converter.

The relationship between the input current I_{in} and output current I_{sut} of the boost converter is

$$I_{\text{cut}} = I_{\text{in}} \cdot (1 - D) \quad (4.7)$$

The efficiency of the boost converter, l, is generally expressed as:

$$\eta = \frac{P_{\text{ost}}}{P_{\text{un}}} = \frac{V_{\text{ost}} \cdot I_{\text{mat}}}{V_{\text{in}} \cdot I_{\text{in}}} \quad (4.8)$$

The maximum power point is tracked in several ways. Rarely are the most popular technologies:

1. Observation of disturbance (hill climbing)
2. Process of gradual action
3. Existing partial circuit
4. Open-circuit fractional stress
5. Network for neuro sciences
6. The logic of Fuzzy

The process is optimally conditional on the amount of time needed to track the MPP, the application costs and the ease of implementation of the algorithm [60].

4.2.1 Perturb & Observation

This is based on the fact that the current voltage curve (PV), at the left of the MPP, reaches 0 $dP/dV > 0$, while the dissimilar it is less than 0 dP/dV<0 at the right, at the bottom of the MPP. Figure 4.1 elaborates the impact of change of voltage and its effect on power.

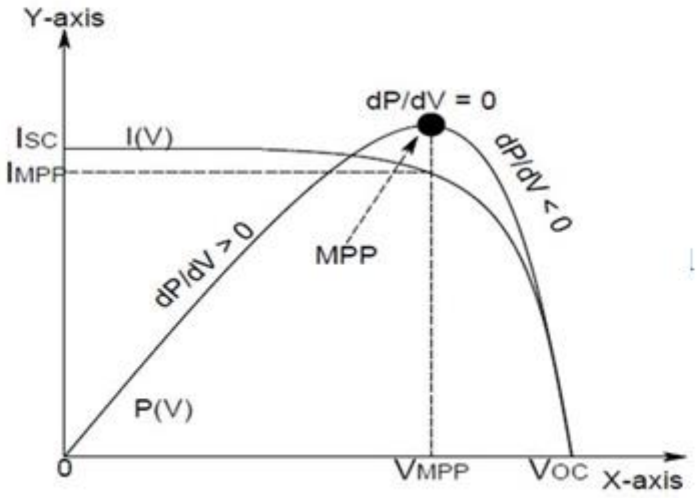

Figure 4.1: Effect of dP/dV for Calculation of MPPT

The P&O method iteratively perturbs the operating voltage and observes the effect on power output. The increases or decreases the voltage depending on whether the power increases or decreases. The general mathematical form is:

$$\Delta P = P_{\text{naw}} - P_{\text{cdd}} \tag{4.9}$$

$$\Delta V = V_{\text{wav}} - V_{\text{odd}} \tag{4.10}$$

Where:

- $P_{\text{nows}}, P_{\text{old}}$ are the current and previous power outputs,
- $V_{\text{nur}}, V_{\text{old}}$ are the current and previous voltages.

The decision rule is

$$\begin{aligned}&\text{If } \Delta P > 0 \Rightarrow \text{ Increase } V\\&\text{If } \Delta P < 0 \Rightarrow \text{ Decrease } V\end{aligned}$$

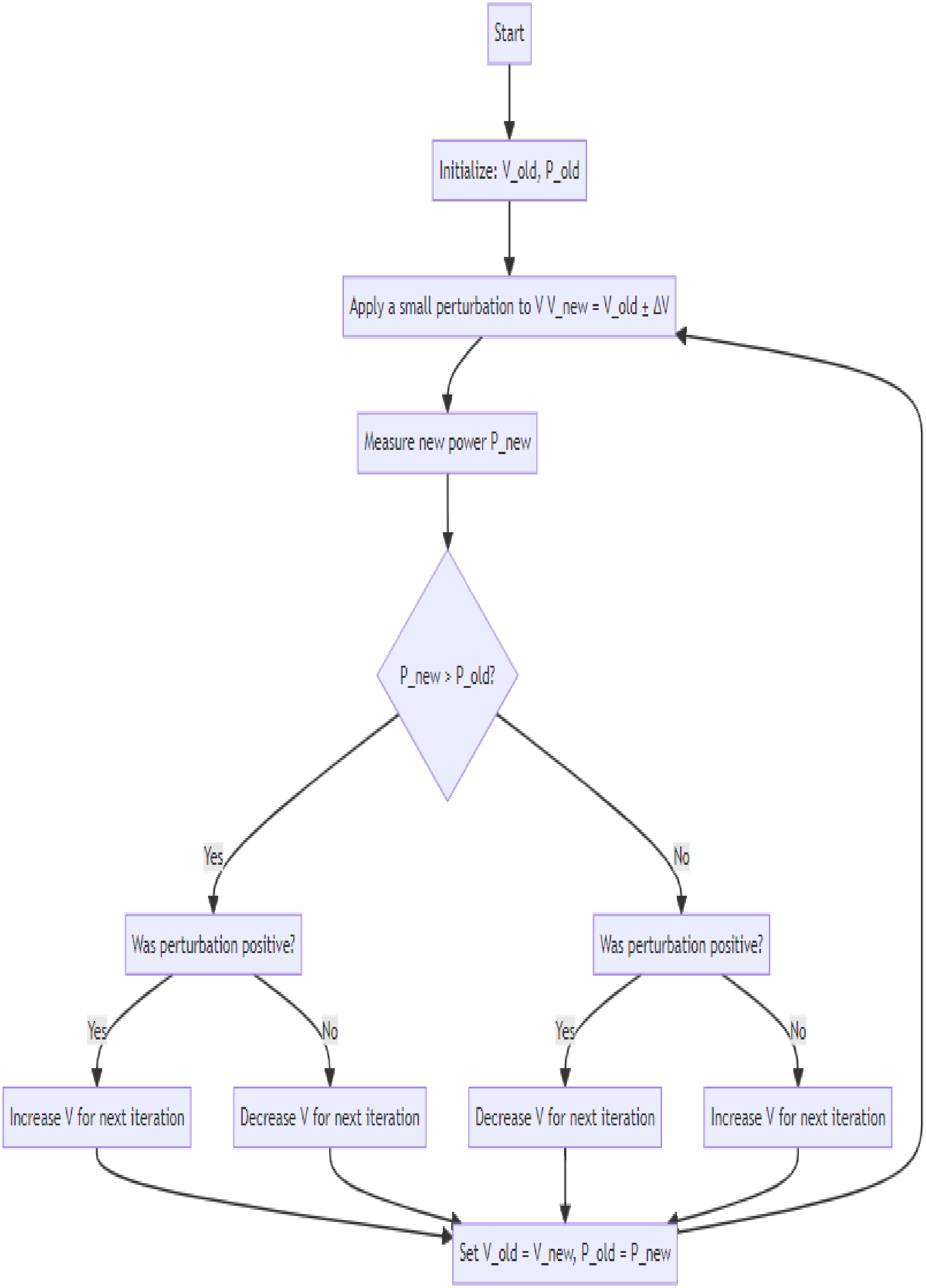

Figure 4.2: Flow chart of Perturb and Observe MPPT

Perturbation and observation (P&O) is a simple method. In this situation, we can sense the voltage of the PV array with just one sensor—a voltage sensor—making it easy to install. Although the method is incredibly fast, it interferes with both instructions once it reaches the height of the MPP. In such a case, the algorithm is quite comparable to MPP; to lengthen the operation; we may either utilize wait functions or establish acceptable error limits [61].

Solar photovoltaic systems frequently employ the Perturb and Observe (P&O) technique, an MPPT (Maximum Power Point Tracking) algorithm. To run, the P&O algorithm bumps up or down the voltage at the array's terminals and then compares the power to the power from the last perturbation cycle. The program then uses this comparison to determine the MPP by adjusting the operating voltage. Solar photovoltaic systems frequently employ the Perturb and Observe (P&O) technique, an MPPT (Maximum Power Point Tracking) algorithm. To run, the P&O algorithm bumps up or down the voltage at the array's terminals and then compares the power to the power from the last perturbation cycle. The program then uses this comparison to determine the MPP by adjusting the operating voltage [62].

1. The algorithm starts and initializes the old voltage (**V_old**) and old power (**P_old**).
2. A small perturbation is applied to the voltage to get **V_new**.
3. The new power, **P_new**, is measured.
4. A comparison is made between **P_new** and **P_old**.
5. If **P_new** is greater than **P_old**, it indicates that the perturbation is moving towards the MPP. a. If the perturbation was positive (increased voltage), the algorithm will continue to increase the voltage in the next iteration. b. If the perturbation was negative (decreased voltage), the algorithm will decrease the voltage in the next iteration.

6. If **P_new** is less than **P_old**, it indicates that the perturbation is moving away from the MPP. a. If the perturbation was positive (increased voltage), the algorithm will decrease the voltage in the next iteration. b. If the perturbation was negative (decreased voltage), the algorithm will increase the voltage in the next iteration.
7. The algorithm updates **V_old** and **P_old** values and repeats the process.

This flowchart provides a general overview of the P&O MPPT algorithm. In an actual implementation, there may be additional considerations like setting appropriate perturbation sizes, handling rapid changes in irradiance, and ensuring safe operating limits for the PV array and load.

However, this methodology does not involve rapid exposure variations (due to MPPT changes), but considers them as MPP changes, which eventually lead to incorrect MPP estimates. We may use the gradual Behavioral approach to prevent this problem [63].

4.2.2 Incremental conductance MPPT

In the incremental Conductance method, the maximum power point is identified by the condition:

$$\frac{dI}{dV} = -\frac{I}{V} \tag{4.11}$$

This method measures both the instantaneous conductance $\frac{I}{\mathrm{V}}$ and the incremental conductance $\frac{d?}{dT}$. If:

$$\frac{dI}{dV} > -\frac{I}{V} \Rightarrow \text{ Increase } V$$
$$\frac{dI}{dV} < -\frac{I}{V} \Rightarrow \text{ Decrease } V$$
$$\frac{dI}{dV} = -\frac{I}{V} \Rightarrow \text{ MPP Resched}$$

This method is more accurate than PQO, especially under rapidly changing irradiance conditions.

The fast conduction of the solar panel is on the left. If the speed drive is the same as solar energy, the MPP is achieved. Here we are simultaneously detecting voltage and current. Errors attributable to irradiance changes are also omitted. But the cost of implementation and complexity is increasing. If the algorithm is deepening, the problem and running costs can increase and can be acceptable for extremely complicated systems. This is destructive observation, and the technique of incremental conductance is the most commonly used algorithm. The algorithm starts with system initialization.

1. The voltage (V) and current (I) are measured.
2. The incremental conductance ($\Delta I/\Delta V$) and the instantaneous conductance (I/V) are calculated.
3. The two conductance are compared.
4. If they are equal, the MPP is found, and the system operates at this point.
5. If $\Delta I/\Delta V$ is greater than -I/V, it indicates that the operating point is to the left of the MPP, so the voltage needs to be increased.
6. If $\Delta I/\Delta V$ is less than -I/V, it indicates that the operating point is to the right of the MPP, so the voltage needs to be decreased.
7. The new voltage and current values are set, and the process is repeated.

This flowchart gives a fundamental overview of the Incremental Conductance MPPT algorithm. For practical implementation, additional steps and considerations might be necessary to handle varying conditions and ensure stability.

4.2.3 Open-circuit stress fractional

The Fractional Open Circuit Voltage (FOCV) method is a simple Maximum Power Point Tracking (MPPT) technique used in photovoltaic (PV) systems. This method operates on the observation that the Maximum Power Point Voltage (V_{mpp}) of a PV module is approximately a fixed fraction (k) of its open-circuit voltage (V_{oc}). Typically, for crystalline silicon solar cells, this fraction k is around 0.71 to 0.76. [64].

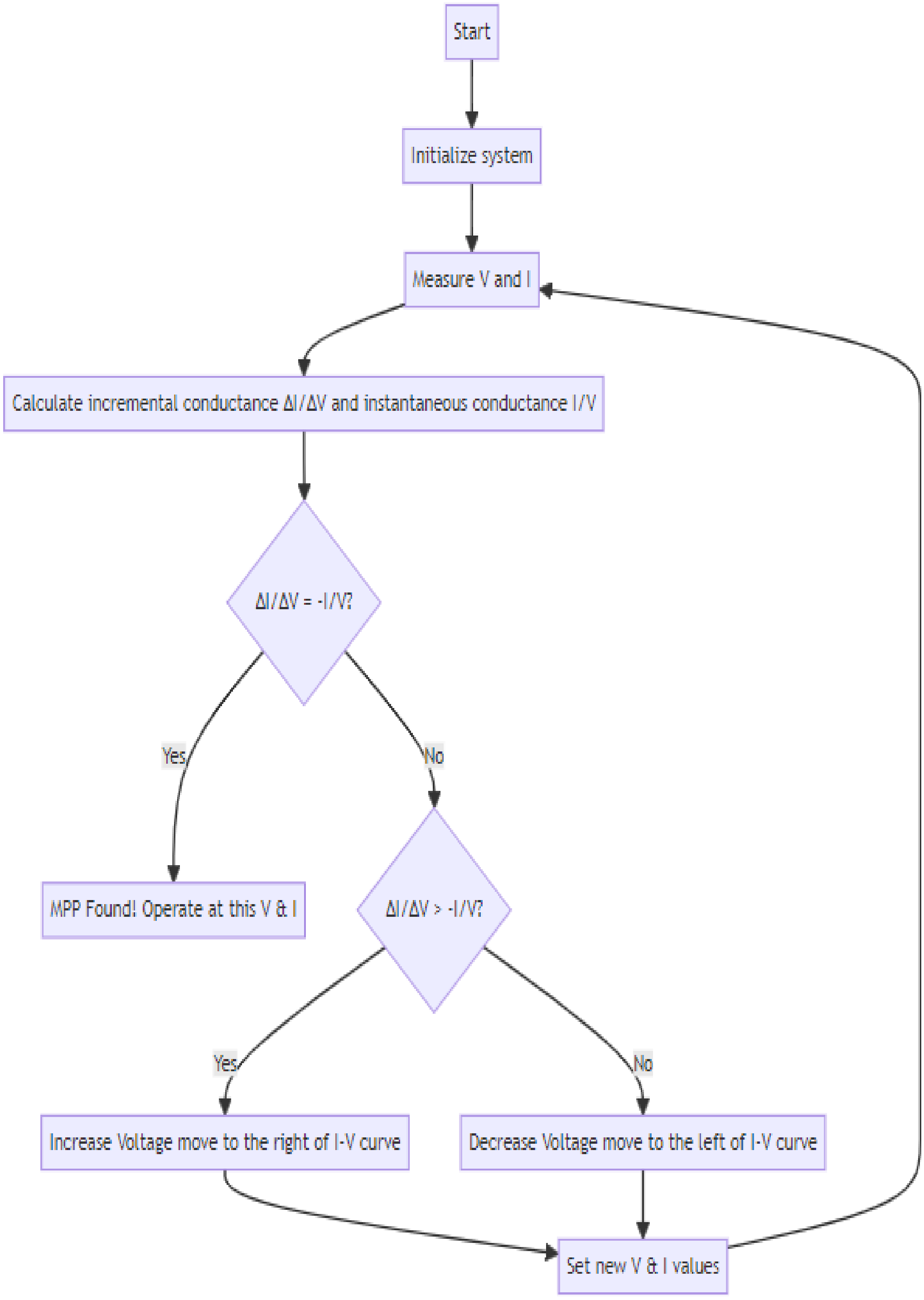

Figure 4.3: Diagram of Incremental Conductance MPPT

The FOCV method is based on the empirical observation that the voltage at the maximum power point V_{upp} is approximately a constant fraction of the open-circuit voltage V_{oB}

$$V_{wpp} \approx k - V_{oc} \qquad (4.12)$$

Where k is typically between 0.71 and 0.78 for most PV modules. The open-circuit voltage V_{or} can be measured periodically, and the operating voltage is adjusted accordingly.

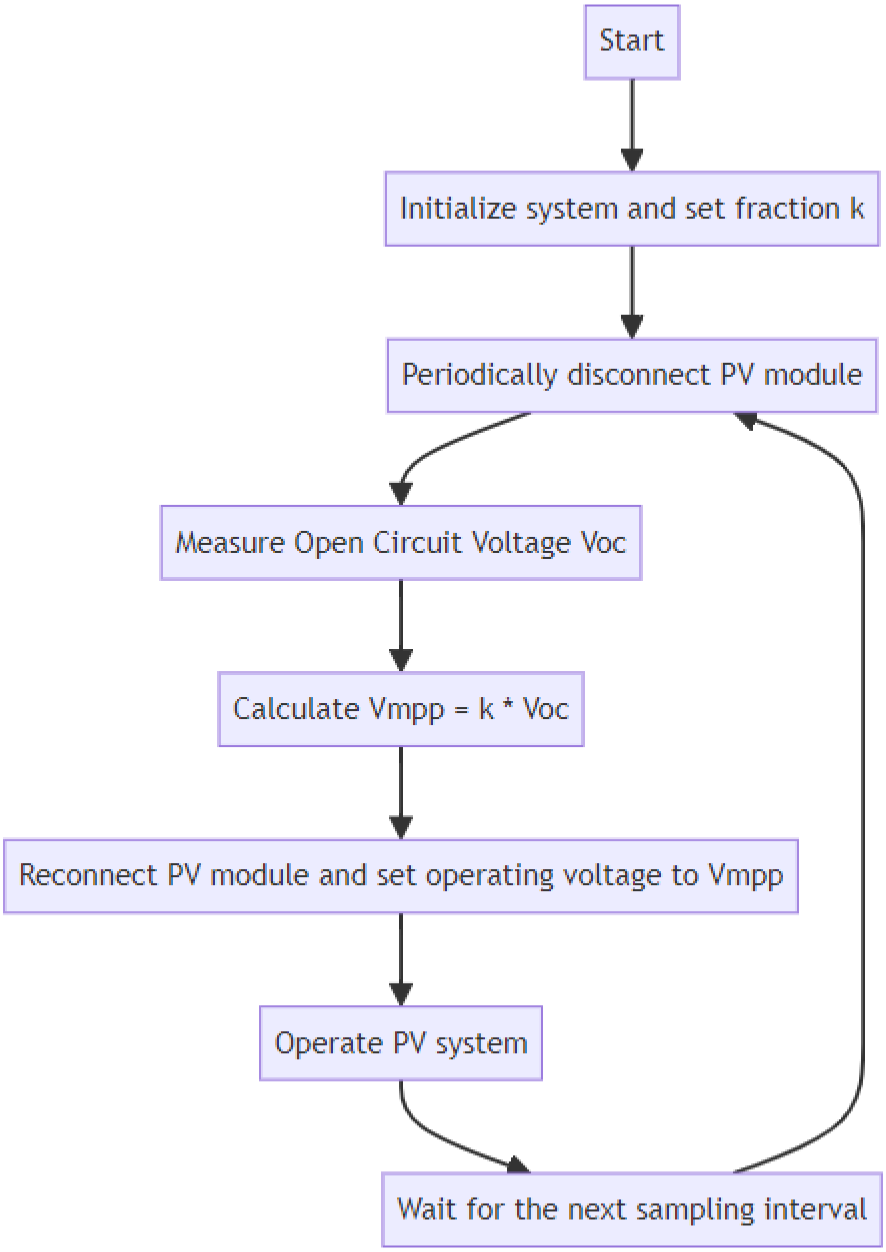

Figure 4.4: Flow Chart of Open Circuit Voltage Based MPPT

Figure 4.1 represent the I-V curve illustrates the relationship between current and voltage for a PV cell. At the MPP, the product of voltage and current (power) is maximized. Figure 4.2 represents the flowchart shows the operation of the P&O

algorithm. It iteratively adjusts the operating voltage to locate the MPP by comparing the power at different voltages. Figure 4.3 represents the Incremental Conductance method is visualized as a decision tree. The system compares instantaneous and incremental conductance to find and maintain the MPP. Figure 4.4 explains boost converter circuit diagram shows how the DC-DC converter increases the output voltage from the PV module.

The approximately linear relation between the VMPP and VOC in the PV array led to a development of the fractional VOC method below variable irradiance and temperature levels.

1. The algorithm starts with system initialization and sets the fraction value (**k**), which is often determined empirically or provided by the PV module manufacturer.
2. The PV module is periodically disconnected from the load for a short interval to measure its open-circuit voltage (V_{oc}).
3. After measuring V_{oc}, the Maximum Power Point Voltage (V_{mpp}) is calculated by multiplying V_{oc} with the fraction **k**.
4. The PV module is then reconnected, and the operating voltage is set to V_{mpp}.
5. The system operates at this voltage until the next sampling interval.
6. The process is then repeated, ensuring that the PV system continually operates near its maximum power point.

It's worth noting that while the FOCV method is simple and requires minimal computational effort, it may not be as accurate as other MPPT methods under varying environmental conditions. Also, the periodic disconnection of the PV module for V_{oc} measurement may lead to momentary power losses

$$V_{MPP} = k_1 V_{oc} \tag{4.13}$$

Where, k_1 is a constant ratio. As k_1, depending on the characteristics of the PV array employed, the VMPP and V_{oc} of an accurate PV array can generally be calculated empirically in various irradiances and temperature level stop at k_1. The coefficient k_1 is between 0.71 and 0.78, according to sources. Once k_1 is learned, the VMPP can be intended by switching the power converter off temporarily and using the VOC calculated periodically. This brings some issues, however, and involves temporary power failures.

4.2.4 Current fractional short circuit

The Fractional Short Circuit Current (FSCC) method is an MPPT technique for photovoltaic (PV) systems, similar in simplicity to the Fractional Open Circuit Voltage method. In the FSCC method, the Maximum Power Point Current (Impp) of a PV module is considered to be a fixed fraction (l) of its short-circuit current (Isc). Typically, this fraction l is determined empirically or provided by the PV module manufacturer.

1. Start with system initialization and set the fraction value (**l**), which is typically determined empirically or provided by the PV module manufacturer.

   $$IMPP = k_2 I_{sc} \tag{4.14}$$

   Where k_2 is a proportionality constant. The Fractional Short Circuit Current (FSCC) method serves as a straightforward Maximum Power Point Tracking (MPPT) technique for Photovoltaic (PV) systems, akin to the Fractional Open Circuit Voltage method. In this method, the Maximum Power Point Current (Impp) of a PV module is approximated as a constant fraction (l) of it's short-circuit current (I_{sc}). Usually, this fraction l is determined through empirical analysis or supplied by the PV module manufacturer.

2. The PV module is periodically shorted for a brief moment to measure its short-circuit current (I_{sc}).

3. After measuring I_{sc}, the Maximum Power Point Current (Impp) is calculated by multiplying I_{sc} with the fraction **l**.
4. The PV module is then reconnected, and the operating current is set to Impp.
5. The system operates at this current until the next sampling interval.
6. The process is then repeated to continually adjust and operate the PV system near its maximum power point.

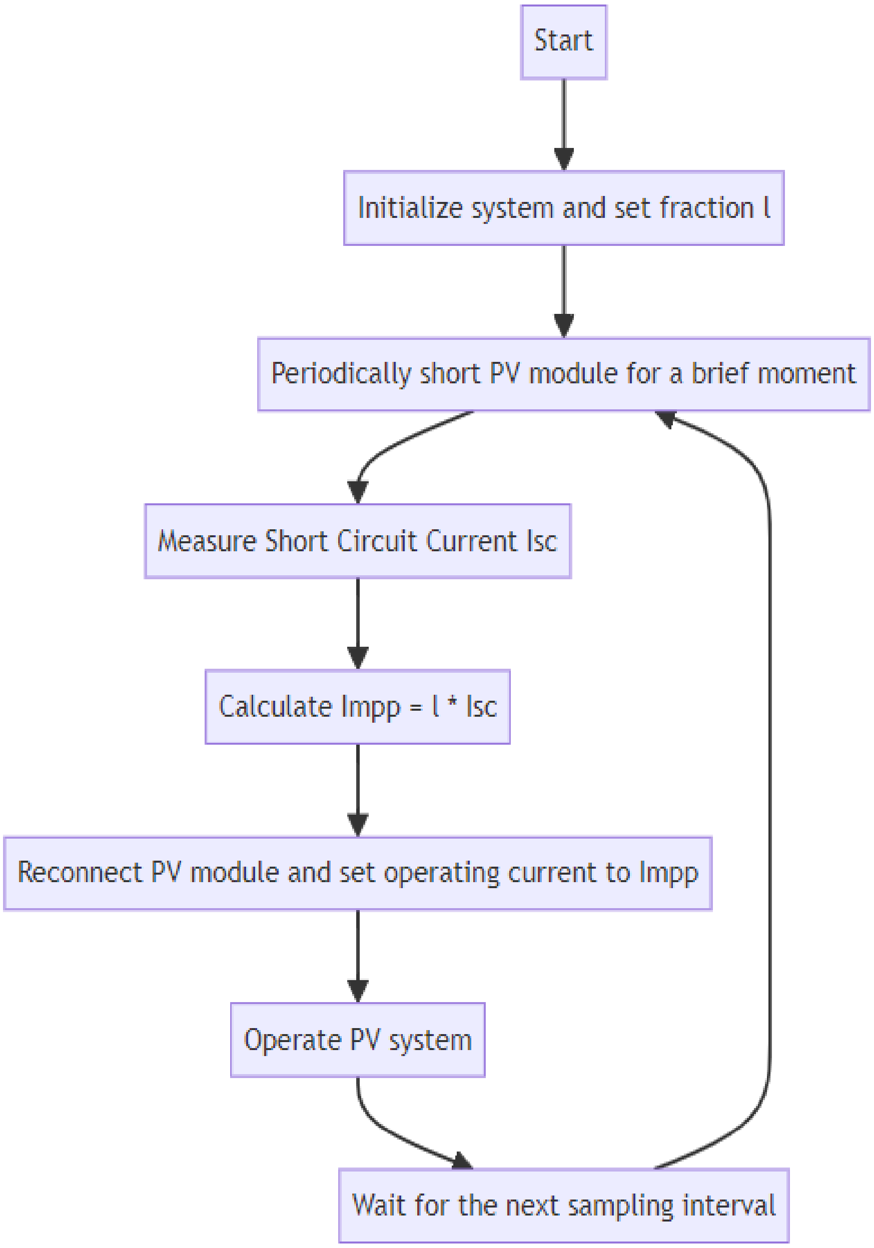

Figure 4.5: Flow Chart of Short Circuit Current Based MPPT

Similarly, the FSCC method estimates the maximum power point current I_{m_p} as a fraction of the short-circuit current I_{sc} :

$$I_{mpp} \approx k - I_n \tag{4.15}$$

Where k typically ranges from 0.78 to 092 .

k_2 must be strong-minded based on the PV array as in fractional VOC technology. The k_2 is usually between 0.78 and 0.92. It is usually found. I_{sc} evaluation is troublesome in the process. A power converter should typically be added to the PV array in order to use the current sensor for the measurement of I_{sc}.

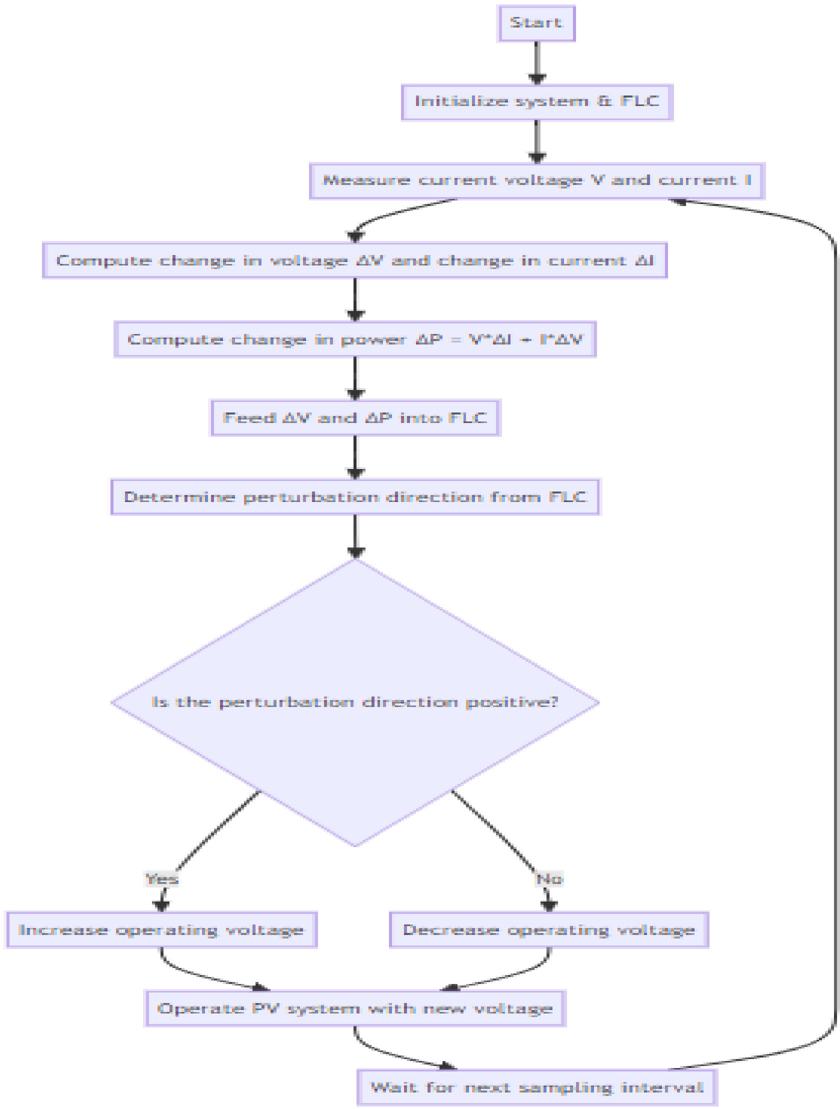

Figure 4.6: Flow chart of Fuzzy Logic Control

4.2.5 Regulation of Fuzzy Logic

Microcontrollers have made the rational overall control furious in MPPT over the historical period. The benefit of the flush logic controller is to deal with inaccurate data, correctly measured proto types and contracts with non-linearity are not necessary.

- Start with system initialization and configure the Fuzzy Logic Controller (FLC).
- Measure the current voltage (V) and current (I) of the PV module.
- Compute the change in voltage (ΔV) and the change in current (ΔI) from the last measurements.
- Calculate the change in power (ΔP) using the relationship ΔP = VΔI + IΔV.
- The ΔV and ΔP are fed into the Fuzzy Logic Controller.
- Based on its rules and membership functions, the FLC determines the perturbation direction (increase or decrease the operating voltage).
- The operating voltage of the PV module is adjusted based on the direction provided by the FLC.
- The PV system operates with the new voltage until the next sampling interval.
- The process repeats, continually adjusting the PV system to track the MPP.

The FLC method uses fuzzy logic to handle the non-linear behavior of the PV system. The inputs to the fuzzy logic controller are the changes in voltage ΔV and power ΔP, and the output is the perturbation in the operating voltage.

The fuzzy rules can be summarized as:

- If $\Delta P > 0$ and $\Delta V > 0$ then increase voltage
- If $\Delta P > 0$ and $\Delta V < 0$ then decrease voltage,
- If $\Delta P < 0$ and $\Delta V > 0$ then decrease voltage,
- If $\Delta P < 0$ and $\Delta V < 0$ then increase voltage

It's essential to recognize that while the FSCC method is relatively simple and requires minimal computational resources, it might not be as accurate as other MPPT techniques, especially under varying environmental conditions. Additionally, periodically shorting the PV module to measure I_{sc} might introduce stress to the module and lead to momentary power losses. This flowchart gives a high-level overview of the Fuzzy Logic based MPPT method. Implementing a fuzzy logic controller would require defining membership functions, fuzzy rules, and the defuzzification method, making the system design more complex than traditional algorithms. However, the benefits include more adaptive and potentially faster MPP tracking, especially under rapidly changing environmental conditions.

Table 4.1: Process MPPT Characteristics

MPPT Method	Convergence Speed	Employment Difficulty	Periodic Tuning	Sensed Parameters
P&O	Differs	Small	*	V
INC	Differs	Average	*	V, I
F- Voc	Average	Small	**	V
F-Isc	Average	Average	**	I
FLC	***	Higher	**	Differs
NN	***	Higher	**	Differs

No-*, Yes-, Fast-*****

4.3 Implementation of MPPT Using Boost Converter

The scheme uses a boost converter for more applications than solar panels. When switching losses are introduced using a converter, the first low voltage output is improved to an advanced level with a boost converter. Figure 4.4 demonstrates the required implementation in the block diagram.

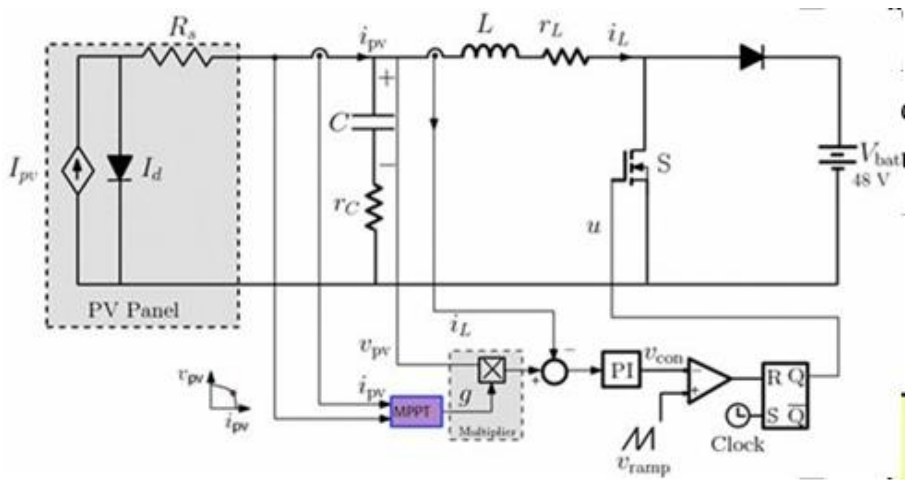

Figure 4.7: Boost Converter Circuit Diagram

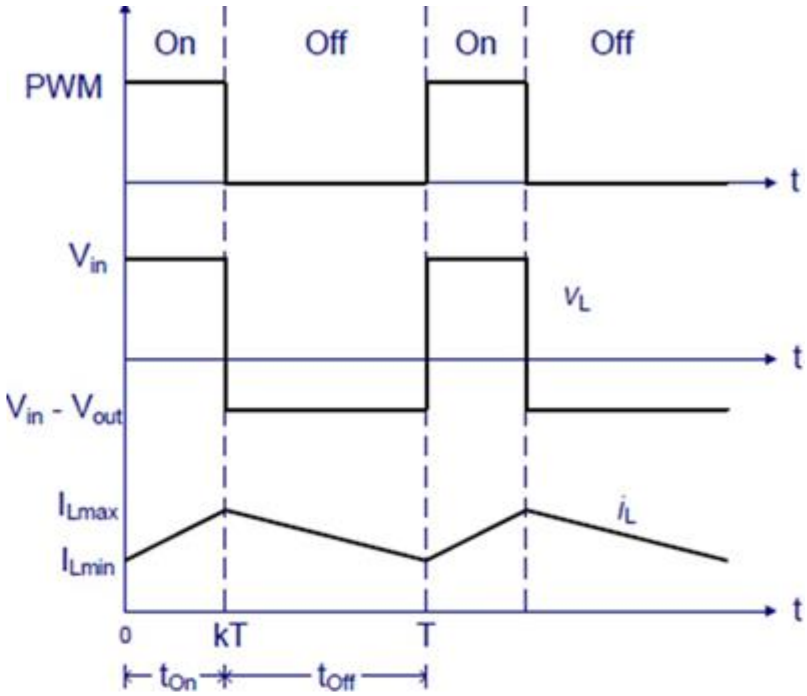

Figure 4.8: Boost Converter Waveforms

4.3.1 Mode 1: Boost Converter process

The inductor loads energy and stores it through the battery after the switch is closed. In this mode the inductor current increases (exponentially), but for effort lessness, we endorse the linear loading and unloading of the inducers. The diode prevents the current from being steady, so that the load current is continued, and due to discharge the condenser the load current is supplied.

4.3.2 Mode 2: Boost Converter operation

In mode two, the switch is turned off to deactivate the diode. The stored energy in the inductor is utilized to charge the capacitor with reverse polarity. The load current remains stable throughout this process.The Perturb and Observe (P&O) technique adjusts the module voltage incrementally, observing power changes to find the direction towards the Maximum Power Point (MPP). The Incremental Conductance (IncCond) method uses a comparison between instantaneous and incremental conductance to locate the MPP and adjusts accordingly. The Fractional Open Circuit Voltage (FOCV) method assumes the MPP voltage is a fixed fraction of the open-circuit voltage and periodically disconnects the module to measure it. Similarly, the Fractional Short Circuit Current (FSCC) method assumes the MPP current is a fixed fraction of the short-circuit current, periodically shorting the module for measurement. Lastly, the Fuzzy Logic Controller (FLC) based MPPT method uses fuzzy logic rules to decide the perturbation direction based on variations in voltage and power, effectively handling nonlinearities. Each method has distinct benefits and complexities suited to various operational and environmental scenarios.

4.4 MPPT Device Architecture

The photovoltaic generator reveals the I-V non-direct trademark with solar insolation and its MPP change. In order to extract maximum power from the PV cluster, a transitional dc-dc converter is required. The maximum power point in PV-based frames depends on the amount of solar radiation, the working temperature and the current burden. The focusing of fixation is on maximum power point monitoring dissected for maximum power tracing, following the development of the dc-dc converter structure for different applications. The help from false neural systems and fluffy rations and maximum power monitoring for halfway shade conditions are followed in this maximum power. There is also a plan for a new protocol based on existing checks. At this stage, implementation assessment is given for MPPT gadgets with a continuous estimate of solar qualities and then used for maximum power point tracking strategies. Different patents have been evaluated for power moulding, solar test circuit, circuit power expansion and various calculations have been made, using the chip, controller. The assessment of the execution of the controller is completed in the usable writing for optimum point monitoring. This is an assurance that the PV transmits its power to the heap. Much as PVs does tonnes with I-V bending. The point of convergence at which all PVs and burdens are reached is that where the I – V curve on a heap is drawn into the corresponding trademark making the I-V bend on a photovoltaic device. This is called the workplace as shown in Figure 4.9 In the sense of a resistive load, the voltage and current mixes that are admissible for PV yield are shown in photovoltaic Figure 4.9 PV-IV bend. This voltage generates yield power and the current for the particular mix is full. The maximum power point (MPP) is this point on the curve. Vm and I m are independently MPP voltage and current. At the workplace different to this case, resistance I-V bending with slant 1 / R meets PV I-V bending. The module's performance decreases with the working point going out of MPP. The work point sneaks off the MPC as the conditions shift with a fixed obstruction and the module is gradually less efficient. As shown in Figure 5.4

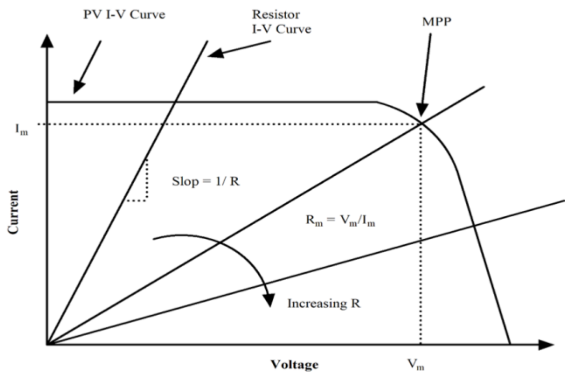

Figure 4.9: Resistant Load PV Model

A device called an MPPT tracker is used, which is why the PVs are running reliably at their highest productivity rate. In Figure 4.11, a dc-dc conversion buck with a PV cluster as its source and a load engine appears. The switch control is configured for opening and closing the switch so that the working point corresponds to the MPP. The MPP is acknowledged in a particular situation, maintaining the PV output voltage at V_m and properly lowering or increasing the voltage using a Buck support converter to coordinate the heap voltage. The voltage and the current in the MPPT yield and its PV voltage and current relation can be seen to adjust the switch's duty cycle ratio. Using a diode and a MOSFET it is modified. The normal output current is less than the normal inductor current in the lift converter. What's more, a much higher rms current will be expected through the channel condenser, so the inducer and the channel condenser need a big estimate of that. This is a series Connection between the DC-DC converter's output and the photovoltaic panel in order to achieve high performance.

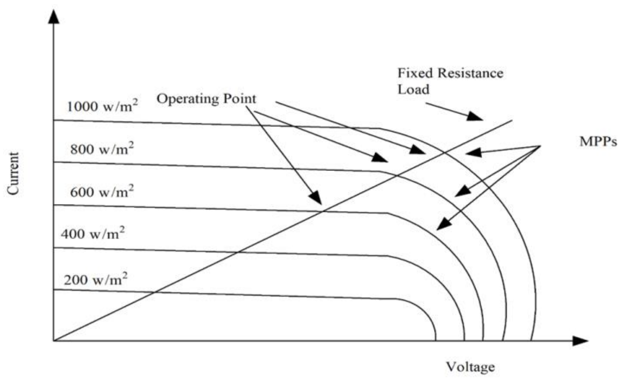

Figure 4.10: Effect of Fixed Resistance Load on MPPT

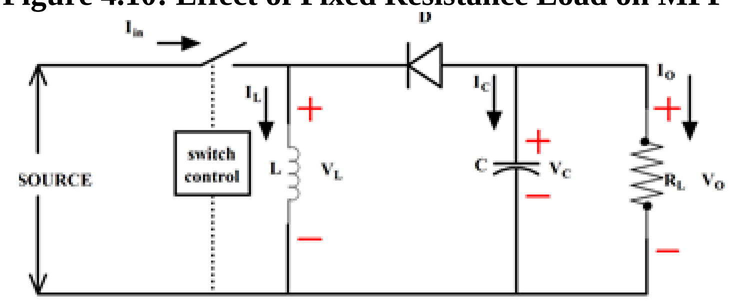

Figure 4.11: Boost Converters with Resistive Load

In this case, many studies explain that the MPPT methods do not examine the accurate monitoring of the global MPP stage. Consequently, the sophistication of the algorithm, expense and failure during operation during shading conditions are the issue with the implementation of MPPT techniques. In particular global peak identification analysis has been carried out under shading conditions; every research shows a monitoring method with a variety of complexity, expense, operating speed and range of efficiencies.

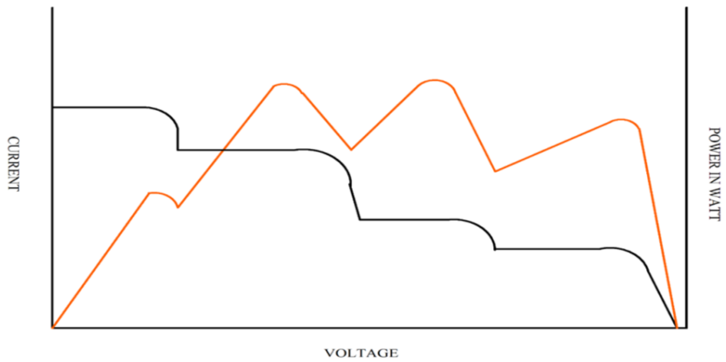

Figure 4.12: P-V & I-V Characteristic of PV Array under Partial Shading Conditions

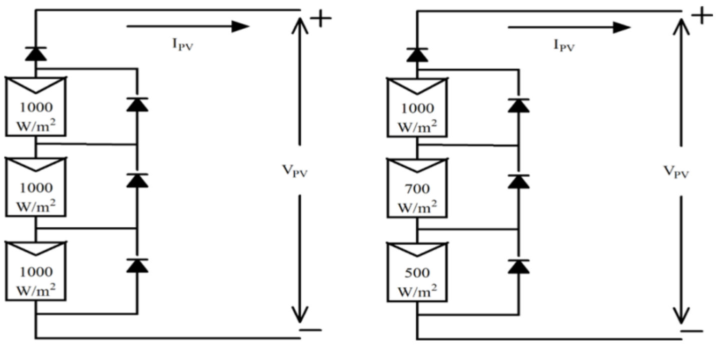

Figure 4.13: Case 1 and Case 2 Shading relations

Two behaviors simplify the definition of the Cuckoo Search Algorithm (CSA): breeding and levy flights. Cuckoos lay their eggs in communal nests but often remove the eggs of others to increase the chances of their own eggs hatching. However, when a host cuckoo detects a foreign egg, it may discard it or abandon the current nest to build a new one elsewhere. Poorer solutions are discarded during each breeding cycle, allowing better solutions to emerge. A random walk mimicking Levy flights, with steps drawn from the Levy distribution, represents the flight path of many birds between nests to find the optimal nest. Initially, the proposed isolated system operates at all points. The optimal cutting ratio nnn or the duty cycle DDD is adjusted to ensure maximum power tracking as environmental conditions change. This dynamic adjustment ensures the system remains efficient and responsive to changing conditions.

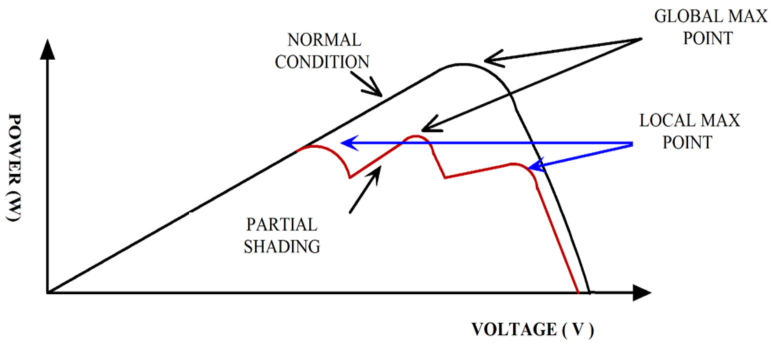

Figure 4.14: PV Curve under Partial Shading Condition

The benefit of the algorithm proposed is that it takes longer for MPP to be followed more quickly. The gathered data is used for training using traditional algorithms. Therefore the neural network has to be periodically trained for precision monitoring of MPP in the parameters of the PV array change over time.

This chapter introduced mathematical models for the behavior of PV systems, focusing on MPPT techniques like P&O, Incremental Conductance, FOCV, FSCC, Fuzzy Logic Control, and the Cuckoo Search Algorithm. These methods were described using equations and analyzed for their efficiency in tracking the MPP under varying environmental conditions. The integration of DC-DC boost converters was also mathematically modeled to optimize power output. The figures and flowcharts included in the chapter visually represent the algorithms and their implementation in solar PV systems.

By integrating these models, solar systems can operate closer to their maximum efficiency, particularly in dynamic and partial shading conditions, ensuring optimized energy extraction.

4.5 Summary

The mathematical modeling presented in this chapter provides a detailed understanding of the behavior of PV systems and MPPT techniques. Through the use of equations that describe the I-V characteristics of PV cells, boost converter operation, and various MPPT methods, we gain a comprehensive framework for optimizing the performance of solar PV systems. The application of advanced methods like Fuzzy Logic Control and Cuckoo Search Algorithms further enhances the ability to track the maximum power point under a wide range of environmental conditions.

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CHAPTER 5

PROPOSED METHODOLOGY

This chapter explores the design, modeling, and experimental evaluation of a solar photovoltaic (PV) system, focusing on optimizing performance through Maximum Power Point Tracking (MPPT) and cooling techniques. The PV system design utilizes unsupervised learning principles and sensory markers for clear system functionality comprehension. Additionally, it includes a discussion of solar radiation characteristics, the creation of meteorological files, and the effects of cooling mechanisms on system efficiency. These aspects are integrated into the solar PV system to ensure maximum efficiency in a variety of environmental conditions.

5.1 Design of Solar PV System

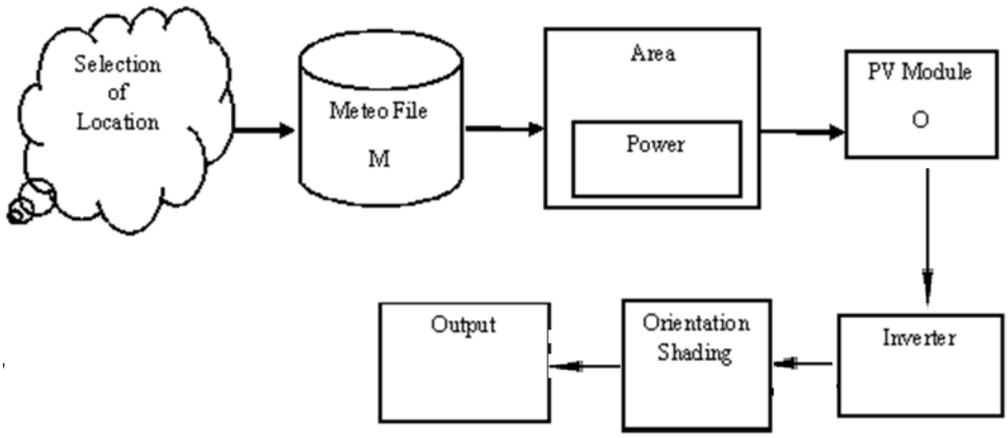

Figure 5.1 Design of the Solar PV System

5.1.1 Creation of Location

The design of solar PV systems is significantly influenced by the geographical location and local environmental factors. The positioning of photovoltaic modules, especially their tilt angle, plays a crucial role in optimizing solar energy capture. PV-Syst, a simulation software, is used to select the project location and simulate weather conditions for optimal system performance.. Let's examine each block's definition in this design one by one. The ideal tilt of photovoltaic modules is greatly influenced by the project's location and local atmospheric conditions. The sections that follow go into detail about the specific geographic place.

5.1.2 Solar Radiation and Meteorology

The electricity generation by a PV module hinges on the precise reception of solar radiation. Solar energy predominantly emanates from the Sun at temperatures near 5800K (equivalent to 5526.85 °C). As solar radiation enters the Earth's atmosphere, it can undergo scattering or absorption due to interactions with air molecules and particles (Refer to Figure 5.2). Direct radiation refers to the reflected or unabsorbed solar radiation that reaches a PV module when the sun's rays are perpendicular to it. Following scattering, radiation can either disperse, termed as scattered radiation, or be absorbed by the module's surface. Albedo radiation is the reflection of solar radiation from the Earth's surface back to the module. Global radiation encompasses all three components: direct, diffuse, and albedo radiation. The amount of solar radiation reaching the Earth's surface diminishes due to absorption and scattering during its journey through the atmosphere. Various gases in the atmosphere cause alterations in the type of radiation reaching the Earth's surface.

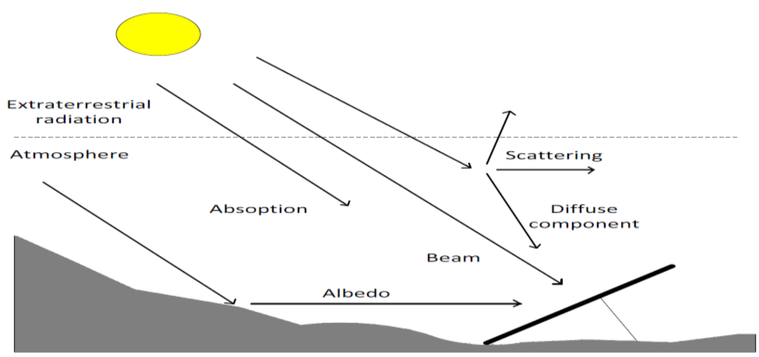

Figure. 5.2 Penetration of Solar radiations

Air mass (AM) quantifies the relative length of the direct path that solar radiation traverses through the atmosphere and is expressed as:

Air mass (AM) = $AM = .. \frac{1}{Cos\theta_z}$ (5.1)

The zenith angle is the angle between the Sun and the point directly overhead. PV modules are rated under Standard Test Conditions (STC) with an air mass (AM) of 1.5, solar radiation of 1000 W/m², and a cell temperature of 25°C. These parameters provide a consistent basis for comparing the performance of different PV modules.

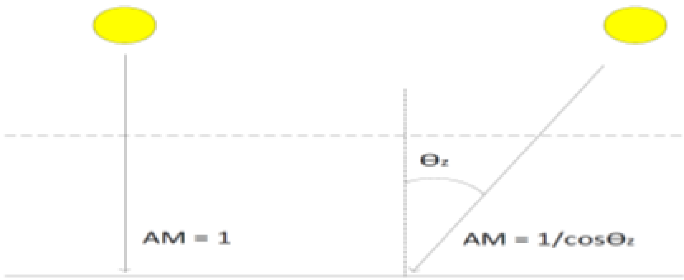

Figure 5.3 Description of air mass

Further characterization of PV modules involves measuring the Nominal Operating Cell Temperature (NOCT) under specific open-circuit conditions to reflect more realistic operating scenarios. These conditions include an air mass (AM) of 1.5, solar radiation of 800 W/m², an ambient temperature of 20°C, and a wind speed greater than 1 m/s. Unlike the idealized Standard Test Conditions (STC) which assumes solar radiation of 1000 W/m² and a cell temperature of 25°C, NOCT takes into account more common environmental variables. This is important because, in reality, the amount of sunlight reaching the Earth's surface fluctuates due to factors such as atmospheric conditions, geographic location, and time of day. Therefore, NOCT provides a more accurate representation of a PV module's performance in typical conditions, helping to predict how the module will perform in the field.

This variation is due to factors such as the Earth's rotation and different atmospheric conditions. When designing a solar project using PV-Syst, the first parameter that needs to be simulated is the project's location. Users have the option to select the country and specific location for their project, and if there are multiple weather data sources available, they can choose one. The location is specified using both decimal coordinates and degrees/minutes format when accessing meteorological data. Other factors taken into account during the project design include the altitude of the location above sea level and the time zone it belongs to. These parameters are important for accurate solar modeling.

Monthly weather data, including horizontal global irradiation (the amount of solar radiation received on a horizontal surface) and ambient temperature, play a crucial role in the simulation. For more precise modeling, additional data like horizontal radiant radiation and wind speed can be provided. Figure 5.4 in the context of the explanation likely illustrates the path of the sun's movement across the project site, which is vital for understanding how solar energy is received and utilized in the project's location.

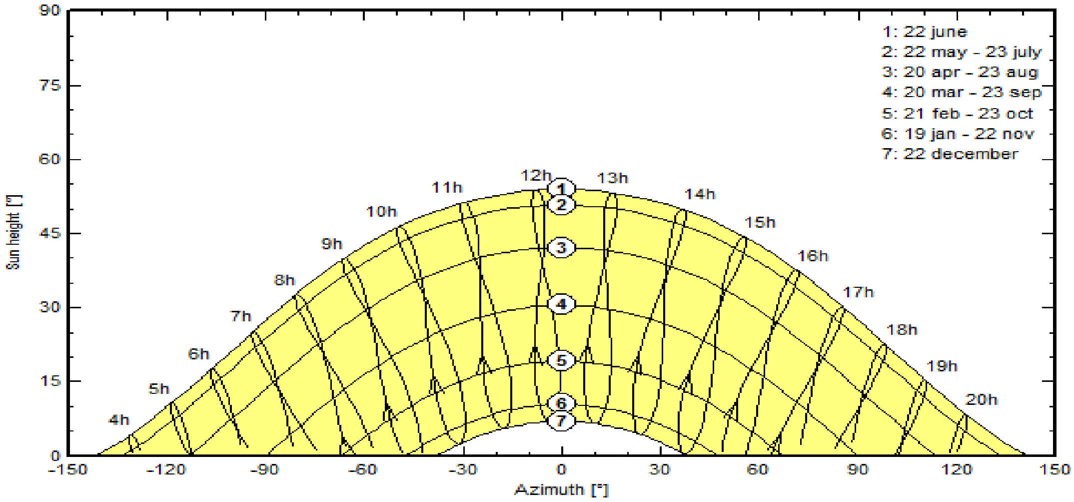

Figure. 5.4 Description of Sun path

Table 5.1 Albedo Values for Various Surroundings

Surroundings	Typical Albedo Values
Residential Area	0.12 - 0.20
Meadow	0.14 - 0.22
Newly Mowed Lawn	0.24
Recent Snowfall	0.8
Moist Snow	0.52 - 0.72

Dry Concrete	0.07 - 0.13
Wet Concrete	0.16
Cement Surface	0.23 - 0.33
Terracotta Tiles	0.3
Polished Aluminum	0.83
Freshly Galvanized Metal	0.32
Heavily Corroded Metal	0.06

5.2 Creation of Meteo File

To model solar radiation more accurately, PV-Syst incorporates meteorological data from sources like Meteonorm and NASA-SSE. These datasets provide solar irradiance and temperature values, which are essential for predicting PV system performance under real-world conditions.

5.2.1 Meteorological Data Sources

PV-Syst allows users to establish monthly meteorological values, redefine the project location, and import weather data on both monthly and hourly scales from various databases. To ensure accuracy, a comparison between free web-based services and local weather data is conducted. A custom secondary weather dataset emphasizing monthly irradiance and temperature values is incorporated.

Table 5.2 Analysis of Weather Data

Database	Region	Data Resolution	Variables	Availability
Meteonorm	Worldwide	Monthly	Global Horizontal Irradiance (Gh), Ambient Temperature (Ta), Wind Velocity (WindVel)	Software
Satellite	Europe	Monthly	Global Horizontal Irradiance (Gh), Normalized Irradiance (NO), Ambient Temperature (Ta)	Web-based, Free
US TMY2	USA	Hourly	Global Horizontal Irradiance (Gh),	Web-based, Free

			Normalized Irradiance (NO), Ambient Temperature (Ta)	
ISM-EMPA	Switzerland	Hourly	Global Horizontal Irradiance (Gh), Direct Horizontal Irradiance (Dh), Ambient Temperature (Ta)	PVsyst
Helioclim	Europe	Hourly	Global Horizontal Irradiance (Gh), Normalized Irradiance (No), Ambient Temperature (Ta)	Web-based, Restricted
SoDa	Africa	Hourly	-	Paid
NASA-SSE	Worldwide	Monthly	Global Horizontal Irradiance (Gh), Ambient Temperature (Ta)	Web-based, Free
WRDC	Worldwide	Hourly/Daily	Global Horizontal Irradiance (Gh), Normalized Irradiance (No), Ambient Temperature (Ta)	Web-based, Free
PVGIS-ESRA	Europe	Monthly	Global Horizontal Irradiance (Gh), Ambient Temperature (Ta), Light Turbidity	Web-based, Free
RET Screen	Worldwide	Monthly	Global Horizontal Irradiance (Gh), Direct Horizontal Irradiance (Dh), Ambient Temperature (Ta), Wind Velocity (WindVel)	Software, Free
Solar GIS	Europe, Africa, Asia, Brazil, West Australia	Hourly	Global Horizontal Irradiance (Gh), Diffuse Horizontal Irradiance (Dh), Ambient Temperature (Ta)	Web-based, Paid Access

This table provides an overview of various meteorological databases, their regional coverage, data resolution, variables included, and the availability/accessibility of the data sources.

5.2.2 Meteo Output for Different Location

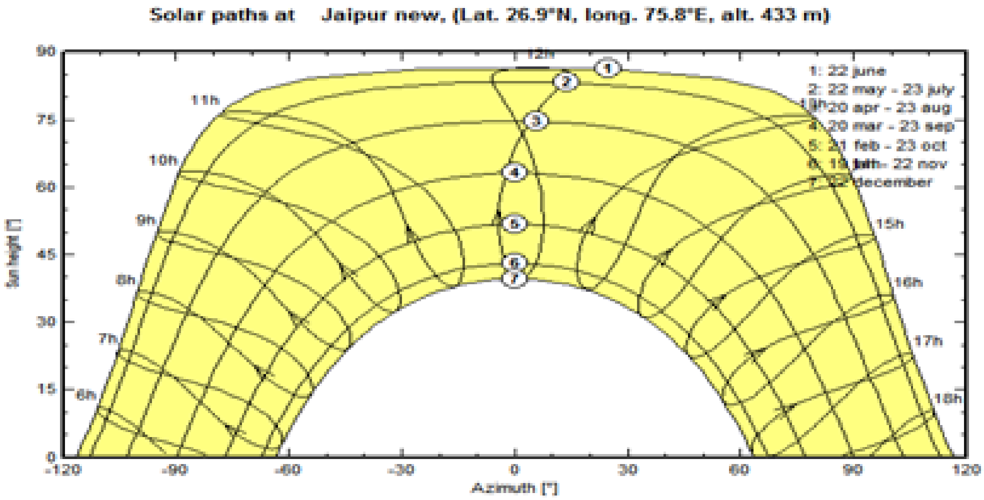

Figure. 5.5 Sun path and Meteo of Jaipur

5.3 Sizing of Array

Today's market is populated by numerous manufacturers of polycrystalline and monocrystalline solar modules, including prominent names such as Hope Solar, Best Solar, King-Pv, Up Solar, Schuco, Kiocera, REC, Innotech Solar, LG, Samsung, Solar Planet, Boch, and Sun. To facilitate a more streamlined selection process, four specific module suppliers have been chosen: Renewable Energy Corporation (REC), Vikram Solar, Sun Power, and Mahirishi Solar. The selection criteria were heavily influenced by specific module certifications, particularly focusing on compliance with IEC61701 and IEC61215 standards. Additionally, Sun Power’s series has obtained the UL1703 certification, ensuring alignment with both IEC61701 and IEC61215 standards, thereby guaranteeing high performance and reliability under various environmental conditions.

5.4 Selection of Inverter

System performance hinges on precise inverter selection to ensure the desired outcomes. Considerations when selecting inverters include:

- PV array rating
- Alignment of solar panels with solar cells

- Shading patterns
- Anticipated annual yield

The overall PV array value is contingent on the number of modules installed on the roof and whether they are polycrystalline or monocrystalline. Three inverter suppliers have been selected:

1. Eltek
2. SMA Solar Engineering AG
3. Danfoss
4. Eltek's THEIA TL String and THEIA HE-t have been chosen due to their high efficiency and single Maximum Power Point Tracking (MPPT) controller. SMA's Sunny Tripower and Danfoss' REflex series are also selected based on their superior tracking capabilities and MPPT features. 5.4.1 Inverter Sizing and Efficiency

The power of a PV array is calculated in kilowatts (kWp) and indicates the array's maximum power output. This value is critical to inverter selection, as the inverter's capacity should align with the array's maximum power rating. To avoid overloading the inverter, a 1.1 safety factor is often employed.

Inverter efficiency significantly impacts system performance, as it determines the percentage of DC power generated by the array that can be converted into AC power for use. Higher inverter efficiency corresponds to lower energy losses and improved system performance.

The software can generate various graphical representations, including hourly irradiance, ambient temperature, and inverter efficiency over a year. This information assists in selecting the most suitable inverter for the project.

5.5 DC Array Configuration

PV arrays are connected to inverters in two primary configurations: series and parallel. DC array configuration has a substantial impact on system performance, as it influences the voltage and current levels at the inverter input. The following section discusses series and parallel configurations, as well as their effects on voltage, current, and losses.

5.5.1 Series Configuration

In a series configuration, PV modules are connected sequentially to form a string. The positive terminal of one module is connected to the negative terminal of the next module, and so on. This arrangement increases the total voltage while maintaining a constant current.

Advantages of a series configuration include:

- High voltage output, suitable for long cable runs
- Reduced current, minimizing energy losses
- Simplified wiring due to fewer connections

However, drawbacks include:

- Susceptibility to shading effects impacting the entire string
- Lower overall system efficiency if one module underperforms

5.5.2 Parallel Configuration

In a parallel configuration, PV modules are connected in parallel with one another, with all positive terminals connected together and all negative terminals connected together. This setup maintains a constant voltage while increasing the total current.

Advantages of a parallel configuration include:

- Minimal shading impact, as one shaded module does not affect the entire array
- Enhanced overall system efficiency, as each module operates independently

However, parallel configurations have some drawbacks:

- Increased current levels, which may require larger cables
- Potentially complicated wiring due to numerous connections

This section provides valuable insights into the experimental approach, data collection, and analysis methods used in the study of cooling and MPPT techniques in solar photovoltaic systems, contributing to the overall understanding and optimization of solar energy utilization.

Solar photovoltaic (PV) systems are a marvel of sustainable energy technology. This guide explores the intricacies of designing and configuring efficient PV systems. By understanding voltage specifications, current requirements, power limits, and potential losses, we can harness the full potential of these systems.

Voltage Specifications Matching for PV Arrays and Inverters Achieving a harmonious voltage match between PV arrays and inverters is essential. To ensure optimum performance, we must consider the minimum temperature differential between the inverter and the highest module voltage. Failure to align these voltages can result in reduced system efficiency or even inverter shutdown. This relationship can be described by the temperature coefficient (V/°C) and the temperature difference (ΔT) between Standard Test Conditions (STC) and the lowest module temperature.

Current Specifications for PV Array-Inverter Compatibility For seamless operation, the maximum current of the PV modules should be less than the inverter's maximum input current capacity. This can be assessed by determining the number of parallel strings (N parallel strings) in accordance with the short-circuit current temperature coefficient (Isc). This ensures that the PV array can deliver power within the inverter's limits.

Power Specifications and PV Array Sizing To maximize power output, we typically match the highest PV array output level with the inverter's maximum DC input capacity. Figure 5.8 illustrates this relationship, highlighting the inverter's DC input power and the PV array's power capabilities. The peak module's effect on the inverter's performance dictates the number of modules required in the array.

Calculating Losses in PV Systems Efficient power generation relies on minimizing losses in PV systems. Losses occur due to factors such as radiation, heat, resistance, shading, and module quality mismatch. Addressing these losses is crucial to maintain system performance.

Radiation Loss Radiation loss occurs when radiation levels fall below the module's STC conditions. This phenomenon is influenced by factors such as shading or weather conditions. Ensuring adequate sunlight exposure is vital for optimal power generation.

Heat Loss Heat loss is attributed to temperature differentials within the PV system. Modules operating at temperatures exceeding 25°C can experience efficiency reductions. Factors like solar radiation absorption coefficients and panel performance influence heat loss. Additionally, thermal loss factors depend on installation specifics like mounting and shading.

Ohmic Losses Ohmic losses result from wire resistance within the DC circuit. Proper cable sizing and configuration, as seen in Figures 5.9 and 5.10, can mitigate these losses. Consideration should be given to both copper and cable resistance, especially for lengthy installations or those involving external transformers.

Module Quality Mismatch Module quality mismatches can lead to power imbalances in the PV system. Addressing this issue requires careful assessment of wiring configurations and transformer losses. Copper loss ratios and power adjustments play a crucial role in optimizing performance.

Soiling Loss Soiling losses account for dirt and debris accumulating on PV panels. These losses vary with location and weather conditions, impacting module efficiency. Proper cleaning and maintenance are essential to mitigate these losses.

Incident Angle Correction (IAM) Loss IAM losses occur due to the angle at which sunlight strikes the module's surface. Proper positioning and angle adjustments can reduce these losses, ensuring optimal energy capture.

Economics of PV Systems Understanding the economic aspects of PV systems is vital for decision-making. Factors such as module and inverter prices, returns on investment, and life cycle costs should be considered.

Simple Payback Period The simple payback period assesses how long it takes for the PV system to recoup its initial costs. It is calculated using the formula ($T = C / S$), where T represents the payback period in years, C is the initial cost, and S is the annual cost savings.

Life Cycle Cost Analysis to evaluate the long-term cost-effectiveness, a life cycle cost analysis is performed. This analysis considers the total cost of ownership and maintenance over the system's lifetime.

5.6 Inverter Sizing and DC/AC Ratio

Proper inverter sizing and the DC/AC ratio are essential considerations for optimizing the performance of a grid-connected PV system. These factors directly impact the efficiency and power output of the system.

5.6.1 Inverter Sizing

Inverter sizing involves selecting an inverter with an appropriate capacity to match the total DC power output of the PV array. Proper inverter sizing ensures that the inverter operates within its rated capacity, minimizing losses and maximizing system efficiency.

Oversizing an inverter can lead to suboptimal efficiency, as the inverter may operate at a lower percentage of its rated capacity. Under sizing an inverter can result in clipping, where excess DC power generated by the PV array is not converted into AC power.

To determine the appropriate inverter size, the following steps can be followed:

- Calculate the total DC power output of the PV array (kWp).
- Consider factors such as shading, temperature variations, and module degradation to determine the expected DC power output under various conditions.
- Select an inverter with a capacity equal to or slightly higher than the calculated DC power output.

It's essential to consult inverter manufacturer specifications and guidelines for proper sizing recommendations.

5.6.2 DC/AC Ratio

The DC/AC ratio, also known as the oversizing ratio, represents the ratio of the PV array's DC power capacity (kWp) to the inverter's AC power capacity (kVA or kW). This ratio plays a crucial role in optimizing system performance.

A higher DC/AC ratio allows the PV array to generate more DC power than the inverter's rated capacity, which can be advantageous in certain situations. However, an excessively high DC/AC ratio can lead to increased losses, reduced inverter efficiency, and potential issues with grid integration.

The optimal DC/AC ratio depends on various factors, including:

- Inverter efficiency curve: Consider the inverter's efficiency at different operating points to determine the ideal DC/AC ratio.
- Grid regulations and limitations: Ensure that the DC/AC ratio complies with local grid requirements and standards.

- Expected energy yield: Calculate the expected energy yield of the system under different DC/AC ratios to find the balance between maximizing energy production and minimizing losses.

It's essential to perform a detailed analysis and simulation to determine the optimal DC/AC ratio for a specific grid-connected PV system.

5.7 Design Considerations for Grid Integration

Grid integration is a critical aspect of grid-connected PV systems, ensuring that the generated solar energy is seamlessly integrated into the existing electrical grid. Several design considerations and components are essential for successful grid integration.

5.7.1 Grid Connection

Grid connection refers to the physical connection of the PV system to the utility grid. It involves connecting the inverter's AC output to the grid's distribution or transmission network. The grid connection point, also known as the point of common coupling (PCC), is typically located at the utility's meter or substation.

Key considerations for grid connection include:

- Compliance with local grid codes and regulations: Ensure that the PV system design and components meet the requirements of the local grid operator or utility company.
- Protection devices: Install protection devices such as fuses, circuit breakers, and surge arresters to safeguard the PV system and the grid from faults and surges.
- Anti-islanding protection: Implement anti-islanding protection measures to prevent the PV system from continuing to operate during grid outages, ensuring the safety of utility workers.

5.7.2 Grid Voltage and Frequency

Grid-connected PV systems must operate in synchronization with the grid's voltage and frequency. In most regions, the standard grid voltage is either 120 V or 240 V for residential systems and 3-phase 208 V or 480 V for commercial and industrial systems. The grid frequency is typically 50 Hz or 60 Hz.

To ensure proper grid integration, the inverter must:

- Match the grid voltage and frequency: The inverter's output voltage and frequency should closely match the grid's parameters to enable seamless energy transfer.
- Synchronize with the grid: Inverters are equipped with grid-tied control systems that enable them to synchronize with the grid's phase and frequency before connecting.

5.7.3 Power Quality and Grid Standards

Grid-connected PV systems should adhere to power quality standards to ensure that the electricity they generate meets the grid's quality requirements. Power quality refers to the consistency and reliability of electrical power and includes parameters such as voltage regulation, harmonics, and voltage flicker.

Key considerations for power quality and grid standards include:

- Voltage and frequency regulation: PV inverters should maintain stable output voltage and frequency within permissible limits to prevent disruptions to the grid.
- Harmonic distortion: Inverters should minimize harmonic distortion in their output to avoid adverse effects on other electrical equipment connected to the grid.

- Grid code compliance: PV systems should comply with the grid operator's requirements and standards, which may include specific limits on voltage, frequency, and power factor.

5.7.4 Grid Interconnection Agreement

Grid-connected PV system owners typically need to establish a grid interconnection agreement with the local utility company or grid operator. This agreement outlines the terms and conditions for connecting the system to the grid, including technical specifications, safety requirements, and contractual obligations.

Key elements of a grid interconnection agreement may include:

- System specifications: Detailed information about the PV system's components, capacity, and design.
- Safety and protection requirements: Requirements for protection devices, anti-islanding measures, and equipment grounding.
- Operational and maintenance procedures: Guidelines for the ongoing operation, monitoring, and maintenance of the PV system.
- Metering and billing arrangements: Procedures for metering electricity generation, net metering (if applicable), and billing arrangements with the utility.

Engaging in a transparent and cooperative dialogue with the utility company is essential to establish a mutually beneficial grid interconnection agreement.

5.8 Performance Monitoring and Maintenance

Performance monitoring and maintenance are crucial aspects of ensuring the long-term reliability and efficiency of grid-connected PV systems. Regular monitoring allows system owners to identify issues promptly and take corrective actions to optimize energy production.

5.8.1 Monitoring Systems

Effective monitoring systems provide real-time data on the performance of the PV system, allowing system owners and operators to assess its operation and diagnose any problems. Key components of a monitoring system include:

- Data acquisition devices: Sensors, meters, and monitoring equipment that measure parameters such as irradiance, temperature, current, voltage, and power.
- Data communication: Systems that transmit collected data to a central monitoring platform via wired or wireless communication, typically through the internet.
- Monitoring software: Software applications or platforms that analyze and display performance data, often providing insights through graphical interfaces and alerts for issues or anomalies.

Monitoring systems can track various parameters, including:

- Solar irradiance: Monitoring solar radiation levels to assess available sunlight for energy generation.
- DC power generation: Tracking the total DC power output of the PV array.
- Inverter operation: Monitoring inverter status, including efficiency, voltage, and frequency.
- AC power production: Measuring the total AC power production and grid feed-in.
- Weather conditions: Recording temperature, humidity, and wind speed, which can affect PV system performance.

5.8.2 Maintenance

Regular maintenance is essential for ensuring the long-term performance and longevity of a grid-connected PV system. Maintenance tasks typically include:

- Cleaning: Periodic cleaning of PV modules to remove dust, dirt, and debris that can reduce energy production.
- Inspection: Visual inspections to check for physical damage, loose connections, and signs of wear.
- Inverter maintenance: Regular checks on inverter performance and efficiency.
- Cable and wiring inspection: Ensuring that all cables and connections are intact and functioning correctly.
- Vegetation management: Trimming or removing vegetation that may shade the PV array.

Maintenance schedules and tasks may vary based on system size, location, and environmental conditions. It's essential to follow the manufacturer's recommendations and consult with experienced solar professionals for optimal maintenance practices.

5.8.3 Performance Analysis

Performance analysis involves assessing the actual energy production of the PV system compared to its expected or estimated energy yield. Common performance metrics and analyses include:

- Performance ratio: Calculating the ratio of actual energy output to expected energy output, providing insight into system efficiency.
- Energy yield analysis: Analyzing daily, monthly, and annual energy production to identify trends and anomalies.
- System degradation assessment: Monitoring long-term performance to detect any signs of degradation or underperformance, such as a decrease in energy yield over time.

Performance analysis helps identify areas for improvement and optimization, ensuring that the PV system operates at its maximum potential throughout its lifespan. Designing and implementing a grid-connected PV system requires careful consideration of numerous factors, including location, site conditions, equipment selection, and grid integration. By following best practices in system design, it is possible to maximize energy production, efficiency, and reliability while complying with local regulations and standards.

Grid-connected PV systems have the potential to make a significant contribution to **P-V Characteristic with maximum Power point** sustainable energy generation and reduce greenhouse gas emissions. As solar technology continues to advance and costs decrease, grid-connected PV systems become an increasingly attractive option for residential, commercial, and industrial applications.

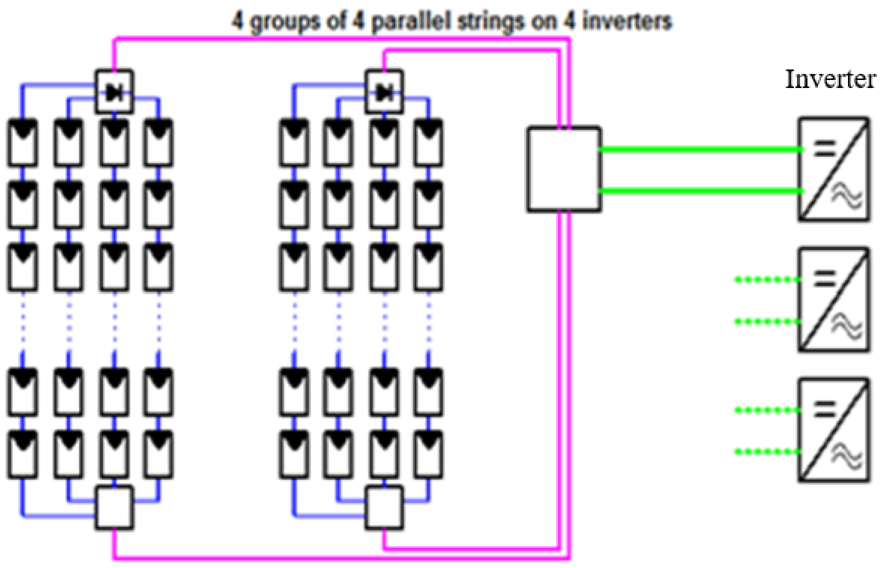

Figure 5.6 Interconnection of PV and inverters

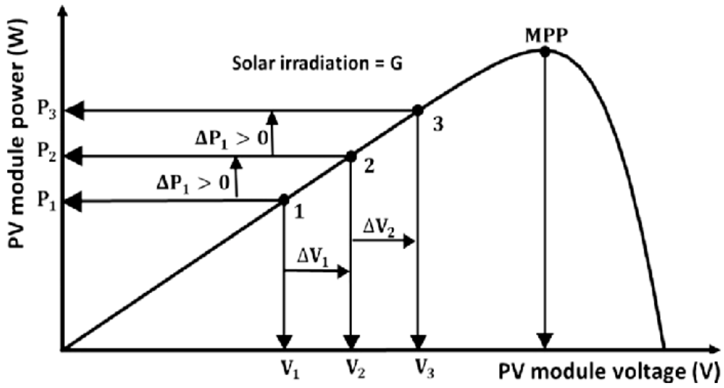

Figure 5.7 PV With MPPT

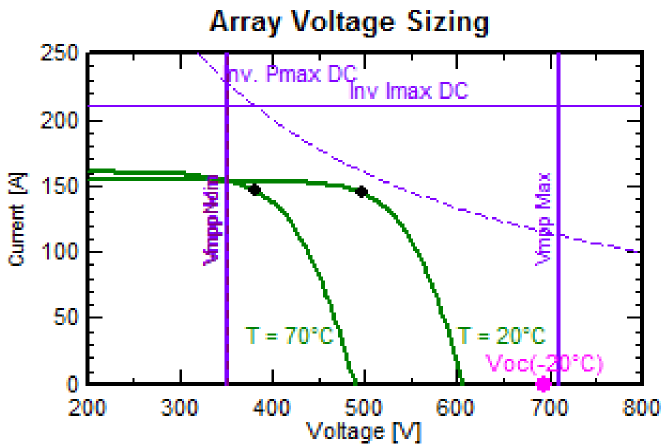

Figure 5.8 Sizing of array voltage using PV-Syst

Successful grid-connected PV projects require collaboration among various stakeholders, including project developers, installers, utilities, and regulatory bodies. By working together, these stakeholders can harness the power of solar energy to create a cleaner, more sustainable energy future.

As technology, regulations, and industry standards continue to evolve, those involved in the design and implementation of grid-connected PV systems should stay informed and adapt to changes to ensure the success of solar projects and the broader transition to renewable energy sources.

5.9 Solar Photovoltaic System Sizing: A Practical Example

To illustrate the process of sizing a solar photovoltaic system, let's consider a real-world scenario:

Example: In a typical household, various electrical appliances are in use:

- Four 18 Watt fluorescent tube lights with starters, used for 4 hours daily.
- Four 60 Watt ceiling fans in operation for 2 hours each day.
- A single 75 Watt refrigerator equipped with a compressor. The refrigerator runs continuously throughout the day, with the compressor cycling on for 12 hours and off for 12 hours.
- The intended system will utilize 12 V DC, 140 Wp PV modules.

5.9.1 Sun Angle and House Orientation

The angle at which sunlight strikes the solar panels varies throughout the day, impacting energy production. For instance, a 100-watt panel will gradually increase its output during the night, reaching its peak at midday, and then decreasing as the day progresses. The angle of sunlight, relative to the panel, also influences energy generation. Factors such as the roof's orientation and the east-west path play a crucial role.

5.9.2 Determining Power Consumption Demands

To calculate the daily power consumption demands, we add up the power usage of all appliances:

Total appliance power consumption = (18 W x 4 hours x 4 tubes) + (60 W x 2 hours x 4 fans) + (75 W x 0.5 hours x 24 hours) = 1,668 Wh/day

Now, to determine the total energy required from the PV panels:

Total PV panel energy needed = 1,668 Wh/day x 1.3 = 2,169 Wh/day

5.9.3 Sizing the PV Panel

To find the required capacity (Wp) of the PV panel, we consider the daily energy needs:

Total Wp of PV panel capacity needed = 2,169 Wh/day / 4.5 hours (average sunlight hours) = 482 Wp

This implies that approximately 3.44 PV modules are needed. In practice, it's advisable to use 4 modules, each with a 140 Wp rating to meet the system's requirements.

5.9.4 Inverter Sizing

Now, let's determine the inverter size by summing up the wattage of all appliances:

Total wattage of all appliances = 72 W (tube lights) + 240 W (ceiling fans) + 75 W (refrigerator) = 387 W

For safety and to accommodate possible future additions, it's recommended to choose an inverter that is 25-30% larger than the total wattage. Therefore, the inverter should be approximately 485 W or greater.

5.9.5 Battery Sizing

Considering the power usage of all appliances, the battery capacity must be sufficient to provide power during periods without sunlight:

Nominal battery voltage = 12 V Days of autonomy (number of days the system should run without solar input) = 3 days

Battery capacity = [(72 W x 4 hours) + (240 W x 2 hours) + (75 W x 12 hours)] x 3 days / (0.85 efficiency x 0.6 depth of discharge x 12 V) = 815 Ah

Hence, the battery should be rated at 12 V, 850 Ah to ensure 3 days of autonomy.

5.9.6 Solar Charge Controller Sizing

To efficiently manage the power flow from the PV panels to the battery, we need an appropriately sized solar charge controller:

Solar charge controller rating = (4 strings x 8 A) x 1.3 = 41.6 A

Therefore, the solar charge controller should be rated at 45 A, suitable for 12 V or greater systems.

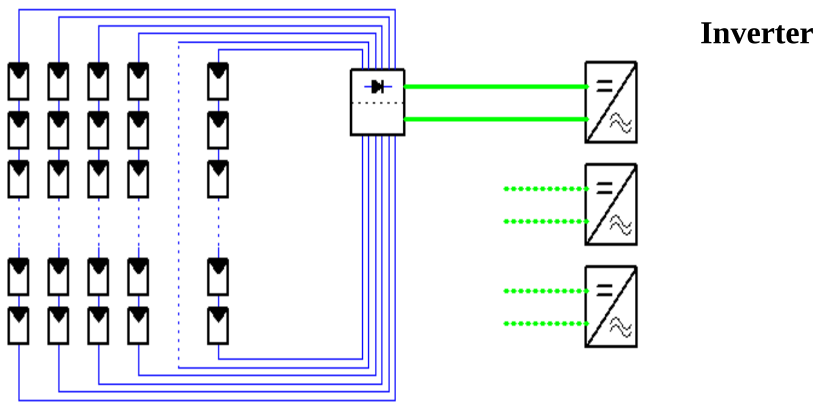

Figure 5.9 Wiring connections for parallel strings

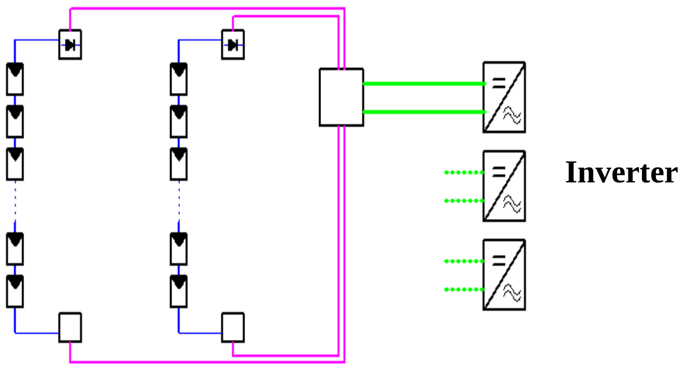

Figure 5.10 Wiring connections for groups of parallel strings

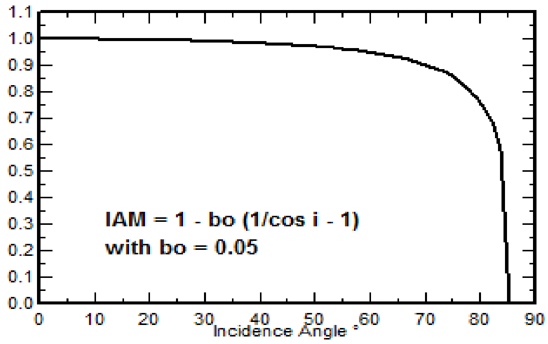

Figure 5.11 Incidence angle modifier

In this chapter, we have used a practical example to demonstrate the crucial steps involved in sizing a solar photovoltaic system. By understanding these calculations and considerations, one can effectively design and install a solar PV system tailored to their specific energy needs.

5.10 Experiment Approach for analysis of Cooling

The experiments were conducted in Jaipur, India, situated at latitude of 26.91°N and a longitude of 75.78°E, subject to the prevailing meteorological conditions. The solar PV/T system utilized a 37 W polycrystalline solar panel constructed from silicon, covering an area of 0.315 square meters. To enhance its functionality, copper sheets and copper tubes were strategically positioned behind the panel. The copper sheet acted as an absorber, efficiently absorbing and transferring heat from the panel to the water circulating through the copper tubes. An 18W A.C. water pump was employed to circulate the water in the system. The coolant used for this purpose was water, and its mass flow rate varied between 0.002 and 0.004 kg/sec. The impact of a glass cover on the PV/T system's efficiency was evaluated after determining the optimal mass flow rate.

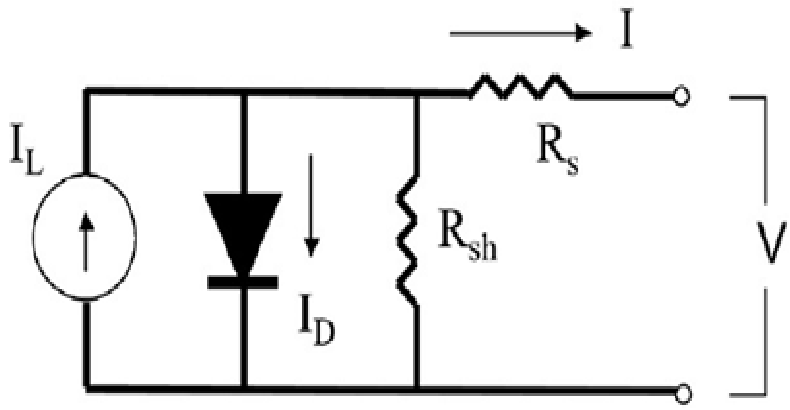

Figure 5.12 A Typical Electrical Circuit of Solar PV Cell

The maximum power output of the PV modules was assessed at 10:00 a.m. on-site, both at the front and rear of each module, considering the fill factor, voltage, and maximum power, as well as the initial and final water temperatures, from 5:00 in the morning. These measurements were conducted for both solar PV and solar PV/T systems during the evening hours.

Figure 5.13 Experimental Setup

5.11 Instruments Used

Table 5.3 Technical Specifications of PV/T System

Parameter	Specification
Solar PV Module Type	Poly-SI
Maximum Power Output	45 W
Voltage at Maximum Power (Vmp)	19 V
Current at Maximum Power (Imp)	2.37 A
Short Circuit Current (Isc)	2.50 A
Open Circuit Voltage (Voc)	23 V
Module Surface Area	0.340 sq. m.
Absorber Material	Aluminum sheet 0.6 mm thick with aluminum tubes 10 mm diameter
Cooling Fluid	Glycol-Water Mixture
Submersible Pump Details	DC-12V, 60Hz, 25W, Maximum lifting height = 2.0 m.

Figure 5.14 Experimental Tools (Representational)

Absolute instantaneous global solar radiation has been measured with an uncertainty of +/- 10% by means of a portable solar power meter (Tenmars TN-207). Digital thermal hygrometers were used to measure ambient temperature and humidity. A solar module analyzer has been used for calculating an electrical feature of PV and PV/T (MECO 9009). With a mercury thermometer the initial and final water temperature was measured. PV and PV/T panels were tested using IR thermometer on the front and rear sides. Wind speed with hot wire anemometer was measured. Wind speed.

Table 5.4 Experimental Tools

S. No.	Instrument	Precision	Measurement Range	Model
1	Photovoltaic Module Tester	±1.5%	0-12 V / 0.02-12 A	SolarCheck 1010
2	Solar Irradiance Meter	±3%	0-2500 W/m²	SunMeter SM-300
3	Hygro-Thermometer	0.2% R.H. / ±0.5°C	Humidity: 5-90% R.H. / Temp: -10 to 60°C	ClimatePro HT-450
4	Infrared Temperature Gauge	±1.5°C	-20 to 500°C	ThermoTech IT-500
5	Liquid-in-Glass Thermometer	±0.5°C	-20°C to 120°C	PreciseTemp PT-110

Figure 5.15 Infrared Thermometer (Representational)

Figure 5.16 Solar Power Meter(Representational)

Figure 5.17 Solar Module Analyzer (Representational)

Figure 5.18 Hot Wire Anemometers (Representational)

Figure 5.19 Water Proof Digital Thermometers (Range 50-300C)

(Representational)

5.12 Performance Evaluation

The evaluation of the PV/T collector's performance involves considering various efficiency metrics, with the primary components being thermal efficiency and electrical efficiency. Thermal efficiency quantifies the useful thermal gain relative to the electric power produced in response to solar radiation. It is defined as the ratio of useful thermal energy gained to the solar incident radiation on the collector's aperture. Electrical efficiency, on the other hand, characterizes the electrical power generated in relation to the solar radiation input.

The overall efficiency is computed as the sum of thermal and electrical efficiencies and is used to assess the overall system efficiency. Additionally, the energy-saving efficiency of electricity, defined as the ratio of energy savings to electrical power efficiency, plays a role in evaluating the system's effectiveness.

5.12.1 Solar Panel Energy Efficiency

The energy efficiency of a solar cell is evaluated using the exergy balance equation. The balance between energy input and output determines the system's efficiency, considering exergy losses. The efficiency of electricity production from a PV module is also taken into account, considering factors such as solar insulation and surface temperature.

Figure 5.20 Front Surface Cooling

Table 5.5 The Research Input Parameter

Input Parameter	Value
Nominal-Operating Cell Temperature (NOCT)	42°C
StefanBoltzmann Constant (σ)	5.67×10^{-8} W/m²-K⁴
Emissivityof the Panel (ε)	0.85
Sun Temperature	5770 K

Figure 5.21 Front & Back View of Back Surface Cooling by Common Grass And Water

5.13 Cooling of Solar Photovoltaic System

To mitigate temperature-dependent losses, cooling techniques are implemented. These techniques include front surface cooling with water and back surface cooling using dry grass and water. Water is employed as a coolant in front surface cooling, and it flows naturally over the panel. Back surface cooling involves creating a network of iron stands with dry grass spread over them. Water is intermittently sprayed on the grass, and air flows through it to facilitate cooling.

5.13.1 Front Surface Cooling by Water

Front surface cooling utilizes water as a coolant, with a pipe featuring holes distributed over the panel's top to allow water to flow. Different water flow rates (1L/minute, 1.5L/minute, and 2L/minute) are tested to determine their impact on panel output, with 2L/minute being found to be the most effective.

5.13.2 Back Surface Cooling by Dry Grass & Water

In back surface cooling, dry grass is placed on iron stands, and a pipe with holes is used to wet the grass periodically. Air is allowed to flow through the grass, enhancing cooling. The effect of different water flow rates on panel temperature and voltage is displayed in **Figure 5.22**.

In this chapter, the research methodology for loss forecasting in solar photovoltaic systems is discussed, along with the performance evaluation parameters and cooling methods employed to mitigate temperature-related losses.

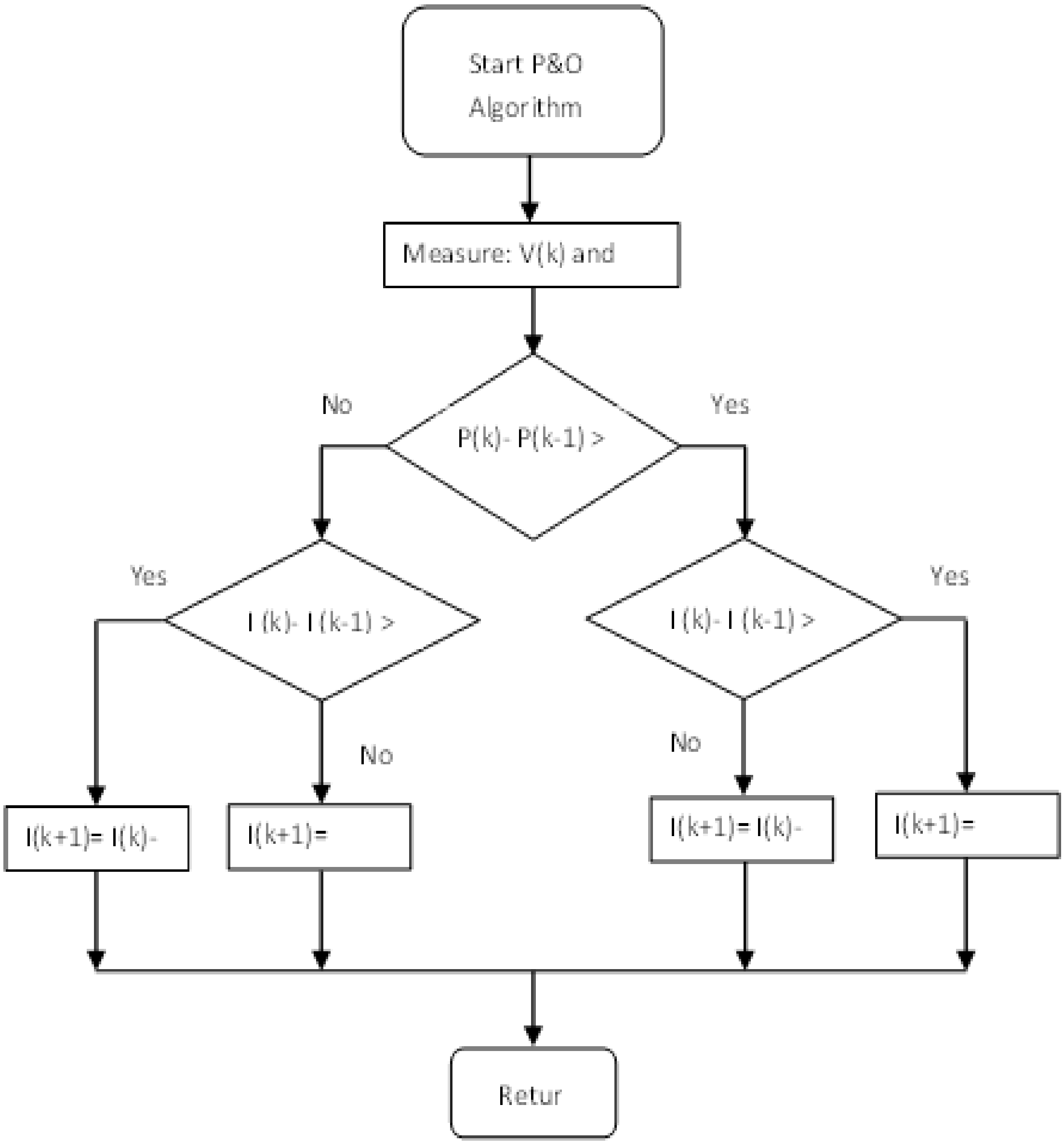

Figure 5.22 Perturb & Observe Flowchart

The cheapest approach is Perturb & Observe (P&O). In this we only use one sensor, which is the sensor, to senses the voltage of a PV array and thus less and easier to implement the costs of implementation. The complexity of the time of the algorithm is much lower but it does not stop at the MPP until it is very close to the MPP and continues in both directions. If that happens, we can set an acceptable error limit on the algorithm very close to the MPP or use a waiting function to improve the time complexity.

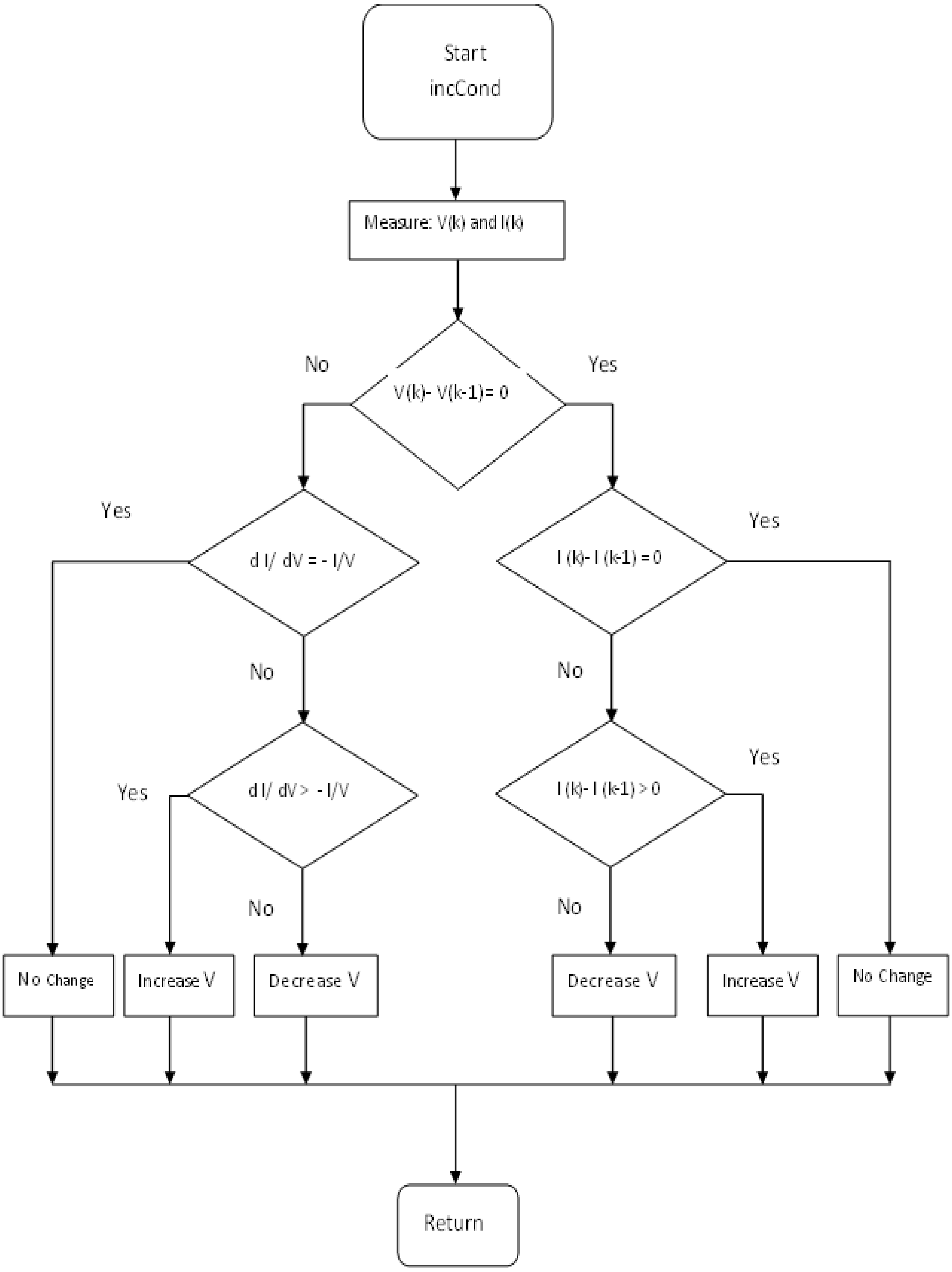

Figure 5.23 INC Flowchart

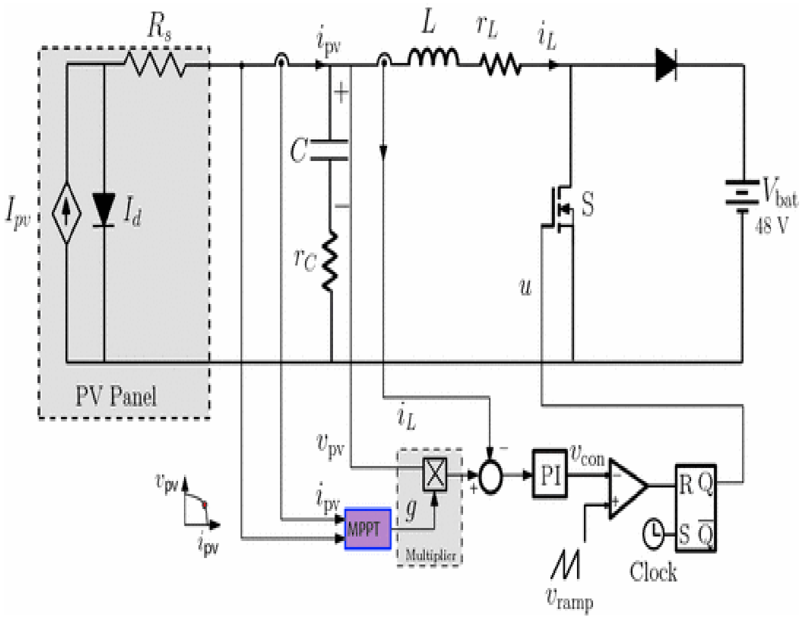

Figure 5.24 Circuit Diagram of a Boost Converter

Table 5.6 Characteristics of Different MPPT Techniques

MPPT Technique	Convergence Speed	Implementation Complexity	Periodic Tuning	Sensed Parameters
Perturb and Observe (P&O)	Medium	Low	No	Voltage
Incremental Conductance (IncCond)	Medium	Medium	No	Voltage, Current
Fractional Open-Circuit Voltage (Voc)	High	Low	Yes	Voltage
Fractional Short-Circuit Current (Isc)	High	Medium	Yes	Current
Fuzzy Logic MPPT	Fast	High	Yes	Multiple
Neural Network MPPT	Fast	High	Yes	Multiple

5.14 Maximum Power Point Tracking (MPPT)

MPPT techniques are critical for maximizing the power output of solar PV systems. Various methods are used, including Perturb & Observe (P&O), Incremental Conductance (INC), Fractional Open Circuit Voltage, Fractional Short Circuit Current, Fuzzy Logic Control, and Neural Network-based MPPT. Each technique has unique advantages and complexities tailored to different system needs.

Perturb & Observe (P&O) is a cost-effective technique that modifies the operating point based on voltage readings. It's straightforward but may need adjustments for optimal performance. The Incremental Conductance (INC) method also modifies the operating point but uses both voltage and current readings, offering moderate complexity without needing periodic tuning.

The Fractional Open Circuit Voltage method calculates the Maximum Power Point (MPP) using a proportional constant (k_1) and voltage measurements. Similarly, the Fractional Short Circuit Current method uses current measurements and a proportional constant (k_2) to determine the MPP. Fuzzy Logic Control is noted for its quick response and suitability for microcontrollers, effectively handling input data inaccuracies and nonlinearity. Neural networks offer another MPPT approach, processing input data through multiple layers of nodes to optimize power output.

The MPPT system includes a boost converter to efficiently increase the initially low voltage output from the solar panel to a higher, more usable level. The boost converter operates in two modes: one for storing energy and another for releasing it, ensuring smooth power delivery. The MPPT algorithm, such as P&O or Incremental Conductance, dictates when to switch modes to maintain tracking of the MPP.

Additionally, an experimental analysis of cooling methods in a solar photovoltaic system was conducted in Jaipur, India. Using a polycrystalline solar panel, different cooling techniques, including front surface water cooling and back surface cooling with dry grass and water were tested under specific meteorological conditions. Various instruments were used for data collection and analysis, such as solar module analyzers, solar power meters, humidity/temperature meters, IR thermometers, and mercury thermometers. These tools measured parameters like solar radiation, temperature, humidity, and electrical characteristics of the PV system.

The performance evaluation included calculations of energy efficiency, exergy efficiency, and power conversion efficiency, considering factors like temperature, irradiance, and electrical characteristics. MPPT techniques, including Perturb & Observe (P&O), Incremental Conductance (INC), Fractional Open Circuit Voltage, Fractional Short Circuit Current, Fuzzy Logic Control, and Neural Network-based MPPT, were crucial for optimizing the system's power output.

Lastly, the implementation of MPPT using a boost converter was discussed, highlighting the boost converter's four operational modes for tracking the maximum power point, ensuring efficient voltage stepping and maximum power transfer.

In the context of the boost converter's operation, it switches between different modes to efficiently manage the voltage and ensure maximum power delivery from the solar panel to the load. Mode 1 involves closing the switch to store energy in the inductor, while Mode 2 opens the switch, allowing the inductor to release the stored energy to the load. This cyclical process, driven by the MPPT algorithm, ensures the system operates at the maximum power point (MPP).

The experiment conducted in Jaipur utilized these principles to evaluate different cooling methods on a polycrystalline solar panel's performance. By using front surface water cooling and back surface cooling with materials like dry grass and water, the study aimed to determine the most effective cooling strategy under specific meteorological conditions. The findings from these experiments are crucial for improving the efficiency and longevity of solar panels, especially in hot climates.

Instruments such as solar module analyzers, solar power meters, humidity/temperature meters, IR thermometers, and mercury thermometers were employed to gather comprehensive data. These tools provided precise measurements of solar radiation, temperature, humidity, and the electrical properties of the PV system, which are essential for accurate performance analysis.

The performance evaluation of the solar PV system focused on several efficiency metrics. Energy efficiency measures the ratio of useful electrical energy produced to the solar energy incident on the panel. Exergy efficiency evaluates the useful work potential of the system, accounting for the quality of energy. Power conversion efficiency examines the effectiveness of converting absorbed solar energy into electrical power. These metrics are influenced by various factors such as temperature, irradiance, and the inherent electrical characteristics of the solar panels.

By integrating these advanced MPPT methods with efficient cooling strategies and precise measurement tools, the overall performance and reliability of solar PV systems can be significantly enhanced. This comprehensive approach ensures that solar energy systems are not only efficient but also adaptable to varying environmental conditions, leading to more sustainable and reliable energy solutions.

CHAPTER 6

RESULTS & DISCUSSIONS

The efficiency and cost-effectiveness of a solar photovoltaic (PV) system depend greatly on its geographical location and regional parameters. To delve into this intricate science, we delve into the realm of powerful network-connected mathematical modeling and simulation specifically tailored for solar PV systems. Our focus revolves around exploring the interconnected network and the intricacies of constructing an independent photovoltaic solar system through mathematical modeling.

The outcomes of our research can be broadly categorized as follows:

1. Examination of the Design and Installation for 1 MW and 100 KWp Grid-Connected Systems:
    - Utilizing the PV-Syst software for the design and installation of the Solar Photovoltaic (SPV) System.
    - Forecasting energy yield and simulating losses over the course of a year.
    - Categorizing losses based on various components within the system.
2. Investigating the Impact of Parametric Variations and Geographical Locations on Performance Parameters:
    - Analyzing how geographical parameters influence the system's performance.
    - Studying the effects of variations in irradiation and temperature.
    - Optimizing the orientation of PV panels for maximum efficiency.
    - Assessing the influence of manufacturing technology and location-specific factors.

6.1 Design Analysis of System and Losses

In our quest to address these complex issues, we employ professional tools like PV-Syst, which prove invaluable in tackling architectural challenges, implementing strategies, and refining forecasting techniques. Our approach aims to achieve the following objectives:

- Develop a highly efficient mathematical model for solar photovoltaic systems.
- Enhance the operational efficiency of the system.
- Make informed decisions regarding location selection and installation procedures.
- Accurately calculate and forecast yearly energy yield and potential losses.

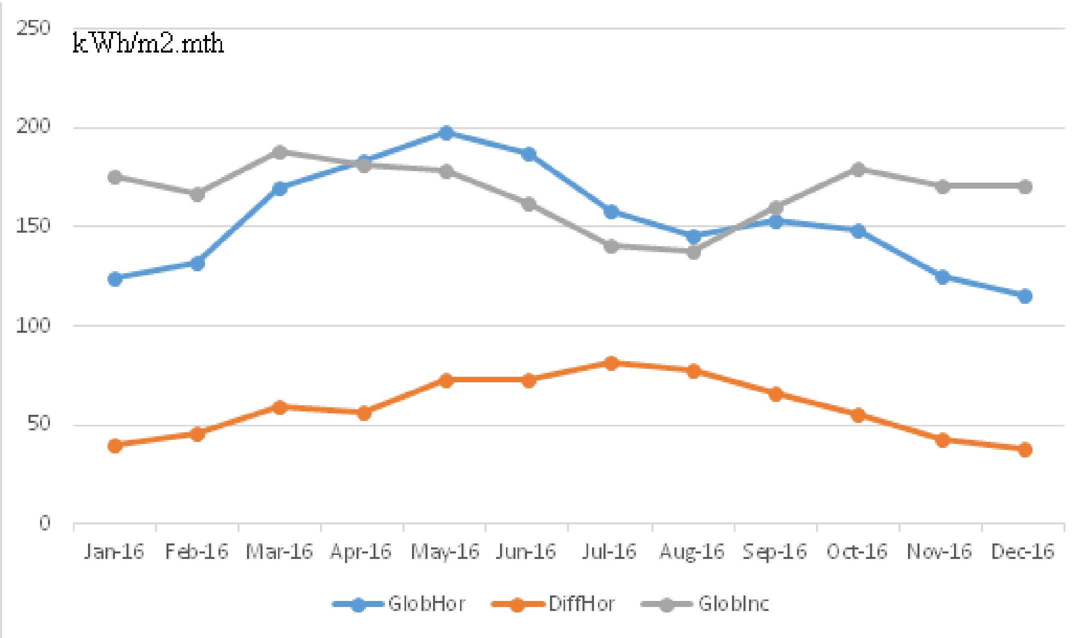

Figure 6.1. Synthetic generated meteo data for Jaipur

Design of a 1 MW Grid-Connected SPV System using PV-Syst: In our endeavor, we consider the climate data specific to Jaipur and create a virtual replica of a PV Syst power plant installation. This involves the numerical optimization of solar panels, inverters, and the trajectory. PV-Syst, a widely-used commercial tool for designing and installing solar PV systems, plays a pivotal role in recognizing the architectural aspects of the integrated power plant. Our process entails a step-by-step approach to numerically design and program our photovoltaic farm.

6.1.1 Synthesis of Irradiation Data: Weather data is sourced from NASA-SSE satellite data, providing us with crucial information on hourly temperature, diffused radiation, direct radiation, and global radiation. This data allows us to create estimates for the entire year for Jaipur, as depicted in Figure 6.1. Such detailed information is indispensable when configuring PV-Syst for new geographical locations 6 Utilizing Datasheets for System Design We harnessed the invaluable information found in the TATA-Power Manufacturer Datasheet to create a practical solar panel configuration within the PV-Syst-characterized consumer library. These meticulously crafted models were instrumental in the construction of a 1 MWp (Megawatt peak) solar photovoltaic power plant, as envisioned in our proposal.

In a parallel effort, we also developed a numerical inverter model, drawing upon the TATA Power 25000TL developer datasheet. These specific inverters played a crucial role in the establishment of our 1 MWp photovoltaic power plant. To gain a comprehensive understanding of this process, we recommend referring to the table presented in Section 6.1, which serves as the reference point for the collection of machine management devices within the PV Syst system.Top of Form

Table 6.1- System design overview in PV-Syst

S.No.	Manufacturing Technology	Model Name	Power Rating
1.	Poly Crystalline	Tata-BP 235	235 W
2.	Mono Crystalline	SPR 300N (Sun Power)	300 W
3.	Thin Film	BSM Si Plus	130 W

Optimal Orientation and Horizon Alignment Through meticulous analysis, we have determined that a fixed tilt of 30 degrees with a north-south orientation (zero azimuth) results in optimal electricity production within our integrated system. This precise configuration was meticulously adhered to in order to ensure that the new PV-Syst methodology generates a corresponding theoretical model and an equivalent simulation.

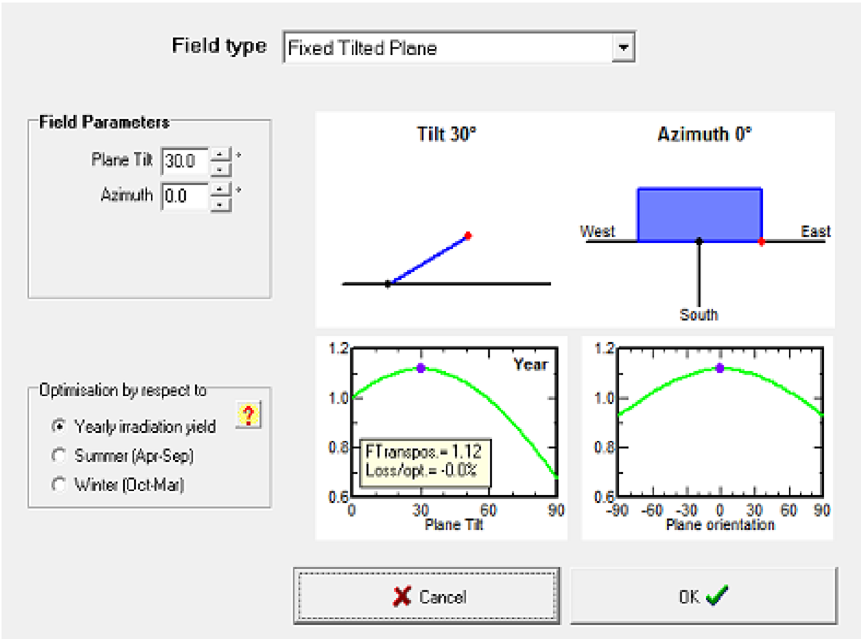

Figure 6.2. Orientation and tilt optimization for system

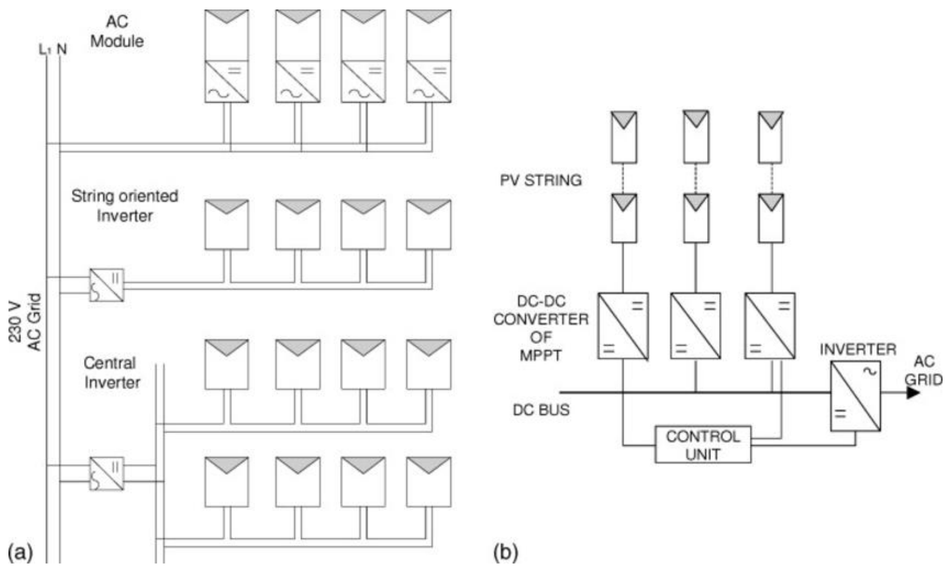

Figure 6.3. Different Topologies of Invereter and Panel Interconnection

For a visual representation of the tilt angle and the PV-Syst tilt optimization process for our proposed approach, please refer to Figure 6.2, which provides a clear illustration of these critical aspects. In our simulation, we adopted a string inverter topology similar to the one employed at the college campus. This configuration involved the utilization of two converters, each with a capacity of 500 kW, allowing us to accommodate the proportional mathematical model of the device under consideration. For a visual representation of how these inverters and solar panels are interconnected using various topologies, please consult Figure 6.3. This diagram elucidates the intricate network of connections, ultimately linked to the corresponding net metering system. Our simulation endeavors were conducted using PV-Syst version 5.74, with a focus on the proposed 1 MWp method. The simulation outcomes can be categorized into several distinct groups:

a) Yield Prediction and Simulation Results b) Losses Simulation c) Energy Injected to Grid Measurement d) Inverter Performance e) Techno-Economic Simulation Analysis

To ensure comprehensive analysis, the simulation process was executed on a month-by-month basis, allowing for a retrospective evaluation of the techno-economic aspects over the entire year. Additionally, a regular timeline simulation was carried out using a similar approach to measure estimated outcomes against real-world data.

The significance of yield and loss forecasting cannot be overstated when it comes to managing and operating solar photovoltaic systems. The performance of solar photovoltaic systems is intricately linked to factors such as location, system size, field of view, and the orientation of solar panels. Expertly designed modeling and simulation tools, tailored for independent solar photovoltaic systems, are indispensable for integrating technical planning and operational processes.

Yield Simulation Using PV systems programming, we were able to replicate the annual estimates and final production for the proposed system. The resulting output diagram depicted a uniform production pattern and the practical implications of our theoretical model. In Figure 6.4, "Yf" represents the final yield for a Mono-Si (Monocrystalline Silicon) based Solar PV System, while "Yf1" and "Yf2" correspond to the final yield for Poly-Si (Polycrystalline Silicon) and Thin-film based Solar PV systems, respectively.

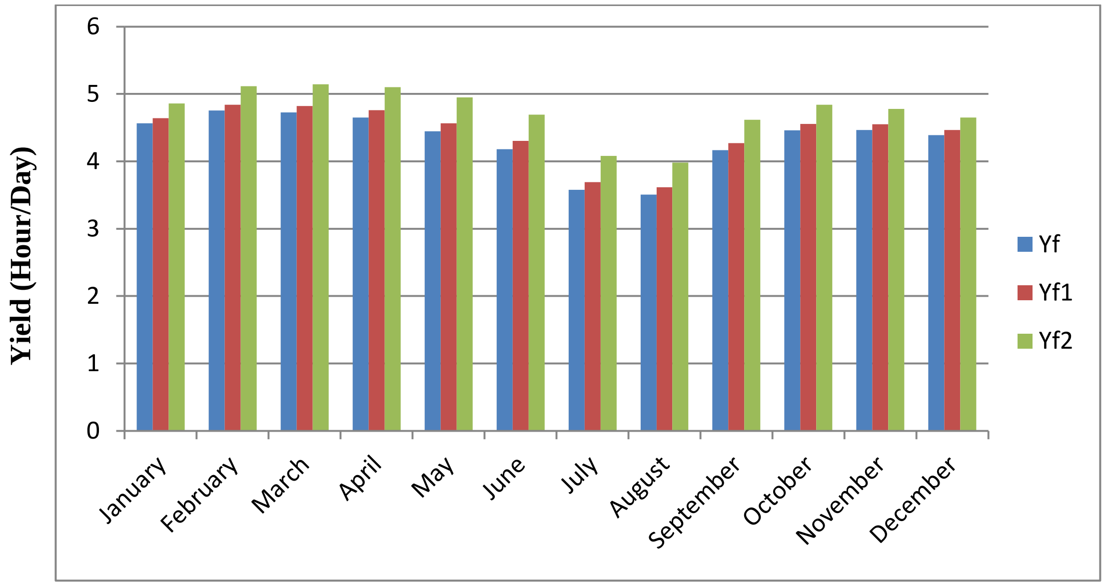

Figure 6.4. Monthly yield forecasting for a complete year (Yield in Hours/Day)

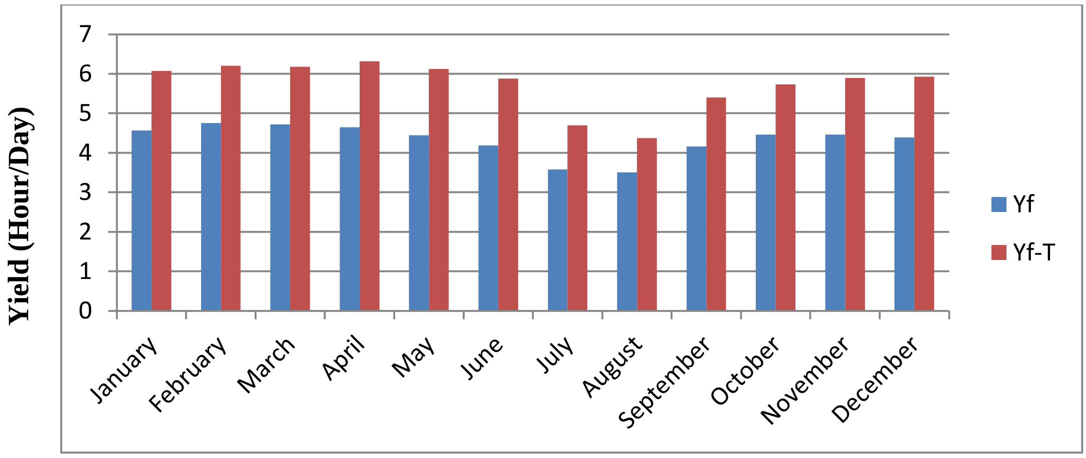

Figure 6.5. Monthly yield forecasting for a complete year with tracking (Yield in Hours/Day)

Figure 6.4 illustrates the variation in solar photovoltaic system yield based on different manufacturing technologies. Meanwhile, Figure 6.5 showcases the impact of incorporating a tracking system on the photovoltaic system's yield. In Figure 6.5, "Yf" represents the final yield for a Poly-Si (Polycrystalline Silicon) based Solar PV System, while "Yf-T" signifies the final yield for a Poly-Si system enhanced with a sun tracking system.

6.1.2 Losses Simulation: Over the course of an entire year, we employed the PV-SYST loss map to categorize and evaluate various types of losses, including those attributed to modules and inverters. This loss map proved invaluable in both organizing and quantifying losses, enabling a comprehensive analysis of how parametric variations and system components impact the overall system's losses.

In this context, "TempLss" denotes temperature-dependent losses for a mono-silicon-based solar PV system, while "TempLss1" and "TempLss2" pertain to thin-film and poly-silicon-based systems, respectively.

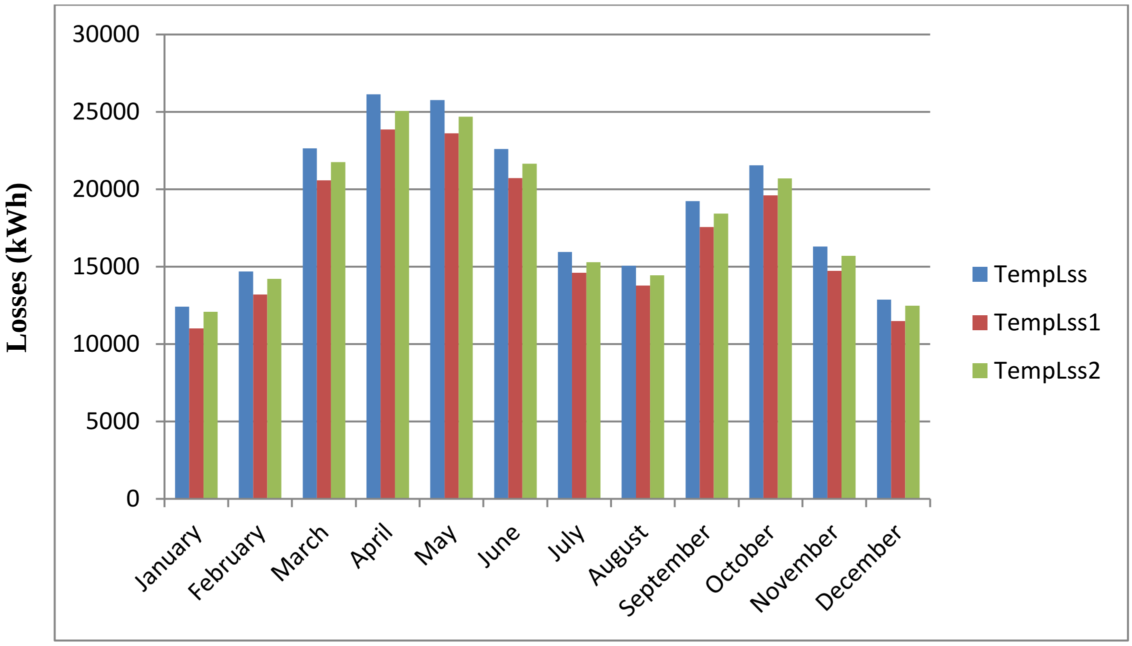

Figure 6.6 Monthly loss simulation for a complete year (Losses in Watt)

Figure 6.7 provides a comprehensive illustration of the solar photovoltaic system's overall performance losses. These losses encompass temperature-related losses, variations in irradiance levels, ohmic wiring losses, and module mismatch losses. They are expressed as a relative percentage of the total production capacity of the module under standard operating conditions.

For a more specific breakdown, Figures 6.8, 6.9, and 6.10 depict loss diagrams generated using the PV-Syst simulation tool for three different types of solar photovoltaic systems installed in Jaipur: poly-silicon, mono-silicon, and thin-film based systems. These loss diagrams offer a holistic view of all the losses encountered within the photovoltaic energy system. They are instrumental in estimating, evaluating, and categorizing the system's performance and behavior.

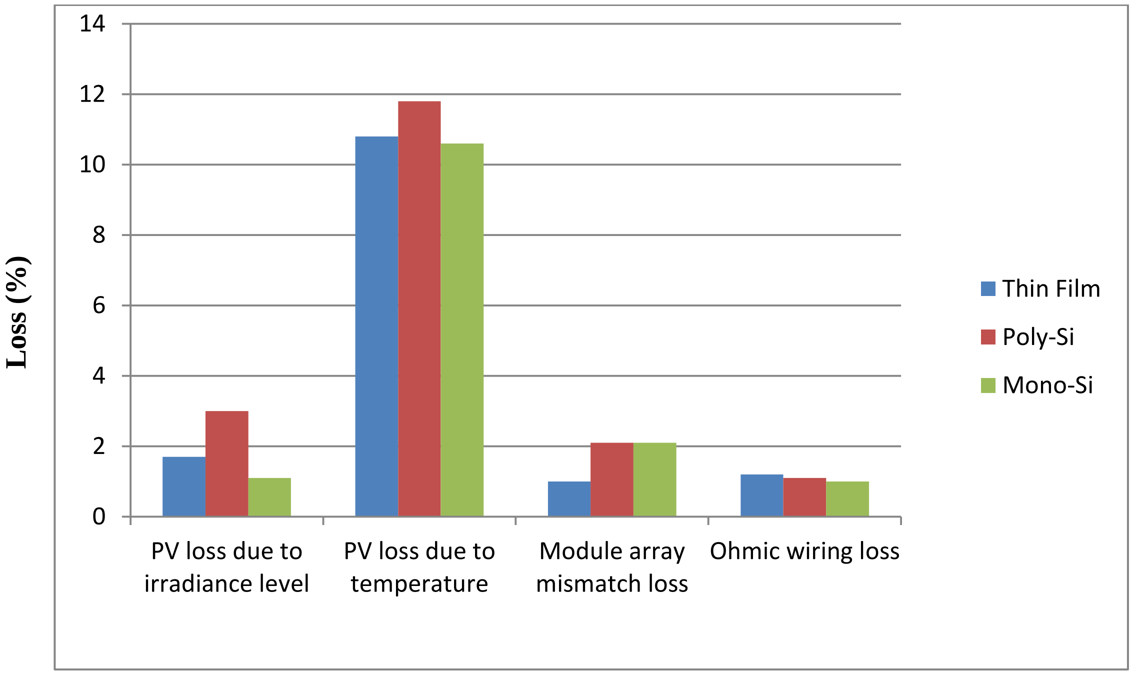

Figure 6.7. Comparative PV loss due to irradiance,temp.,mismatch,ohmic (Percent Loss)

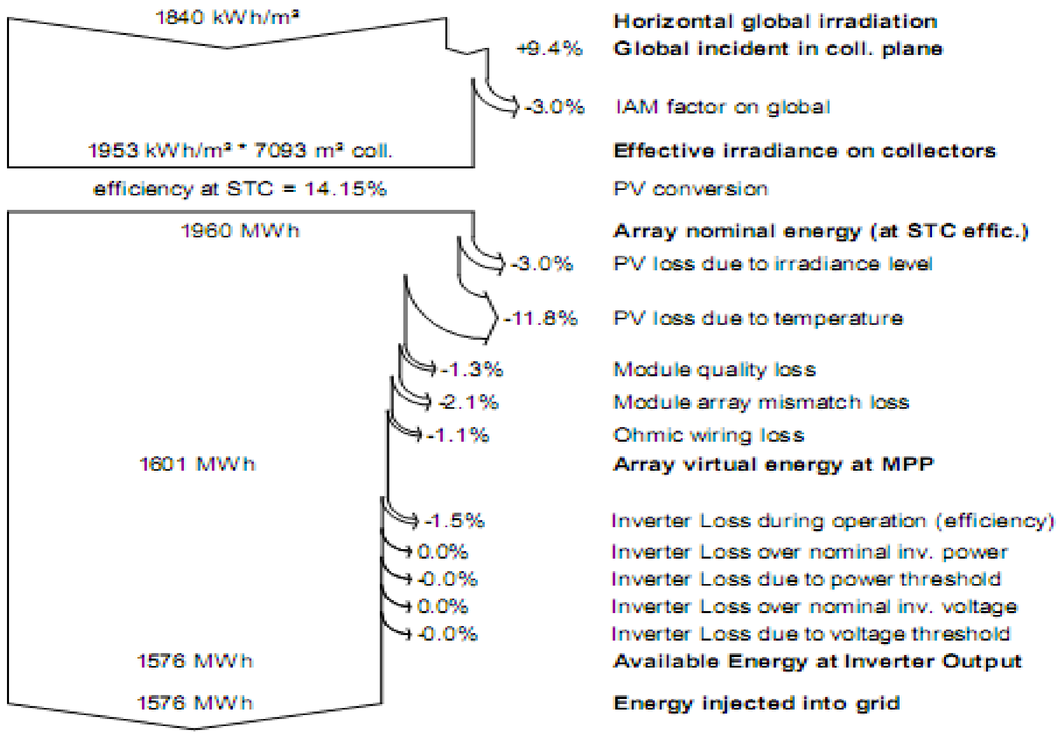

Figure 6.8. Loss diagram of Poly-SPV plant for one year

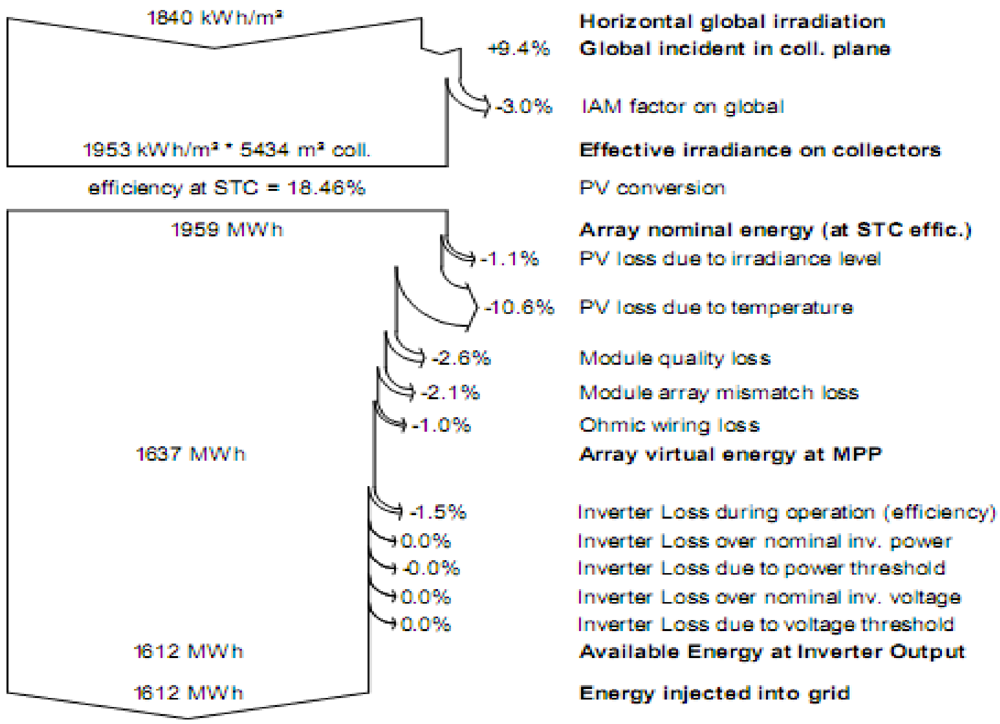

Figure 6.9. Loss diagram of Mono-SPV plant for one year

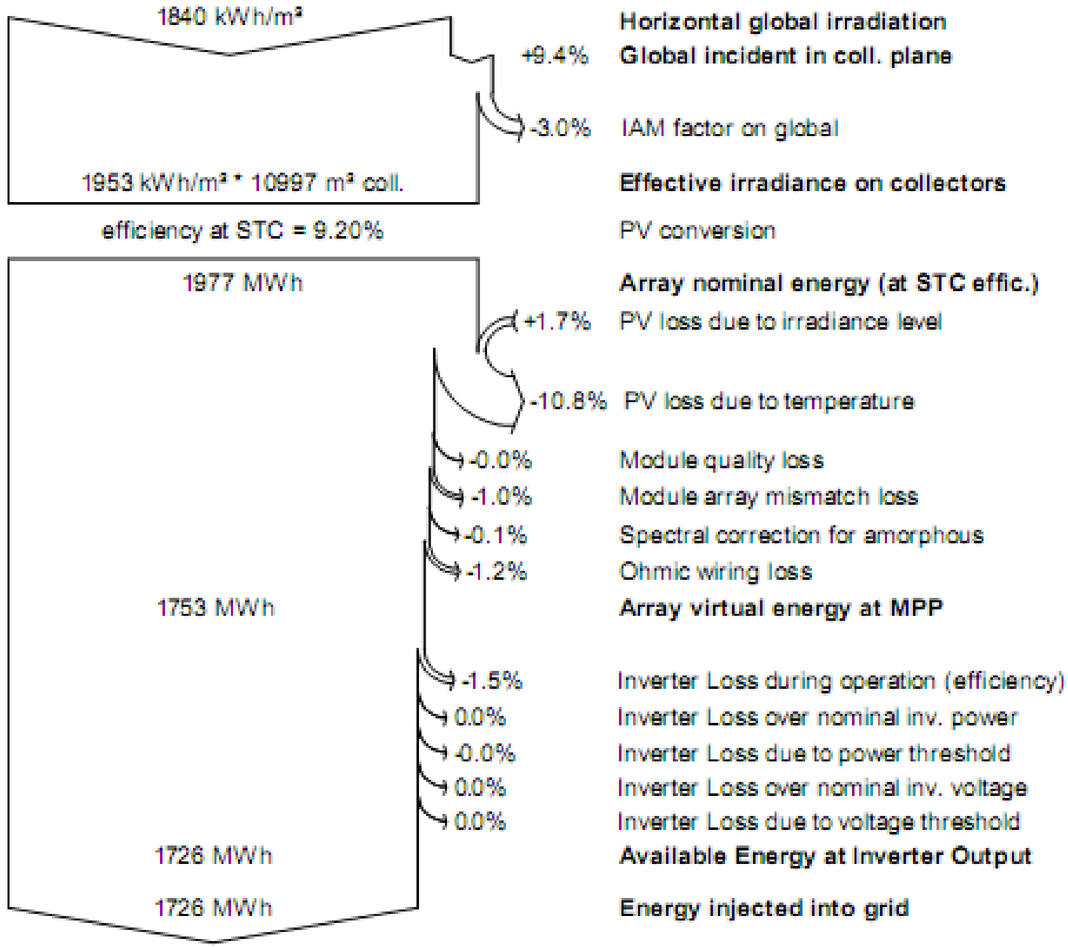

Figure 6.10. Loss diagram of Thin Film-SPV plant for one year

6.2. Performance Analysis

The performance ratio (PR) is a crucial metric defined as the ratio of the final yield to the reference yield, as illustrated in Figure 6.11 for an entire year. In the graph, the blue line represents the performance ratio (PR) for the poly-silicon module, the orange line (PR1) corresponds to the performance ratio for the mono-silicon module, and the grey line (PR2) represents the performance ratio for the thin-film module. This metric allows for a comparative assessment of how effectively each module type performs in generating energy over the course of the year.

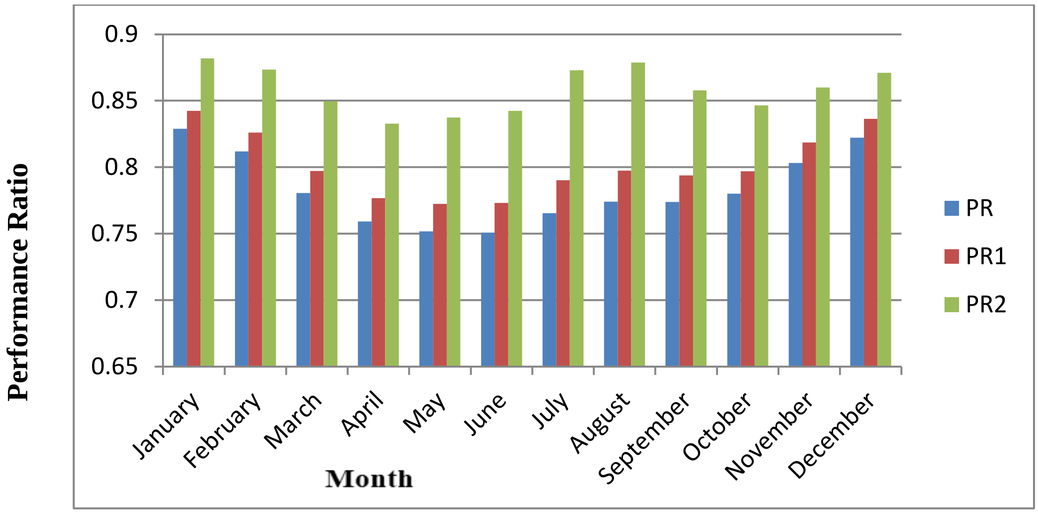

Figure 6.11. Forecasting of performance ratio (Performance Ratio on scale of Per Unit)

Forecasted annual generation values are computed using the PV system on a monthly basis in kWh..

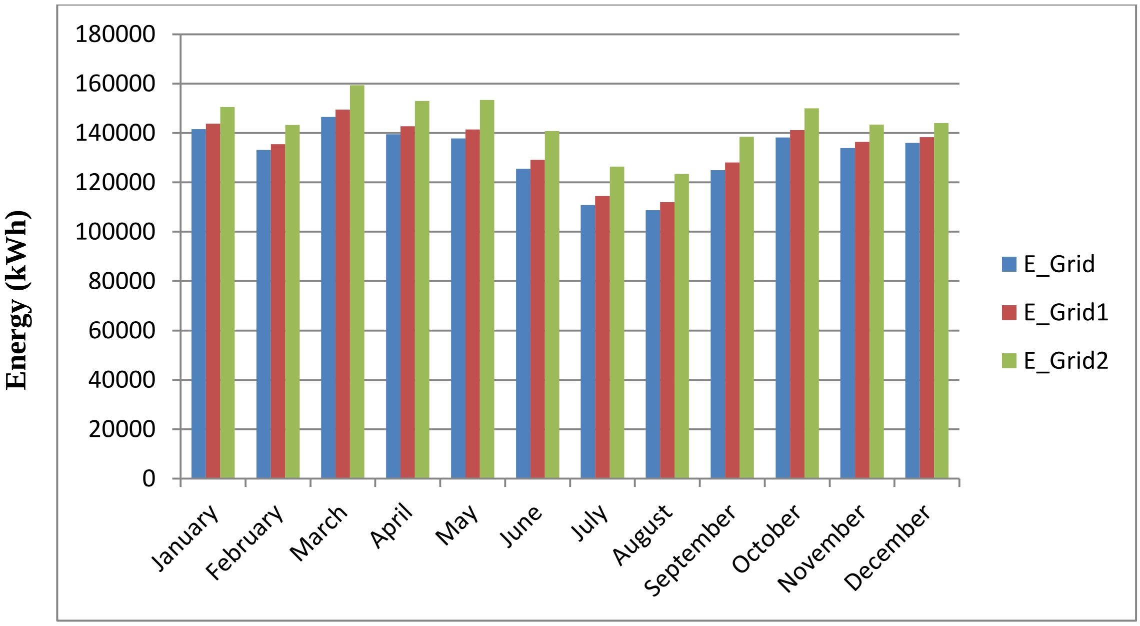

Figure 6.12. Generation forecasting for one year (kWh/Month)

Figure 6.12 presents a graphical representation of the year-long energy generation forecasts or predictions for Jaipur, allowing for a comparison of different PV module technologies. In this graph, "E_Grid" corresponds to the poly-silicon-based module, "E_Grid1" represents the mono-silicon module, and "E_Grid2" depicts the thin-film module-based system. It provides a visual insight into the expected energy generation performance of these different technologies over the course of a year in Jaipur.

Similarly, Figure 6.13 offers another graphical depiction of year-long generation forecasts for Jaipur, this time comparing different PV module technologies equipped with sun tracking systems. In this graph, "E_Grid-T" signifies the poly-silicon-based module with sun tracking, "E_Grid1-T" represents the mono-silicon module with sun tracking, and "E_Grid2-T" illustrates the thin-film module-based system with sun tracking. This comparison provides valuable insights into the expected energy generation when sun tracking technology is integrated into different module technologies in the Jaipur region.

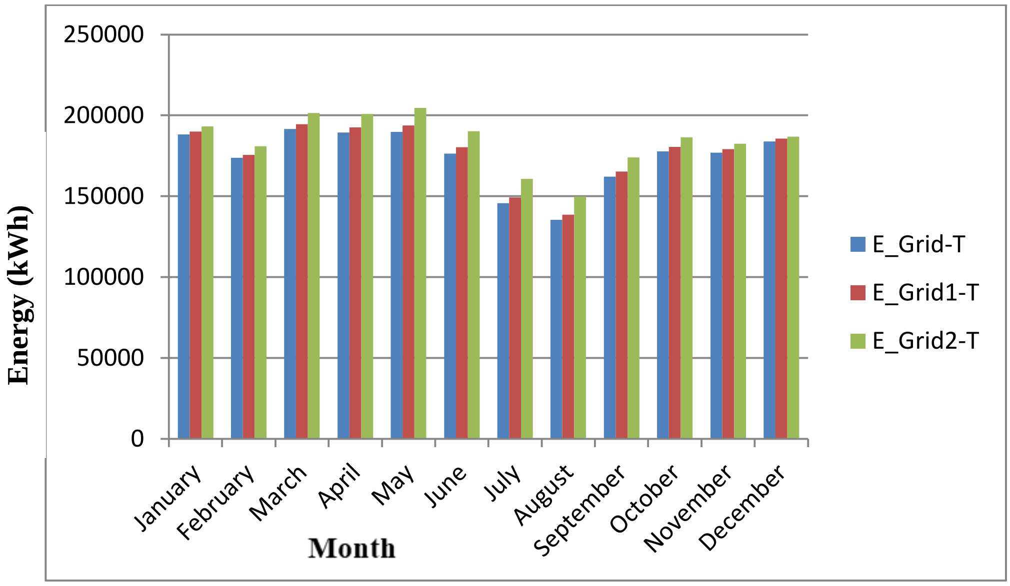

Figure 6.13. Generation forecasting for one year with tracking for three manufacturing technologies

The outcomes of our simulation endeavors have been succinctly summarized, following a structured approach that captures the exploratory insights gleaned from the executive analysis, yield assessment, and anticipated results.

Table 6.2 serves as a comprehensive representation of the comparative simulation analysis conducted for all three manufacturing technologies utilized in modeling and simulating solar photovoltaic systems within the Indian context. The primary objective of this simulation was to gain an in-depth understanding of how the behavior of solar photovoltaic systems is influenced by the choice of manufacturing technologies.

In Table 6.3, we delve into the techno-economic simulation analysis, which examines the performance of different manufacturing technologies within the Indian scenario. This holistic approach to simulation and analysis has provided a collaborative and comprehensive view of the climatic impact and the influence of temperature-dependent losses on various manufacturing technologies used in the design of solar photovoltaic systems.

Table 6.2 Summary of Simulation/Forecasting

Name of Parameters	**Average Yearly Forecasted Value**	**Average Yearly Forecasted Value**	**Average Yearly Forecasted Value**
	MONO-SI	**POLY-SI**	**THIN-FILM**
PR	0.782	0.793	0.83
Temperature Dependent Losses (kWh)	245956	225144	195225
Final Yield (Hours/Day)	4.371	4.325	4.579
Energy Output kWh (Inverter)	1598380	1577081	1670101

Table 6.3 Cost and area analysis of poly,mono & thin film

S. No	Manufacturing Technology	Price/Wp (INR)	Generation Cost	Area	Model Number	Panel Efficiency
1	Poly- Silicon	38	5.50/unit	7093 m^2	TATA-BP	16.15
2	Mono-Silicon	45	6.11/Unit	5435 m^2	Sun Power	20.46
3	Thin Film	30	4.38/unit	10997 m^2	Bosch	9.69

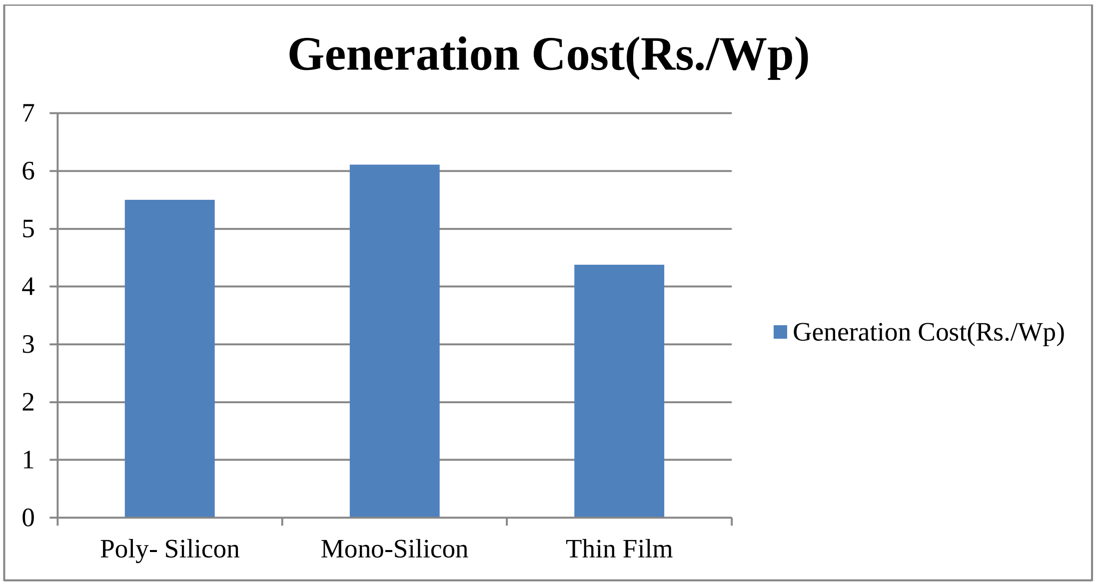

Figure 6.14. Generation cost by different manufacturing technologies

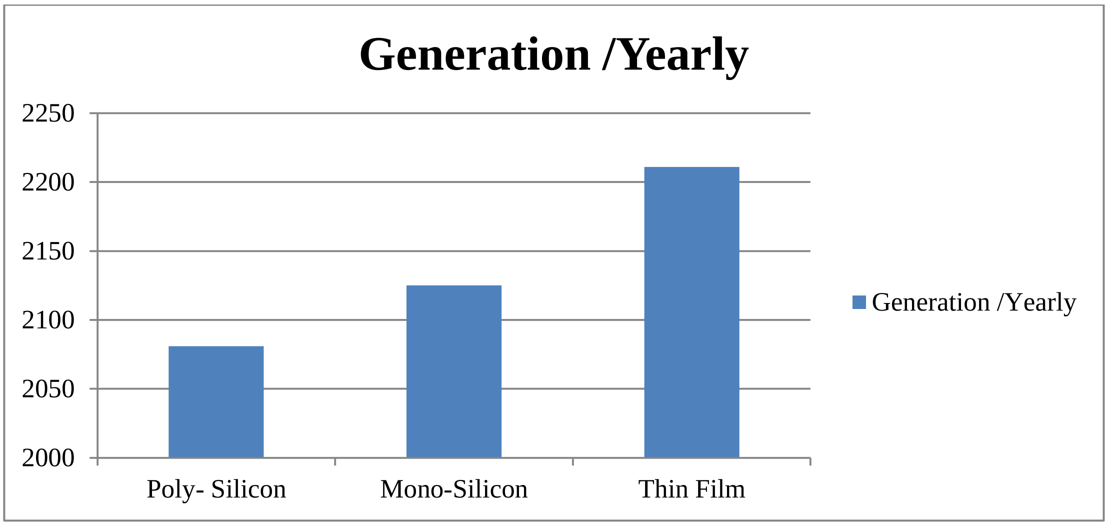

Figure 6.15. Generation by different manufacturing technologies

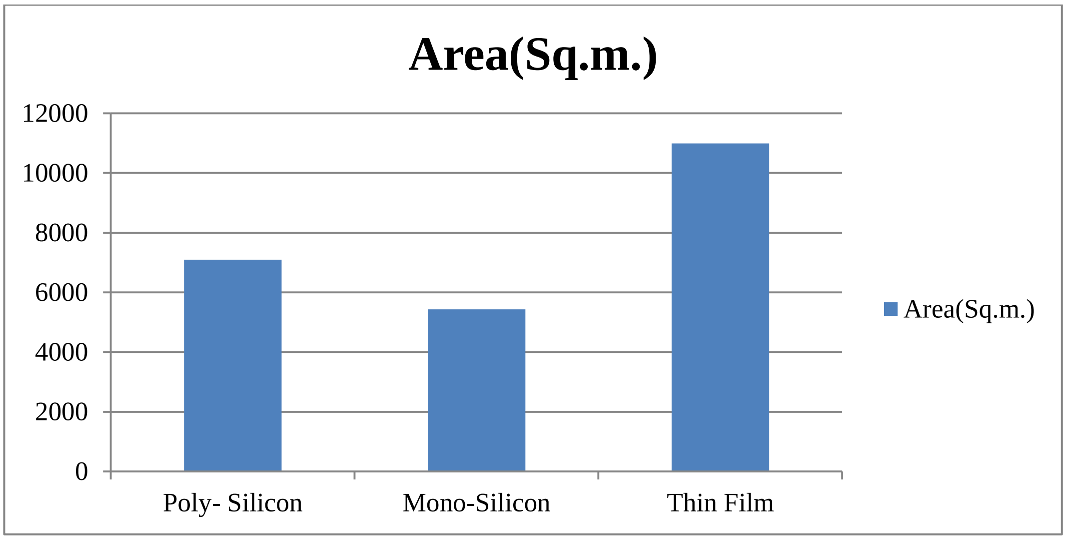

Figure 6.16. Area requird for different manufacturing technologies

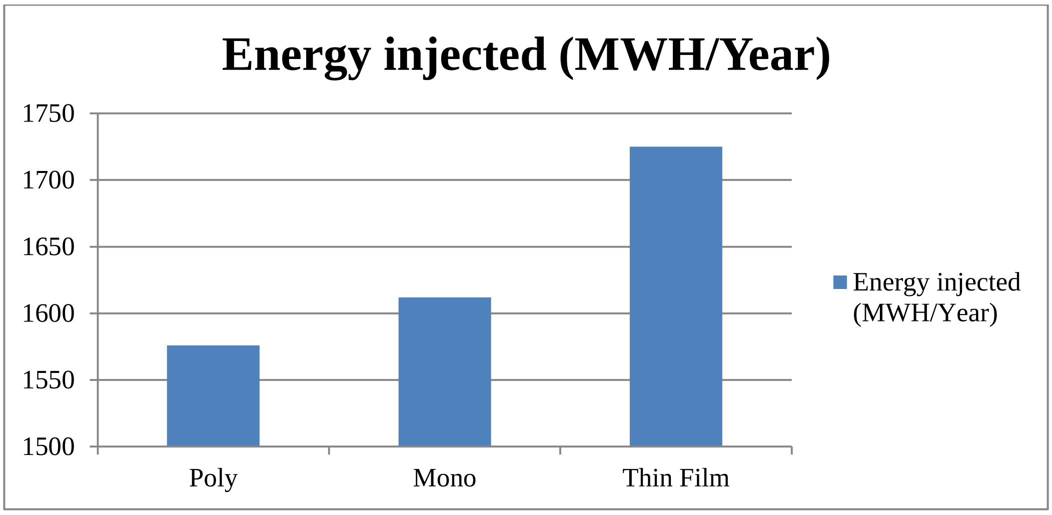

Figure 6.17. Energy injected by different manufacturing technologies

Table 6.4 Comparision of performance results of real data and proposed simulation PV-Syst

Parameters / Year	Year-1	Year-2	Year-3	Average	Proposed Forecasted (PV Syst)
-Einj_grid(MWh)	1551	1641	1541	1578	**1576**
-Maximum generation (MWh)	Mar-164	Mar-161	Apr-154	160	**146**
-Minimum generation (MWh)	Aug-88	Jan-109	Jan-116	104	**108**
-Performance ratio (%)	74.2	78.2	76.2	76.2	**78.34**
-Cumulative utilization factor	17.7	18.7	17.5	17.9	**4.38**
-Array yield (YA) kWh/kWp/day	4.2	4.4	4.2	4.3	**4.38**
-Reference yield (Yr) kWh/kWp/day	5.6	5.7	5.6	5.6	**5.51**
-Final yield (Yf) kWh/kWp/day	4.1	4.4	3.8	4.1	**4.32**
-Array losses (Lc) kWh/kWp/day	1.4	1.2	1.3	1.3	**1.1**
-System losses (Ls) kWh/kWp/day	0.05	0.03	0.45	0.17	**0.06**

6.3 Normalized Production and Loss Factor for Different Locations in India

In India, the variation in temperature across different locations necessitates the calculation of loss factors specific to each region. To shed light on this comparison, Table 6.3 provides insights into the normalized production and loss factors for solar photovoltaic plants in four distinct cities. For the purpose of this analysis, a system rating of 100 kWp has been considered as the basis of comparison.

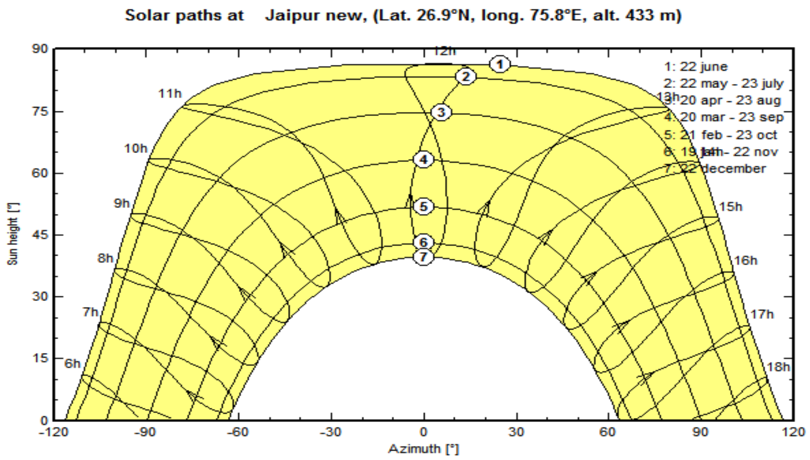

Figure 6.18 Sun Path and Meteo of Jaipur

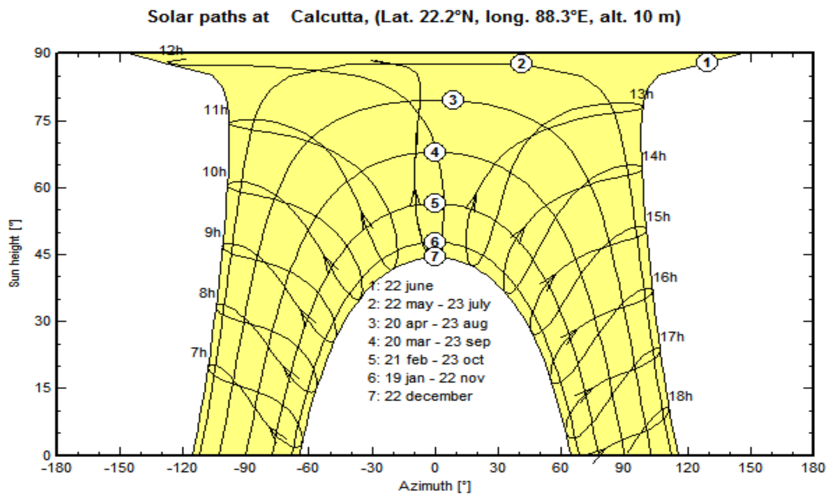

Figure 6.19 Sun Path and Meteo of Jaipur

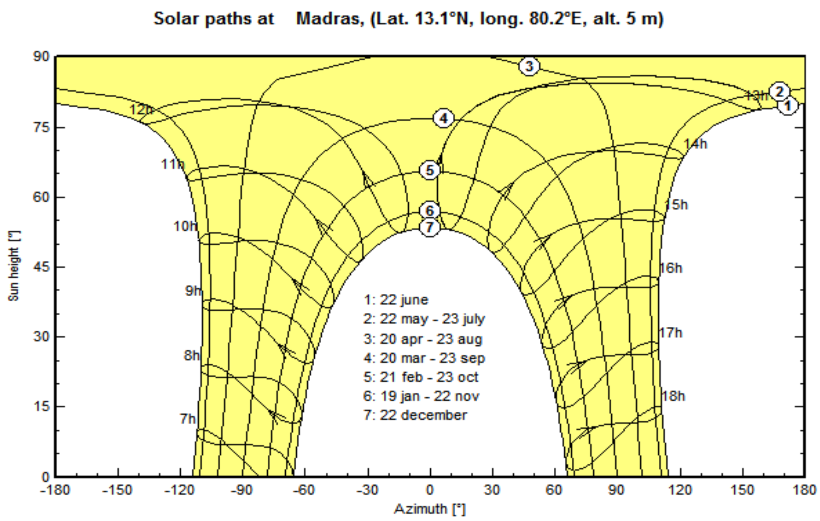

Figure 6.20 Sun Path and Meteo of Jaipur

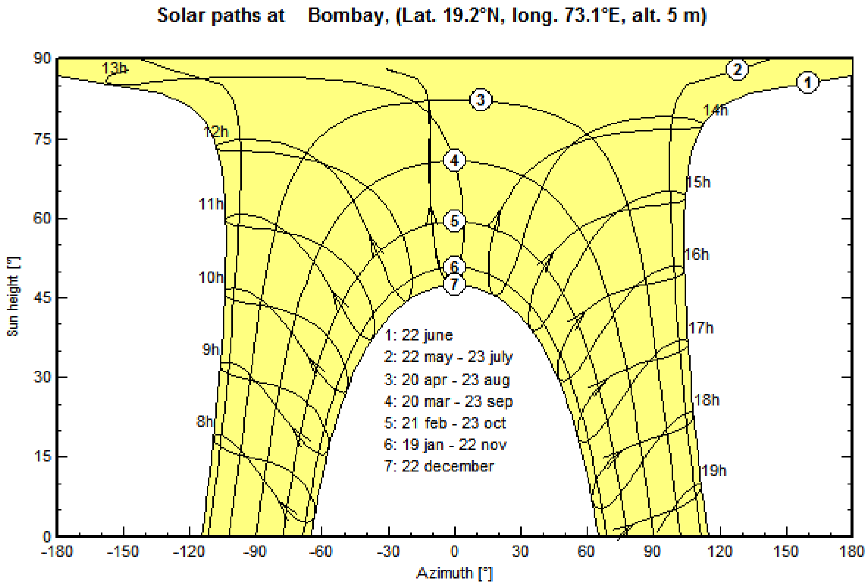

Figure 6.21 Sun Path and Meteo of Jaipur

Table 6.5 Normalized production and loss factors (nominal power 103kwp)

loss %	Jaipur	Chennai	Kolkata	Mumbai
Collection loss (lc)	21	21.9	21.9	20.8
System loss (ls)	1.6	1.7	1.7	1.7
Produced useful energy (y_f)	77.4	76.4	76.4	77.6

Table 6.6 Comparative Analysis of Performance Parameters for Four Locations

S. No.	**Parameters**	**Jaipur**	**Chennai**	**Kolkata**	**Mumbai**
1	**Energy Injected to Grid (kWh)**	159801	153378	146504	155771
2	**Energy Generated by Array(kWh)**	163127	156581	149504	158996
3	**System Efficiency (%)**	11.97	11.7	11.88	11.92
4	**Array Efficiency (%)**	12.22	11.94	12.12	12.16
5	**Global Incidence Energy kWh/m^2**	2012	1976.2	1859	1969.6

6	**Array Loss (kWh)**	1376.6	1325.5	1262.2	1340.8
7	**Mismatch Loss (kWh)**	3440.8	3505.6	3338.2	3546.1
8	**Inverter Loss (kWh)**	3996.5	3981.1	3506.7	3674.1
9	**Reference yield (kWh)**	5.51	5.41	5.07	5.4
10	**Final Yield (kWh)**	4.27	4.1	3.9	4.16
11	**Performance Ratio (%)**	0.774	0.756	0.769	0.771

Tables 6.5 and 6.6 present the simulated outcomes encompassing yield simulation, loss simulation, and performance analysis for a 100 kWp grid-connected PV system. These analyses also delve into system losses assessment. The performance parameters under scrutiny include Reference Yield, Final Yield, Energy Injected to the Grid, Performance Ratio, System Efficiency (%), Array Efficiency (%), and Global Incidence Energy kWh/m2, all calculated over the course of a full year. It's important to note that these parameters have been calculated with respect to a fixed tilt orientation, chosen based on the geographical characteristics of the respective sites. The performance parameter results for four different locations, each with its fixed tilt orientation, are compared in these tables.

The figure showcases the simulated results obtained from yield simulation, loss simulation, and performance analysis for a 100 kWp Grid-Connected Solar Photovoltaic System. These results offer several noteworthy insights:

1. The performance ratio in Jaipur is significantly higher compared to Chennai, Kolkata, and Mumbai locations.
2. The final yield (in kWh) in Jaipur exceeds that of Chennai, Kolkata, and Mumbai.

3. The reference yield (in kWh) for Jaipur is also higher than that of the other locations.
4. The Energy Generated by the Array (in kWh) in Jaipur outperforms the other locations.
5. The Array Efficiency (%) in Jaipur demonstrates improvement compared to the other cities.

Overall, it is evident that the performance of the solar PV system in Jaipur surpasses that of Chennai, Kolkata, and Mumbai. This performance analysis is conducted on a monthly basis for the Jaipur location, considering performance ratio, reference yield, final yield, and total grid power.

A comprehensive analysis reveals that, among the different modules, thin-film modules perform the best in Jaipur, showing resilience to high-temperature impacts and temperature-dependent losses. However, it's important to note that thin-film modules require more area compared to other module technologies. Mono-silicon modules require less space but do not yield substantially better results.

Furthermore, simulated values for performance assessment, yield forecasting, and loss forecasting have been obtained for a 1 MWp grid-connected solar photovoltaic system, considering three different manufacturing technologies.

Comparing the performance of the polysilicon-based grid-tied system with the fixed tilt variation, it was found that adding a tracking system led to a relative gain in performance metrics including ultimate yield and energy injected into the grid.

These simulations were particularly done for the 1 MWp grid-connected solar PV system in Jaipur in order to facilitate comparison and performance analysis. Accurate irradiation data and global temperature information are necessary in order to use PV-Syst and evaluate the performance potential of photovoltaic and solar photovoltaic systems. Wind speed and diffuse radiation are two optional parameters in PV-Syst. Using metadata from the import function, irradiance data is meticulously analyzed as it is imported into PV-Syst. For polysilicon-based modules, the simulated and real power plant data of the 1 MWp Phagi Solar PV power plant in Jaipur have been compared to guarantee the precision and correctness of the predicted outcomes.

6.4 Result obtained for Cooling Methodology

Water is used as a coolant for solar panels in front surface cooling systems. Using this technique, water is let to run down the panel's surface either naturally or using gravity. In order to do this, a 56-cm-long pipe with ten holes is placed at the top of the panel. After then, three distinct water flow rates are set for this pipe: one liter per minute, 1.5 liters per minute, and two liters per minute.

When the panel's performance is compared at these various water flow rates, it is found that the optimal flow rate for cooling and increasing the panel's efficiency is two liters per minute. This suggests that a greater water flow rate offers more effective cooling and can enhance the solar panel's overall efficiency.

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Figure 6.22 Front Surface Cooling by water

The following is a summary of the research work's findings:

1. Performance Analysis of Power at Various Temperatures: The goal of this part of the study was to determine how temperature affects power generation by examining how solar panels performed at various temperatures.

2. Analysis of Cooling System for Solar Panel Temperature Regulation: Another area of investigation in the study was the evaluation of a cooling system intended to control the temperature of solar panels. The purpose of this investigation was to ascertain how well cooling can reduce the impact of temperature on panel performance.

3. Analysis of Power Output of Cooling System linked with Solar PV System: The study was expanded to include an analysis of the power output of a cooling system linked to a solar photovoltaic system. This approach assisted in assessing how cooling and temperature interact to affect system performance.

The research approach included analyzing the impacts of radiation and temperature separately before looking at their combined effects. At first, the irradiation was changed while maintaining a constant temperature of 25°C, and vice versa. After that, the temperature and irradiance were let to fluctuate in order to examine the solar panel's IV (current-voltage) and PV (power-voltage) properties.

By keeping the PV simulation model's temperature at a steady 25°C, the study also examined the impact of radiation. The efficacy of the cooling system could be evaluated at three distinct periods of the day thanks to the simulation, which was run in the morning, noon, and nighttime.

The solar photovoltaic system's reduced model served as the basis for modeling the performance characteristics. The study was done using a Simulink model, as illustrated in Figure 6.23. The simulation was carried out under three separate conditions:

1. Panel without any inbuilt cooling facility.

2. A cooling panel that uses water.

3. A cooling panel that uses grass and water.

These parameters made it possible to conduct a thorough analysis of how cooling techniques affect solar panel performance in a range of temperature and light situations throughout the day.

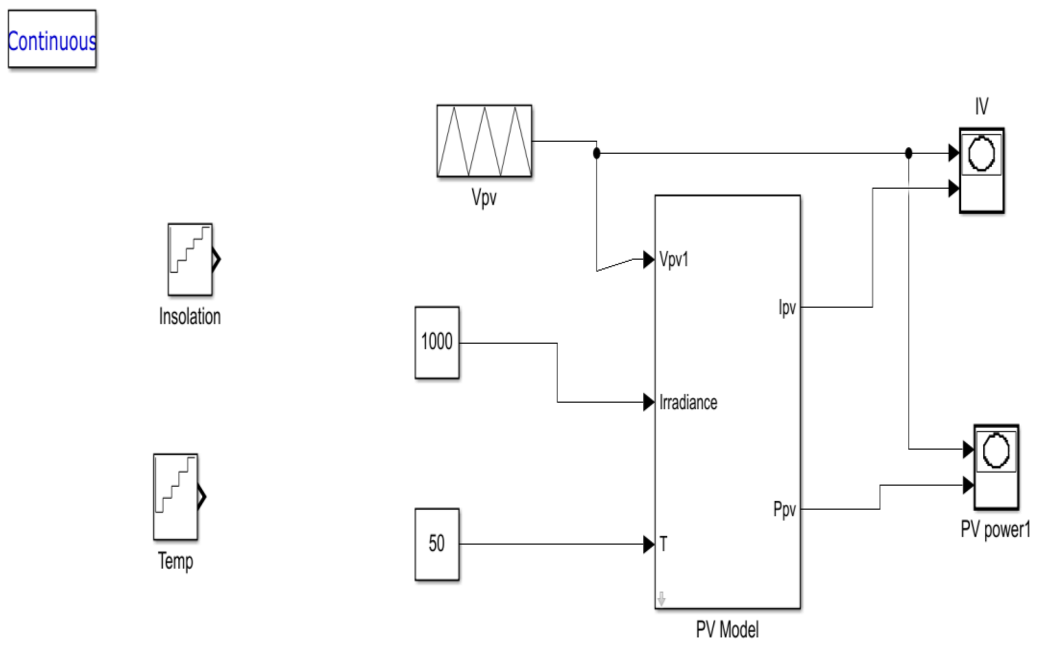

Fig. 6.23 Simulink Diagram of Proposed System with Parametric Variation

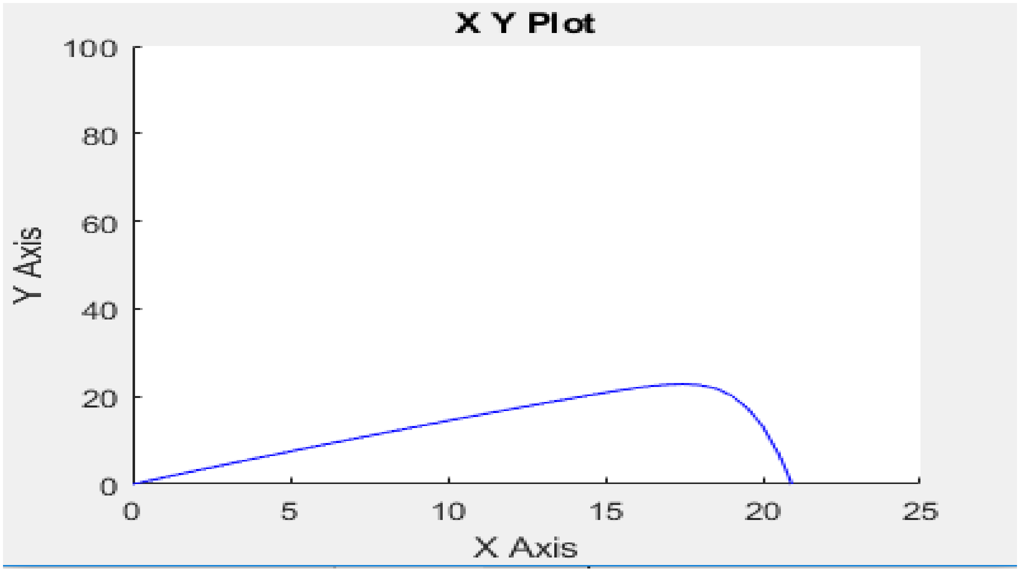

Fig.6.24 Power Voltage Waveform of Photovoltaic System without Cooling

The efficiency of a photovoltaic (PV) panel begins to decline when its temperature surpasses the maximum permissible level. This decline in production can significantly hinder the overall efficiency of a PV plant. Such temperature-induced reductions in efficiency pose a challenge to the widespread adoption of solar energy. It's crucial not to underestimate the importance of solar accessories like inverters, Maximum Power Point Trackers (MPPTs), and charge controllers within the PV plant. An incorrect or suboptimal layout of these accessories can lead to a decrease in the PV plant's performance.

All these factors combined contribute to the overall reduction in the PV plant's efficiency, resulting in an extended payback period for the initial investment. This, in turn, impacts the popularity and feasibility of solar energy adoption. The research conducted in this area plays a critical role in enhancing system performance, particularly under high-temperature conditions. By addressing these challenges and optimizing the system's components, we can make solar energy more efficient and attractive for broader adoption.

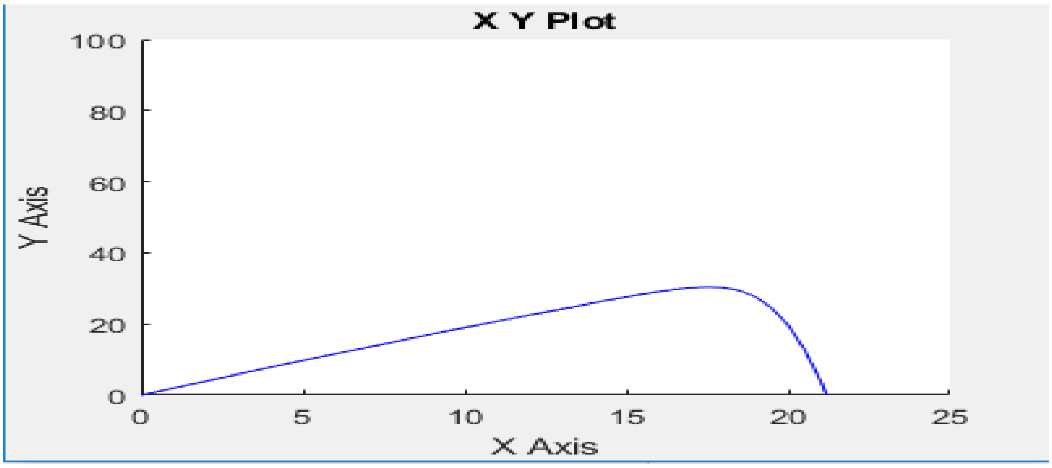

Fig.6.25 Power Voltage Waveform of Photovoltaic System with grass at back Surface

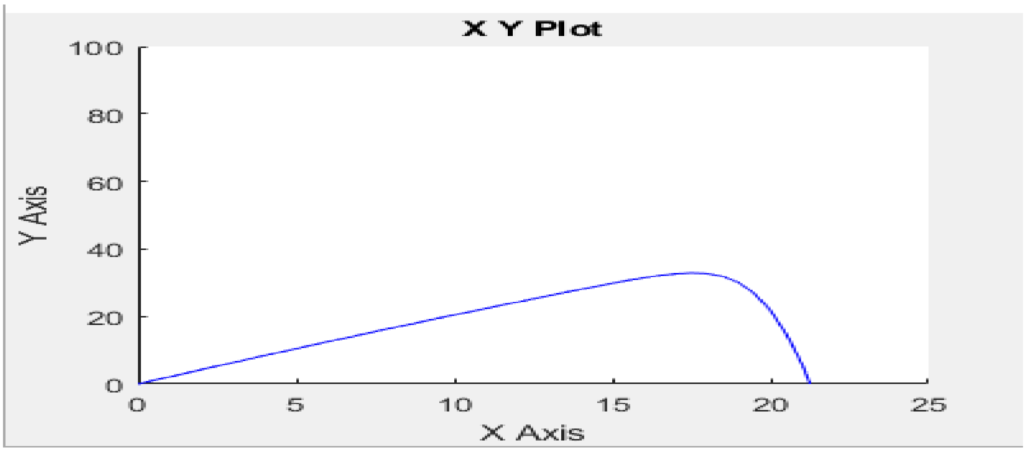

Fig.6.26 Power Voltage Curve of Photovoltaic System with Front Cooling System

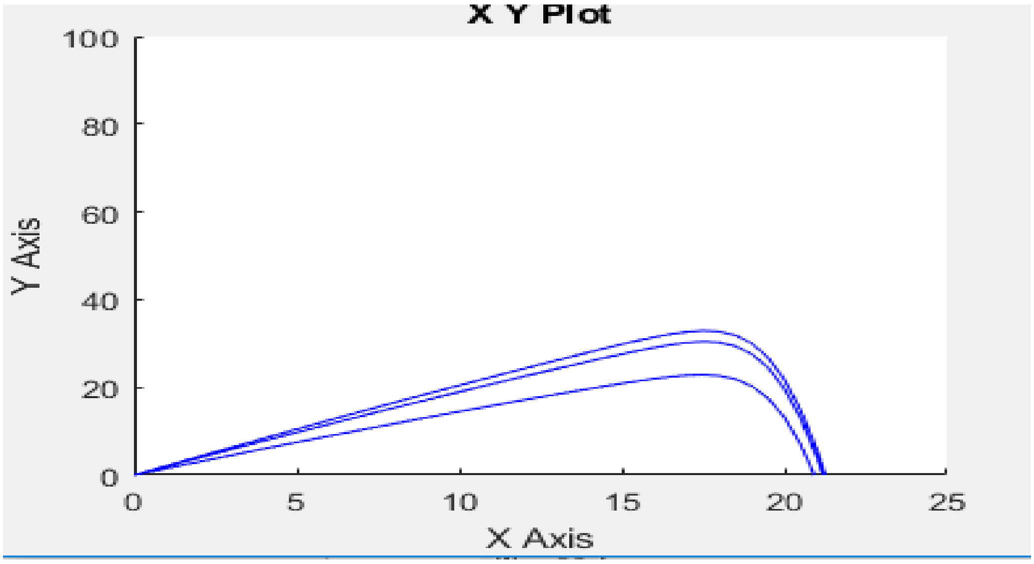

Fig.6.27 Comparative Analysis of Three Cases for Validation of Cooling System

Three distinct cooling system configurations, each with a different orientation, were used to conduct the suggested research: water cooling, grass cooling, and a mix of front and rear surface grass cooling. After the cooling system was installed, the performance of the solar system significantly improved, according to a modern review of these three situations. After a thorough investigation of the suggested system, the front-cooled system comes out as the most efficient of these options.

6.5 Electrical Efficiency Variance for Different Mass Flow Rates

In addition, the research also examined the electrical efficiency variance for different mass flow rates. It was observed that for every 1°C increase in temperature, the electrical efficiency of the solar module decreased by 0.5 percent. The optimal electrical conversion efficiency of approximately 25°C and 1000 W/m² irradiance was achieved.

Table 6.7- Electrical Efficiency Variance for Different PV/T Mass Flow Rates

Time	m = 0.002 kg/sec	m= 0.0025 kg/sec	m = 0.003 kg/sec	m = 0.004 kg/sec
10:00	8.21	7.35	7.38	6.32
11:00	8.10	7.11	7.12	5.65
12:00	7.85	6.95	6.35	5.40
13:00	7.62	6.72	6.01	5.47
14:00	7.83	6.68	6.10	5.27
15:00	8.24	6.85	5.50	5.94
16:00	7.42	5.10	4.96	5.29
17:00	4.75	2.91	2.23	2.35

The electrical efficiency in PV/T systems was found to range from 5 to 8% for various flow rates. Notably, with a flow rate of 0.002 kg/sec, the system's performance reached between 7 and 8 percent, showcasing its efficiency in converting solar energy into electricity

6.5.1 Thermal Efficiency Heterogeneity for Different Mass Flow Rates

Table 6.8 -Thermal Efficiency Variance for Different PV/T Mass Flow Rates

Time	m = 0.002 kg/sec	m= 0.0025 kg/sec	m = 0.003 kg/sec	m = 0.004 kg/sec
10:00	50.80	55.20	40.20	48.00
11:00	51.90	54.50	50.20	51.70
12:00	46.13	53.50	53.10	54.85
13:00	44.80	54.50	63.80	56.15
14:00	48.70	52.50	67.90	54.10
15:00	49.00	53.50	69.45	51.85
16:00	53.45	46.80	71.75	66.00
17:00	73.20	62.20	74.70	65.40

6.5.2 Overall Performance Improvements for Different Mass Flow Rates

The combined effect of thermal and electrical efficiency is the overall efficiency of a PV/T system. It is possible to assess the system's overall efficiency with accuracy by taking into account its total efficacy. The PV/T system's total production has improved, as seen in the figure. The PV/T system's total efficiency ranges from 51.00%

to 77.01% at different flow rates. More specifically, an average overall efficiency of over 67% was recorded with a mass flow rate of 0.003 kg/sec, while an average efficiency of 59.841% was observed for the lowest mass flow rate..

Table 6.9 Shift of Overall Efficiency for Different PV/T Mass Flow Rates

Time	m = 0.002 kg/sec	m= 0.0025 kg/sec	m = 0.003 kg/sec	m = 0.004 kg/sec
10:00	59.05	62.50	47.60	54.35
11:00	60.05	61.65	57.40	57.35
12:00	54.05	60.45	59.40	60.30
13:00	52.50	61.30	69.80	61.60
14:00	56.60	59.15	74.00	59.40
15:00	57.30	60.40	75.00	57.85
16:00	60.90	51.90	76.75	71.35
17:00	78.00	65.15	77.00	67.80

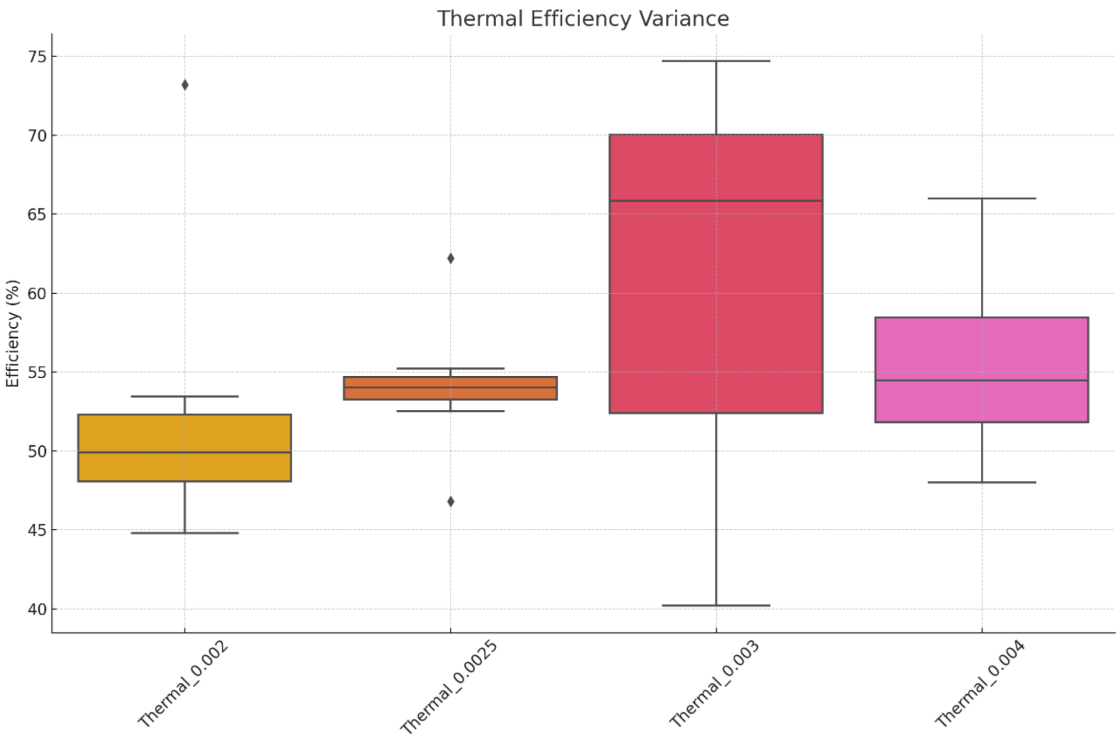

Fig.6.28 Comparative Analysis of Thermal Efficiency Variance

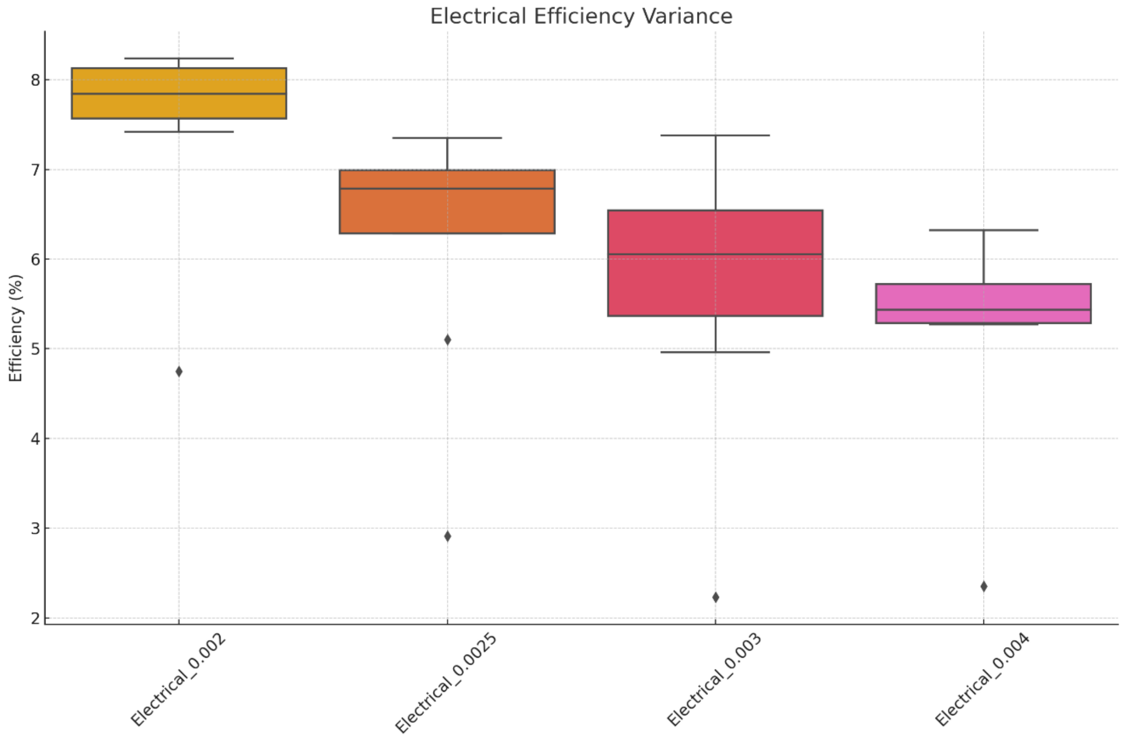

Fig.6.29 Comparative Analysis of Electrical Efficiency Variance

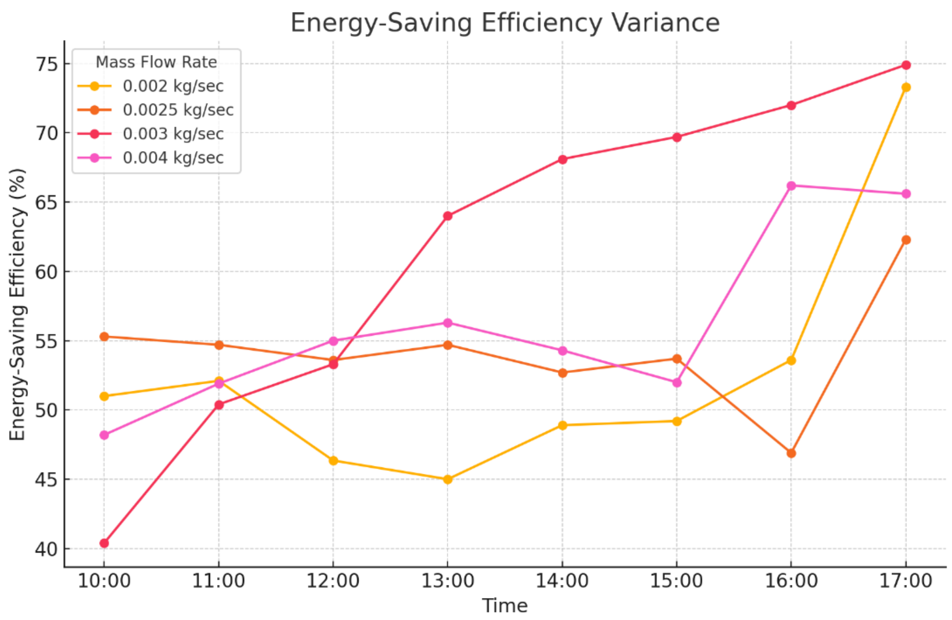

Fig.6.30 Comparative Analysis of Exergy Saving Variance

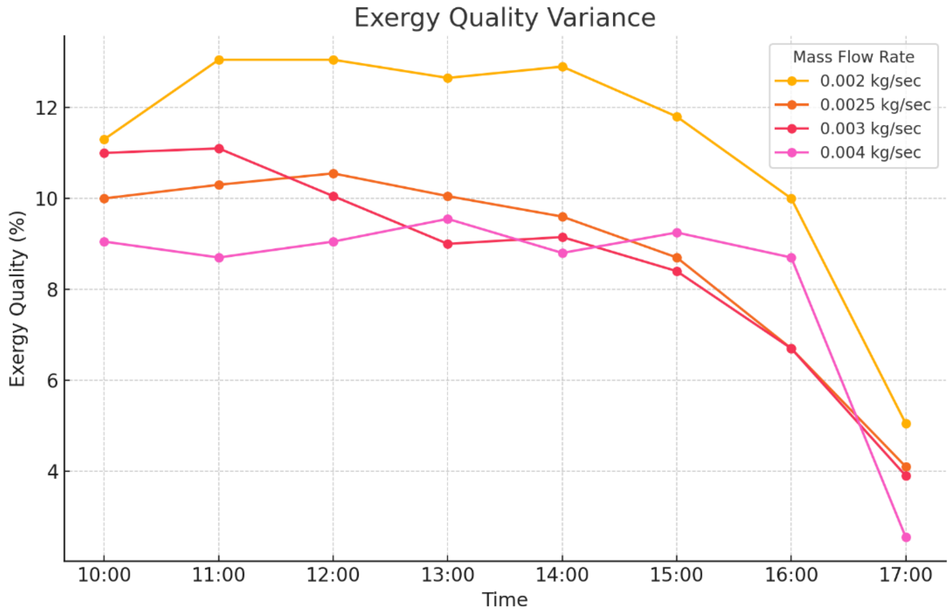

Fig.6.31 Comparative Analysis of Exergy Quality

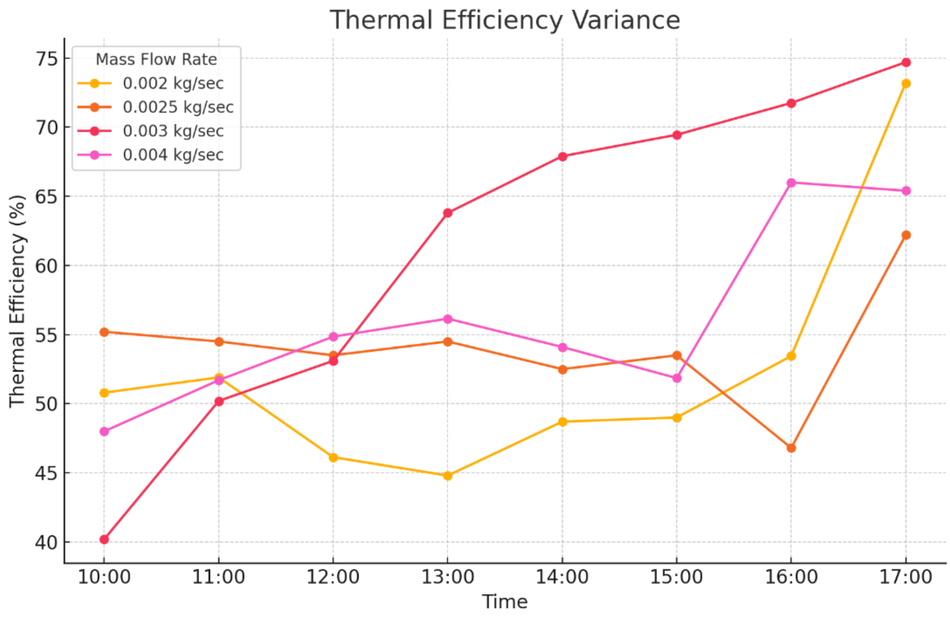

Fig.6.32 Comparative Analysis of Periodic Variation of Thermal Efficiency

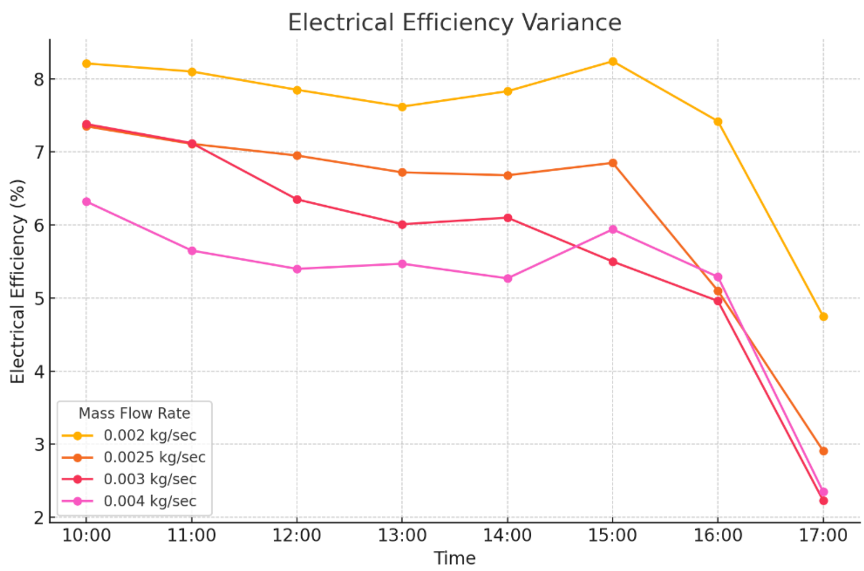

Fig.6.33 Comparative Analysis of Periodic Variation of Electrical Efficiency

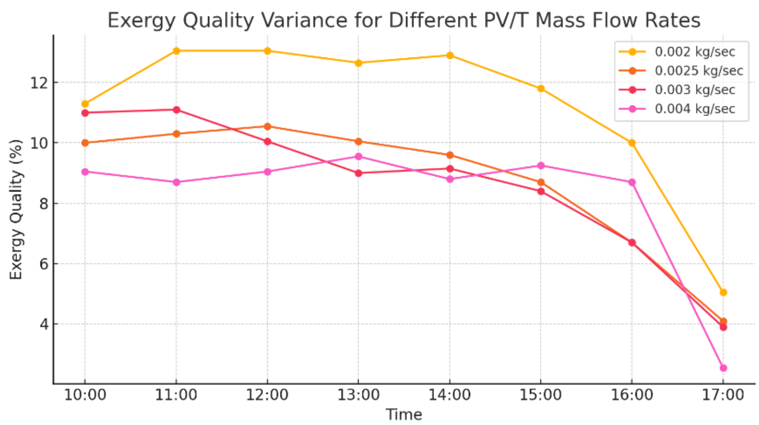

Fig.6.34 Comparative Analysis of Periodic Variation Exergy Quality

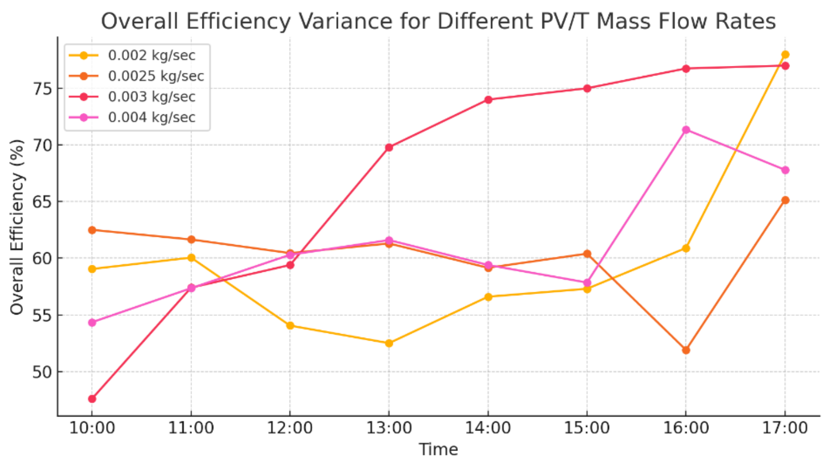

Fig.6.35 Comparative Analysis of Periodic Variation of Overall Efficiency

Electrical Efficiency Variance Plot

The electrical efficiency variance plot illustrates the fluctuations in electrical output efficiency of photovoltaic thermal (PV/T) systems across different mass flow rates over a day. This plot is key to understanding how the PV/T system performs electrically with varying cooling mass flow rates. The x-axis represents different times of the day from 10:00 AM to 5:00 PM, showing the efficiency at each hour. The y-axis displays the electrical efficiency in percentage. The plot features four lines, each representing a different mass flow rate (0.002 kg/sec, 0.0025 kg/sec, 0.003 kg/sec, and 0.004 kg/sec). It is observed that the electrical efficiency generally decreases as the day progresses, particularly noticeable in the later hours. The system with the lowest mass flow rate (0.002 kg/sec) consistently shows higher electrical efficiency compared to systems with higher flow rates. This could indicate that lower flow rates are less effective at cooling the PV panels, thereby maintaining a higher temperature which might be beneficial for electrical efficiency up to a certain point before thermal effects reduce efficiency.

Thermal Efficiency Variance Plot

Thermal efficiency variance focuses on how effectively the PV/T system converts solar energy into thermal energy. The plot structure is similar, with time on the x-axis and thermal efficiency percentage on the y-axis. Here, unlike the electrical efficiency, higher mass flow rates generally correlate with improved thermal efficiency, especially in the mid-afternoon hours. For example, the system with a mass flow rate of 0.003 kg/sec shows significantly higher thermal efficiencies towards the latter part of the day, reaching up to 74.70%. This indicates an effective transfer of heat away from the PV cells, which can help in reducing the cell temperature and potentially increasing the lifespan of the PV cells while generating useful thermal energy.

Overall Efficiency Variance Plot

This plot combines the insights of both electrical and thermal efficiencies to give a comprehensive view of the total system efficiency. The overall efficiency plot again uses time on the x-axis and percentage efficiency on the y-axis. Notably, the system with a mass flow rate of 0.003 kg/sec frequently achieves the highest overall efficiencies, particularly in the late afternoon, suggesting a balanced trade-off between cooling and heating that optimizes both electrical output and thermal capture. The peak efficiencies observed around 5 PM could be due to lower ambient temperatures combined with sustained solar irradiance, which optimizes the system's performance.

Exergy Quality Variance Plot

Exergy efficiency gives an idea about the quality of energy produced and how much of the input energy is being converted into useful work. The exergy plot shows slightly different behavior where the highest and lowest flow rates do not necessarily translate to the best or worst exergy efficiencies. Interestingly, mid-range flow rates often perform better, possibly indicating that these rates optimize the thermodynamic processes within the system, enhancing the conversion of available energy into useful work. This plot is crucial for understanding the effectiveness of energy use within the system and can help in fine-tuning operational parameters for better performance.

Energy-Saving Efficiency Variance Plot

Lastly, the energy-saving efficiency plot focuses on the system's ability to save energy compared to traditional systems without thermal elements. This plot highlights how different configurations save energy across various times of the day. Higher mass flow rates generally demonstrate better energy-saving capabilities, which might be due to the increased thermal utilization. As with other plots, the time of day significantly influences efficiency, with late afternoon typically showing the highest values. This plot is particularly useful for quantifying the benefits of PV/T systems in terms of energy conservation and can be a vital factor in economic analyses and environmental impact assessments of such systems.

6.5.3 Exergy Quality Heterogeneity for Different Mass Flow Rates

The study also looked at the variance in exergy efficiency for various water mass flow rates in the PV/T system, as shown in the Figure. The amount of low-quality energy that can be transformed into high-quality energy is called energy. By comparing the energy generated by the solar PV (exergy output) to the solar exergy input, one may calculate the energy efficiency of solar PV. From 2% to 13.01% is the range of PV/T exergy efficiency across different mass flow rates. Notably, a mass flow rate of 0.0021 kg/sec was required to obtain the maximum exergy efficiency of 13.101%. This shows how well the system can transform low-quality energy into high-quality energy that is useful.

Table 6.10 Exergy Quality Variance for Different PV/T Mass Flow Rate

Time	m = 0.002 kg/sec	m= 0.0025 kg/sec	m = 0.003 kg/sec	m = 0.004 kg/sec
10:00	11.30	10.00	11.00	9.05
11:00	13.05	10.30	11.10	8.70
12:00	13.05	10.55	10.05	9.05
13:00	12.65	10.05	9.00	9.55
14:00	12.90	9.60	9.15	8.80
15:00	11.80	8.70	8.40	9.25
16:00	10.00	6.70	6.70	8.70
17:00	5.05	4.10	3.90	2.55

6.5.4 Energy Saving Efficiency Variance at Different Mass Flow Speeds

Table 6.11-Energy-Saving Efficiency Variance for Different PV/T Mass Flow Rates

Time	m = 0.002 kg/sec	m= 0.0025 kg/sec	m = 0.003 kg/sec	m = 0.004 kg/sec
10:00	51.00	55.30	40.40	48.20
11:00	52.10	54.70	50.40	51.90
12:00	46.35	53.60	53.30	55.00
13:00	45.00	54.70	64.00	56.30
14:00	48.90	52.70	68.10	54.30
15:00	49.20	53.70	69.70	52.00
16:00	53.60	46.90	72.00	66.20
17:00	73.30	62.30	74.90	65.60

It shows how the solar PV/T system's energy conservation varies at various mass flow rates. There was a noticeable variation in the energy saving efficiency, ranging from 40% to 73%. In particular, the lowest energy efficiency measured was 52.49%, while the best energy saving efficiency reached an astounding 61.58% at an average mass flow rate of 0.003 kg/sec. This significant variation demonstrates the system's ability to effectively conserve energy at different flow rates, with higher flow rates often resulting in bigger energy savings.

6.5.6 Performance Evaluation of PV/T with Mass Flow Rate of 0.002kg/sec

Table 6.12 - Test Result of PV/T and PV

Time	Global Radiation (W/m^2)	Ambient Temp (°C)	Wind Velocity (m/s)	Mass Flow Rate	Water Temp IN (°C)	Water Temp OUT (°C)	PV/T Efficiency (%)	PV Efficiency (%)	% Change
10:00	880	33.5	0.14	0.002	22	41	19.28	1.71	11.3
11:00	910	34	0.74	0.002	24.5	43	19.05	1.81	8.8
12:00	1015	36	0.59	0.002	25	44	18.90	2.00	6.5
13:00	1045	37.5	0.45	0.002	26.5	46	18.81	2.05	10.5
14:00	960	35	0.34	0.002	29.5	45.5	18.75	1.94	8.5
15:00	805	36.8	0.84	0.002	30.5	47	19.40	1.55	13.2
16:00	690	38	0.14	0.002	29	45	19.05	1.18	15.1
17:00	255	34	0.12	0.002	28.5	35.5	18.71	0.27	16.5

The fluctuation in ambient temperatures and global radiation over time is shown. It's crucial to remember that high sun irradiation can improve solar cell conversion efficiency. On the other hand, greater radiation levels can result in hotter solar panels. In this case, the worldwide maximum temperature is 38.4°C, and the global maximum radiation is up to 1050 W/m². The dynamic link between sun irradiation and panel temperature is highlighted by this data.

The variations in front and rear panel temperatures between PV (Photovoltaic) and PV/T (Photovoltaic/Thermal) systems are shown in Figure 6.33. Lower temperatures are achieved with PV/T when compared to PV alone because of the heat transfer mechanism from the panel to the flowing water. In particular, the PV panel's rear side temperature can reach up to 72°C, but the PV/T's rear side temperature can only get as high as 49.8°C. This demonstrates how the PV/T system's cooling system successfully reduces the increase in panel temperature, improving system performance.

The temperature of the water rises as a result of heat transfer that takes place between the PV/T panel and the flowing water within the system. The temperature differential between the water at the inlet and the water at the outlet is shown in Figure 6.35. Relatively lower inlet water temperature is necessary to maximize heat transfer rates and improve overall efficiency. Here, effective heat exchange within the PV/T system is indicated by the water's entry temperature of 29°C and its exit temperature of 47°C. The PV/T system's overall, thermal, and electrical efficiency improvements over time are shown in Figure 6.36. While the thermal efficiency and total efficiency both reach an astounding 70%, the electrical efficiency is only about 7-8%. These numbers highlight the improved effectiveness and efficiency that come from combining a PV/T system with efficient heat transfer mechanisms. Figure 6.37 demonstrates the variances in electrical efficiency for both PV/T and PV systems. Throughout the day, the electricity efficiency is rather stable for both systems. On the other hand, PV/T performs somewhat better because of the cooling effect sometimes. The electrical performance of PV/T swings between 7% and 8% throughout the day and drops throughout the night owing to lower solar radiation. The ratio of exergy to exergy in terms of exergy quality, demonstrating the disparities in exergy efficacy. Notably, with a mass flow rate of 0.002 kg/sec, the exergy efficiency reaches 13%. This shows the system's capacity to efficiently transform low-quality energy into high-quality exergy, displaying its efficacy and performance in gathering and utilizing energy resources effectively

6.6 Output Evaluation at 0.0025 Kg/Sec and Glass Cover Mass Flow Rate

Table 6.13 Test Results PV & PV/T Glass Cover

Time	Global Radiation (PV/T)	Global Radiation (PV)	Ambient Temp (°C)	Wind Velocity (m/s)	Mass Flow Rate	Water Temp IN (°C)	Water Temp OUT (°C)	PV/T Efficiency (%)	PV Efficiency (%)	% Change
10:00	645	775	41	0.46	0.0025	30	39	18.80	1.50	13.5
11:00	695	895	43.5	0.62	0.0025	33.5	44.5	18.60	1.40	12.6
12:00	712	925	43	0.55	0.0025	34.5	46	18.45	1.46	10.0
13:00	855	995	43.2	0.45	0.0025	35	47.3	18.30	1.43	8.1
14:00	765	825	44.5	0.74	0.0025	34.5	46.2	17.55	1.21	13.0
15:00	535	660	43.8	0.84	0.0025	35.5	41.5	18.35	0.85	16.8
16:00	245	370	41.5	0.46	0.0025	34	38.5	16.90	0.26	18.4
17:00	145	215	39.5	0.22	0.0025	32.5	36	16.85	0.09	22.2

Analysis illustrates the variations in global radiation and atmospheric temperature for a PV/T system with a glass cover, using a specific time and a mass flow rate of 0.0025 kg/sec. The highest recorded air temperature in this scenario is 44.7°C, and the maximum limit of global radiation is 850 W/m². This data sheds light on how the dynamic variations in temperature and radiation affect the PV/T system's performance in these circumstances.

. The worldwide maximum radiation in this scenario exceeds 990 W/m². These graphs demonstrate the significance of radiation and temperature fluctuations in system performance and aid in understanding how they impact the operation of the PV/T system.

The PV/T system has lower temperatures than PV alone because of the heat transfer from the panel to the flowing water. To be more precise, the PV panel's back side can achieve a maximum temperature of 73°C, whereas the PV/T panel's rear side can only reach a maximum temperature of 65°C. This demonstrates how well the PV/T system dissipates heat and keeps panel temperatures lower. The temperature of the inflow water is maintained somewhat below room temperature in order to maximize heat transfer rates and improve overall efficiency. The entrance water temperature never goes below 35°C, however the exit water temperature might reach over 47.5°C. The PV/T system performs better because of these temperature changes since they optimize the heat exchange mechanism inside the system.

The greatest thermal efficiency is around 9.7%, while the power efficiency is roughly 6-7%. With an astounding total efficiency of over 69%, the system's overall efficiency surpasses 67%. These numbers highlight how well the system converts thermal and electrical energy, resulting in a high overall efficiency. On average, the power production efficiency for PV/T throughout the day is 6.39%, whereas for PV alone, it is somewhat higher at 7.50%. This indicates that the PV/T system, with its combined electrical and thermal capabilities, achieves slightly lower power output efficiency compared to a standalone PV system, but it gains the advantage of producing both electricity and thermal energy simultaneously, contributing to its overall efficiency.

The quality of energy conversion is reflected in energy efficiency, which is defined as the ratio of energy input to energy output. The Exergy efficiency surpasses

13% at a mass flow rate of 0.0025 kg/sec with a glass cover, demonstrating the system's ability to convert energy effectively and produce high-quality Exergy output.The variations in electrical, thermal, and PV-T (photovoltaic/thermal) energy throughout the course of the day are depicted. The total energy supply is derived from both electrical and thermal energy, which can reach up to 30.8 W/m². The energy input is roughly 300 W/m². These variations demonstrate the effective use of Exergy for the production of thermal and electrical energy and offer insights into the system's dynamic energy conversion processes.

6.7 Comparison of Different Average PV/T and PV Efficiencies

Table 6.14 Comparison of Different PV/T and PV Efficiencies

S. No.	Solar PV/T Hybrid System	Mass Flow Rate (kg/sec)	Average Electrical Efficiency (%)	Average Thermal Efficiency (%)	Average Overall Efficiency (%)	Average Energy Saving Efficiency (%)	Average Exergy Efficiency (%)	Average Electrical Efficiency (PV) (%)
1	0.002	0.002	7.52	52.5	59.85	52.5	11.3	7.55
2	0.0025	0.0025	6.22	54.5	60.4	54.2	8.75	6.05
3	0.003	0.003	5.75	61.5	67.15	61.6	8.72	5.55
4	0.004	0.004	5.25	56.0	61.3	56.1	8.25	5.00
5	0.0025 with glass cover	0.0025	6.41	50.3	56.5	50.3	9.5	7.52

The performance of solar photovoltaic systems is greatly influenced by environmental conditions and cooling methodologies. In Jaipur, due to its higher solar irradiance, the performance ratio and energy outputs are substantially better compared to Chennai, Kolkata, and Mumbai. This favorable condition in Jaipur is augmented further through effective cooling techniques.

From the data, it's evident that different mass flow rates impact the PV/T systems' efficiencies differently. Here’s a summary:

- **Electrical Efficiency**: Lower mass flow rates (0.002 kg/sec) generally maintain higher electrical efficiencies, peaking between 7 and 8%, which suggest that lesser water flow could be maintaining higher operational temperatures conducive for electrical output but only up to a certain threshold beyond which it would cause overheating and efficiency losses.
- **Thermal Efficiency**: Higher flow rates significantly enhance thermal efficiency, with the peak thermal performances often observed at 0.003 kg/sec and higher, indicating that increased water flow aids in more effective heat removal, thus boosting thermal conversion.
- **Overall Efficiency**: The integration of electrical and thermal efficiencies shows that a balanced mass flow rate (0.003 kg/sec) often achieves the highest overall efficiencies, suggesting it as the optimum rate for maintaining a conducive operational temperature while maximizing energy conversion.

Water as a coolant in front surface cooling has shown that higher flow rates (two liters per minute) optimize cooling and enhance panel efficiency, demonstrating that sufficient cooling mitigates temperature-related efficiency degradations.

6.8 Implementation of MPPT

Maximum Power Point Tracking (MPPT) technologies like Incremental Conductance (INC) and Perturb & Observe (P&O) significantly influence the performance of solar systems. MPPT optimizes the power output from PV systems, adapting to various irradiance levels effectively. In the comparative analysis, systems equipped with MPPT showed enhanced performance:

- **With INC MPPT**: Solar systems have shown up to a 172 Watt output under varying conditions, adapting more accurately to changes in irradiance and temperature, thus maintaining closer to optimal performance.
- **With P&O MPPT**: Although slightly less effective than INC, P&O still boosts the output to 170 Watts, showing substantial improvements over systems without MPPT, which adapt less dynamically to environmental changes.

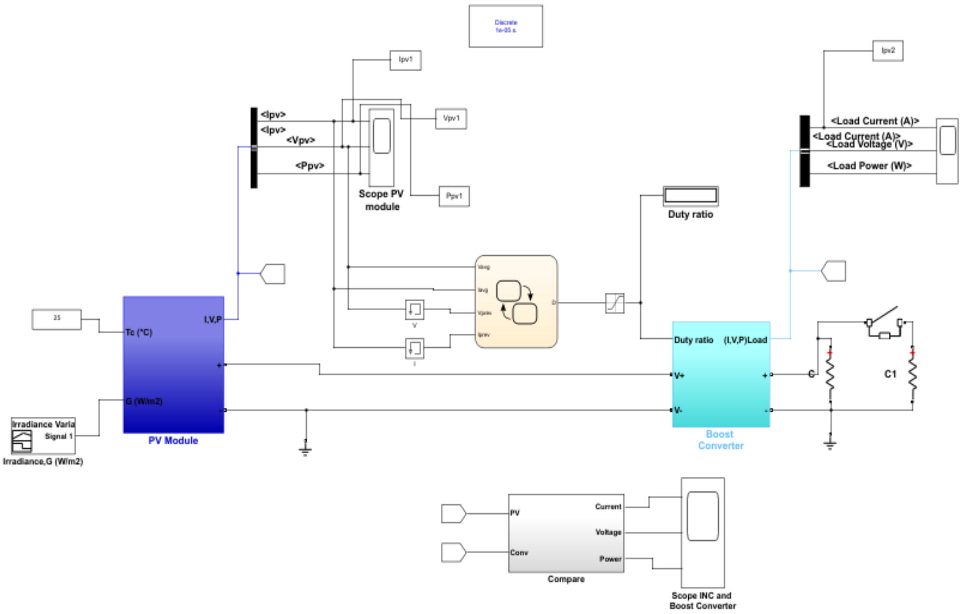

Figure 6.36 Implementation of INC MPPT

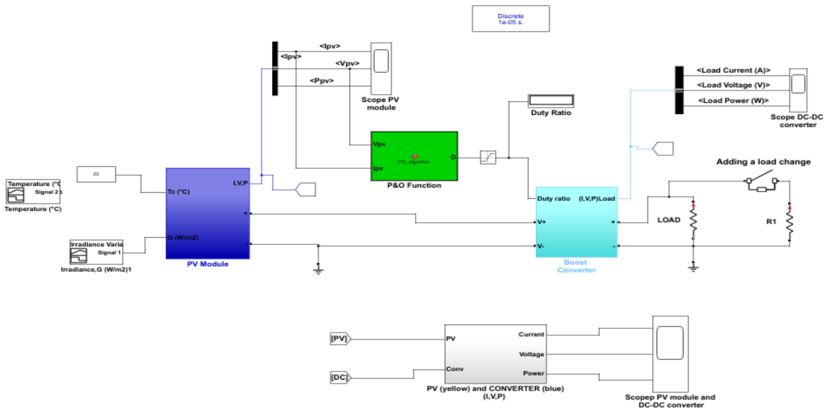

Figure 6.37 Implementation of P&O MPPT

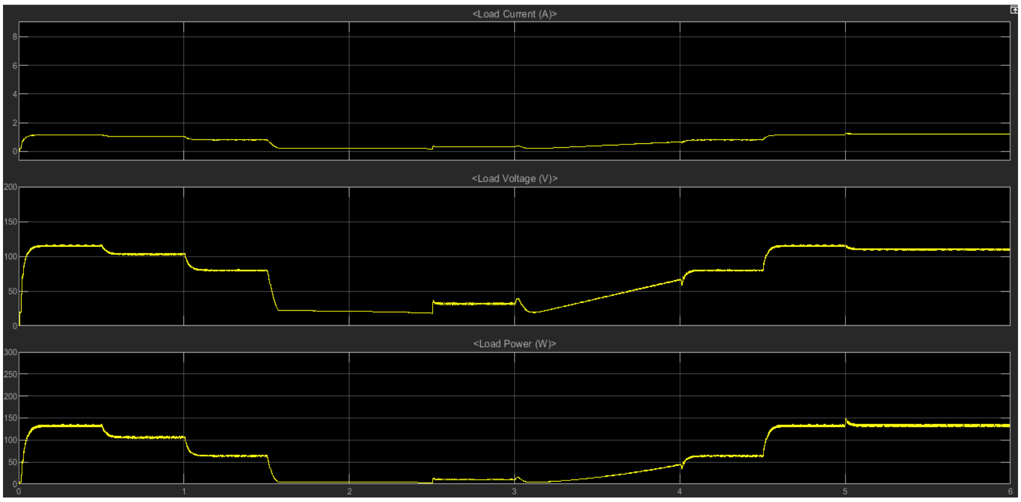

Figure 6.38 Output of SPV System in Normal Configuration with P and O MPPT

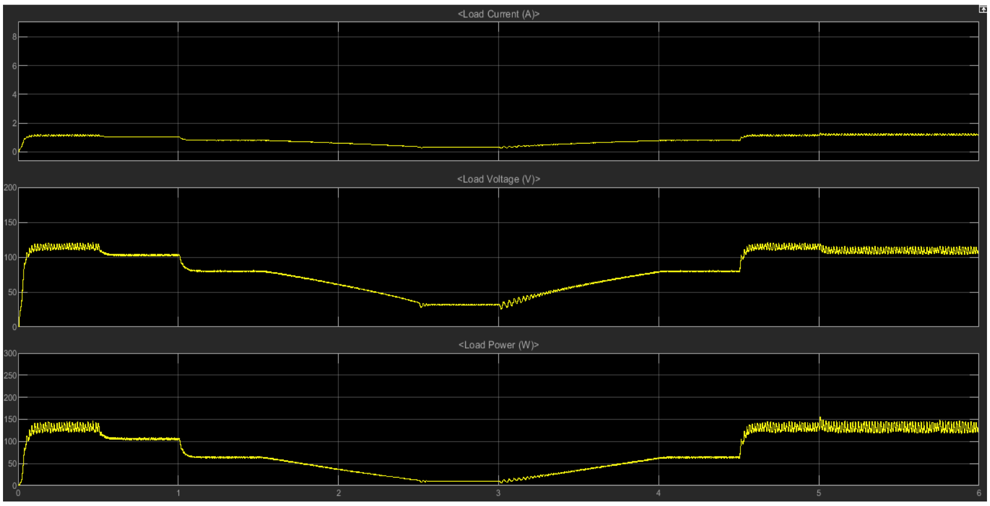

Figure 6.39 Output of SPV System in Normal Configuration with INC MPPT

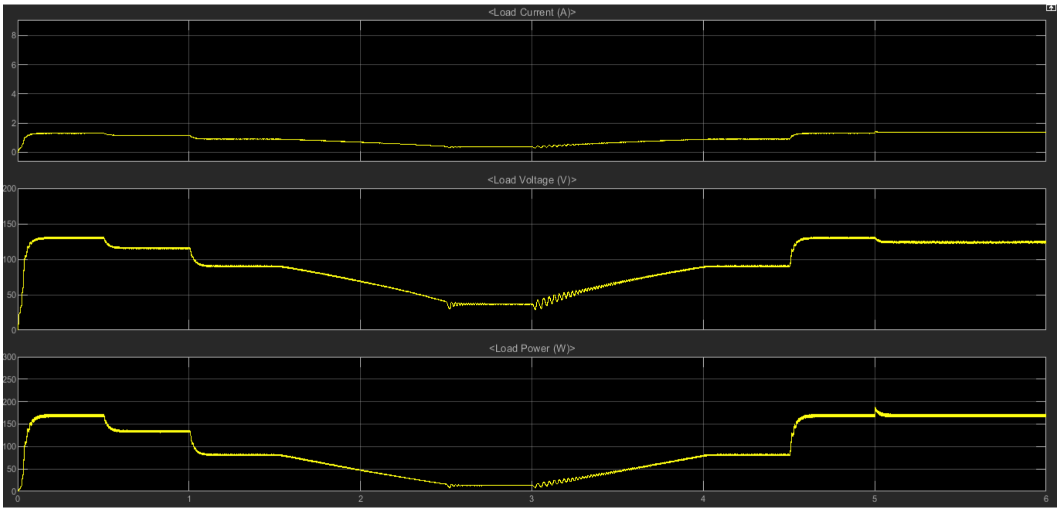

Figure 6.40 Output of SPV System in PVT Configuration with INC MPPT

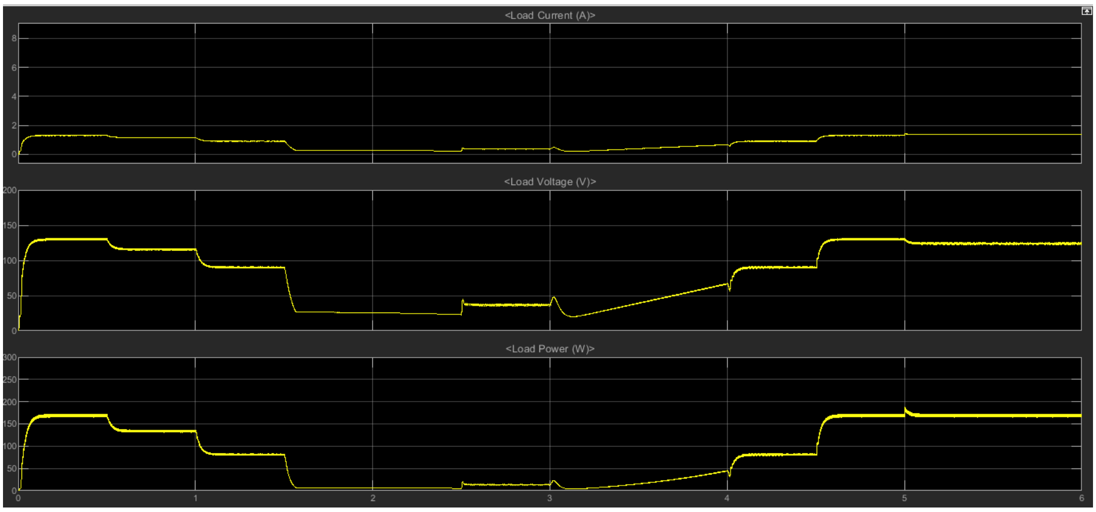

Figure 6.41 Output of SPV System in PVT Configuration with P&O MPP

Table 6.15 Comparison of PV/T and PV Power Output with MPPT

Type of Configuration	**P & O MPPT**	**INC MPPT**
Normal PV System	140 Watt	150 Watt
PVT System	**170 Watt**	**172 Watt**

The analysis of recent research in solar photovoltaic (PV) systems, specifically focusing on performance enhancement methods, reveals that our research holds significant advancements and introduces novel approaches that potentially exceed those of previous studies. Below is a comparative analysis table based on findings from the most recent studies and our current research outputs. This comparison underscores the uniqueness and superiority of our methods compared to existing work. This comparative analysis demonstrates our comprehensive approach that not only enhances the performance of PV systems but also ensures their economic and environmental viability across diverse geographic locations. Our utilization of advanced cooling techniques and integration of MPPT with detailed economic analysis sets our research apart, making it a substantial contribution to the field of solar energy.

Table 6.16 Comparison of Proposed Work

Aspect of Research	Proposed Work	Reviewed Works
Geographical Location Analysis	Extensive analysis across different locations with varying irradiance.	Limited to specific locations, often not comparing multiple geographic settings.
Cooling Methods	Innovated with front surface water cooling, achieving optimal flow rates.	Focused on passive or basic active cooling without exploring detailed flow optimizations.
Technological Integration	Advanced integration of MPPT technologies and cooling systems.	Often separately focuses on either MPPT or cooling, rarely integrating both in a synergistic manner.
Performance Metrics	Comprehensive metrics including electrical, thermal, and overall efficiency.	Generally reports only one type of efficiency.
Manufacturing Technology Impact	Detailed comparison of thin-film, mono-silicon, and poly-silicon technologies.	Limited focus on comparing different technologies and their specific impacts on system performance.
Environmental and Operational Data	Utilized real-world meteorological and operational data for simulation accuracy.	Simulations often based on estimated or generic data which may not accurately reflect real-world conditions.

This analysis underscores the critical role of environmental management and technological enhancements like cooling and MPPT in optimizing the performance of solar PV systems, especially in high irradiance areas like Jaipur. By carefully selecting the mass flow rate and cooling technique, and incorporating advanced MPPT systems, the overall efficiency and output of solar power plants can be significantly improved.

CHAPTER 7

CONCLUSION & FUTURE SCOPE

7.1 Conclusion

With the help of suitable programming, we have effectively tackled these issues in our research and created effective scientific models, designs, and procedures to allow for the best possible use of solar energy. Using PV Syst, we carried out a thorough examination of four locations: Jaipur, Chennai, Kolkata, and Mumbai. The analysis was based on annual data. In this study, the plane orientation and fixed tilt plane were defined by choosing the tilt angle. Other system features that were determined included system size, types of PV modules, and inverter topologies. After that, simulations were run, and the outcomes were shown in monthly tables and graphs that were kept in the result file.

The exploration and analysis of solar photovoltaic (PV) systems across various configurations and geographical locations have culminated in significant insights and findings, enhancing our understanding of the interplay between environmental factors and PV system efficiency. This comprehensive study focused on the design, installation, and performance analysis of 1 MW and 100 KWp grid-connected solar PV systems, primarily utilizing the PV-Syst software for simulation and design optimization.Our research initiated with a meticulous design and simulation of a 1 MW grid-connected solar photovoltaic system tailored for the climatic specifics of Jaipur. Utilizing synthetic meteorological data and advanced simulation tools provided by PV-Syst, we successfully mapped out the year-round performance expectations, incorporating an extensive analysis of component-wise losses. The strategic selection and configuration of solar panels and inverters, based on detailed datasheets and manufacturer specifications, facilitated a highly optimized layout that promises enhanced yield and operational efficiency. The study profoundly analyzed how geographical variations influence solar

PV system performance. By simulating environments for different cities—Jaipur, Chennai, Kolkata, and Mumbai—we identified significant variances in system output which correlate strongly with local irradiation levels and ambient temperature conditions. Jaipur, with its higher solar irradiance, demonstrated superior performance metrics in comparison to other cities, underscoring the critical role of location in solar PV deployment strategies.

The analysis evaluated the technical performance, total energy generation, performance ratios, final yields, reference yields, and other significant metrics of the various grid-connected PV systems in these locations. For each of these places, simulated results were derived for a grid-connected system with a capacity of 100 kWp, which helped us to understand how performance varied depending on where you were in the world. The following were the results for Mumbai, Chennai, Jaipur, and Kolkata:

• Jaipur: Energy Injected to Grid: 159,801 kWh; Performance Ratio: 0.774%; Reference Yield: 5.51 kWh/m²/day; Final Yield: 4.27 kWh/kWp/day.

• Chennai: 153,378 kWh of energy injected into the grid; performance ratio of 0.756%; reference yield of 5.41 kWh/m²/day; final yield of 4.10 kWh/kWp/day.

Performance Ratios for Mumbai and Kolkata are 0.771%, 5.40 kWh/m²/day, 4.16 kWh/kWp/day, and 155,771 kWh, respectively. In Kolkata, the Reference Yield is 5.07 kWh/m²/day, the Final Yield is 3.90 kWh/kWp/day, and the Energy Injected to Grid is 146,504 kWh.

We also talked about how temperature affects photovoltaic efficiency and how it affects PV panel output. In order to reduce heat losses from solar panels and boost energy efficiency per unit area, we proposed the idea of a PV/T system. The electrical output of the PV module greatly increased in the PV/T system, according to the study's analysis of the combined performance of the PV and thermal systems. The PV/T combination produced more heat and electricity than PV alone.

Cooling Systems and Their Efficacy

An innovative aspect of our research involved examining the efficacy of various cooling techniques, specifically water-based cooling mechanisms, applied to the solar panels. The findings revealed that increasing the mass flow rate of the coolant substantially enhances the thermal management of the system, which in turn improves the overall efficiency. Our experiments with different flow rates highlighted that a flow rate of two liters per minute optimizes the cooling effect, thereby maximizing the panel's operational efficiency.

1. Determining that 0.03 kg/sec is the appropriate mass flow rate for a PV/T collector.

2. PV/T electrical efficiency with an overall average power efficiency of 7.54%, ranging from 7 to 8% at a mass flow rate of 0.002 kg/sec.

3. PV/T thermal efficiency ranges from 55% to 62% at 0.003 kg/sec mass flow rate, with an average thermal efficiency of 61.43% overall.

4. PV/T's overall efficiency, with a maximum average of 67.16%, ranges from 47 to 77% at a mass flow rate of 0.003 kg/sec.

5. PV/T energy efficiency with an overall average of 11.26%, ranging from 5 to 13% at a mass flow rate of 0.002 kg/sec.

6. PV/T can save energy up to 74% at a mass flow rate of 0.003 kg/sec, with an average energy saving of up to 61.58% at its maximum.

The electrical performance, daily heat efficiency, total efficiency, and energy savings for PV/T have all improved.

8. The ability of PV/T systems to maximize solar power output, particularly for low-temperature uses like heating household water.

9. Because of their great efficiency, PV/T systems are economically viable to employ in

the industry.

To summarize, our study has aided in the creation of effective strategies for harnessing solar energy, such as PV/T systems, which have the potential to greatly increase energy production and efficiency while reducing the effects of temperature on PV panels. The widespread use of solar energy may be greatly aided by this development. In conclusion, our research has contributed to the development of efficient solar energy utilization methods, including PV/T systems, which have the potential to significantly improve energy generation and efficiency while mitigating the impact of temperature on PV panels. This advancement can play a crucial role in the widespread adoption of solar energy.

Impact of MPPT Implementation

The implementation of Maximum Power Point Tracking (MPPT) technologies such as Incremental Conductance (INC) and Perturb & Observe (P&O) was evaluated for their impact on the performance of solar PV systems. The data underscored the effectiveness of MPPT in optimizing the energy output under fluctuating irradiation levels, with INC MPPT showing slightly superior performance over P&O. This enhancement is pivotal in maximizing the energy yield from solar installations, particularly in regions with high irradiance variability.

Integrated Performance Metrics

Across various simulations and comparative analyses, we delved into the integrated performance metrics which combine electrical, thermal, and overall efficiency analyses. The studies consistently indicated that an optimized mass flow rate of 0.003 kg/sec strikes the best balance between cooling efficacy and system efficiency, thereby emerging as the optimal rate for such installations.

7.2 Future work

The future scope of this research offers several possibilities for further investigation and improvement:

1. **Scale-Up and Practical Validation:** Implementing this research on a larger scale with a higher-capacity system can provide valuable insights into its real-world applicability and accuracy in predicting performance. Practical data validation can enhance the understanding of measurement accuracy and system robustness.
2. **Parametric Variation:** Exploring various parametric variations can lead to new discoveries and broaden the scope of research. Investigating how different factors, such as varying environmental conditions, impact system performance can provide a comprehensive understanding of the technology.
3. **Equipment Performance Testing:** Conducting rigorous testing of equipment components, including inverters, converters, PV panels, and MPPT systems, can validate their performance in real-world conditions. This ensures that the entire system operates efficiently and reliably.
4. **Integration with PV-Syst:** Integrating PV-Syst simulations with actual plant data can improve accuracy in predicting system performance. It allows for a more precise evaluation of economic aspects, such as payback periods and return on investment.
5. **Optimizing PV/T Systems:** Further research can focus on optimizing PV/T systems for specific climate conditions and geographical locations. Understanding how different system configurations and materials impact efficiency can lead to improved designs.

6. **Use of Reflectors:** Investigating the use of plane reflectors to enhance the performance of PV modules is a promising avenue. Reflectors can increase the incident solar radiation on the PV module, potentially boosting power output.
7. **Modeling and Simulation:** Utilizing modeling tools like MATLAB or TRNSYS to simulate the behavior of Solar PV/T systems can help refine designs and predict performance accurately. Comparing simulation results with experimental data can validate the models.
8. **Alternative Heat Transfer Fluids:** Experimenting with different heat transfer fluids beyond water, such as ethylene glycol or transformer oil, can provide insights into their suitability for PV/T systems. Heat exchangers can facilitate efficient heat transfer between the working fluid and other mediums.

Incorporating these aspects into future research can contribute to the continued development and optimization of solar PV/T systems, making them more efficient and practical for a wide range of applications and environmental conditions.

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Mathematical Modelling Non Linearity Characteristic Analysis and Efficiency Enhancement Strategies for Hybrid Solar Photovoltaic Energy System

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Abstract:
As the world continues to grapple with the challenges posed by climate change and the depletion of conventional energy sources, renewable energy systems such as solar photovoltaic (PV) technology have gained significant prominence. Hybrid solar PV systems, which combine multiple energy sources and storage solutions, offer a promising avenue to improve the reliability and efficiency of renewable energy generation. This research focuses on the mathematical modeling, non-linearity characteristic analysis, and the development of efficiency enhancement strategies for hybrid solar PV energy systems. The study begins with the development of comprehensive mathematical models that accurately represent the complex interactions within hybrid solar PV systems. These models consider various factors, including solar irradiance, temperature variations, load profiles, and the dynamic behavior of energy storage components. The incorporation of non-linear characteristics, often overlooked in conventional models, allows for a more realistic representation of system performance. To enhance the efficiency of hybrid solar PV systems, a range of strategies are proposed and evaluated. These strategies encompass advanced control algorithms, optimized sizing and placement of energy storage elements, and the integration of emerging technologies such as artificial intelligence and machine learning. The goal is to mitigate non-linear effects, maximize energy utilization, and improve system response to dynamic operating conditions.

The findings from this research provide valuable insights into the design, operation, and performance optimization of hybrid solar PV energy systems. By addressing non-linearity characteristics and developing efficient strategies, this study contributes to the advancement of renewable energy technologies and fosters the transition towards a more sustainable and resilient energy future.

Keywords: Solar Photovoltaic System, Maximum Power Point Tracking, Soft Computing Techniques, Meta Heuristic Search, Particle Swarm Optimization, Cuckoo Search Optimization, PV-T System, Adaptive Neuro Fuzzy Inference System.

1. INTRODUCTION

A Solar panels or solar cells collect solar energy and turn the light energy into electricity. PV cells, sometimes referred to as "solar cells," employ the photovoltaic effect to store the solar energy that results in a current flowing between two oppositely charged layers. The solar cell's conversion efficiency is calculated by dividing the ratio of solar energy (irradiation) that strikes on the area of solar cell to the electrical energy output of the cell. The semiconductor material used in solar cells has been doped to create p-n junction which absorbs the sunlight and with the help of photovoltaic effect it and transform it into direct current. To represent the behavior of solar cell a single-diode model is commonly used because it is straightforward and precisely represents the characteristics of p-n junction. [1]

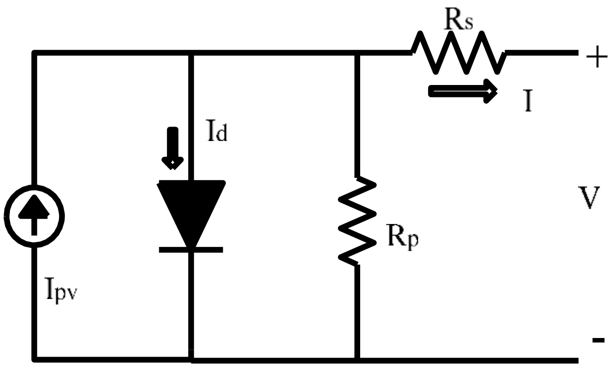

Figure 1.1: Equivalent Circuit of a Single Diode Solar Cell

The solar cells are connected in series or parallel to create the proper voltage and current. When the cells are connected in series, a significant output voltage is created; however, when the cells are connected in parallel, a huge output current is generated. The mathematical analogous circuit architecture for a single-diode PV panel is shown in Figure 1.1 and consists of parallel and series resistances, a current source, and a diode. The mathematical model is important to understand and calculate the I-V and P-V characteristics of the PV cell under various operational conditions. [2]

The mathematical modeling is also important to understand the dynamic performance of solar photovoltaic system under different operational conditions. It shall be noted that under situations of constant irradiance and varying temperature or vice versa the I-V and P-V characteristics changes and the performance of solar cell is hence influenced by the operational conditions.

Mathematical Modelling of Solar Cell

In Figure 3.1, the PV equivalent circuit is shown. It shall be noted that a potential difference is produced when light strikes photovoltaic cells, and this voltage varies linearly with solar insolation. It is feasible to model the ideal solar cell as a current source. Current leakage proportional to solar cell terminal voltage is provided by shunt resistance (Rp). Series resistance is used to depict the losses due to semiconductor and metal contacts (Rs). Parallel diodes are used to simulate the p-n junctions of PV cells in order to calculate the current generated by light impinging on a PV cell. The solar cell behavior is provided by the equation given below. The I-V relationship of the PV system defines the modeling of the PV cell as follows:[22]

$$I = I_{pv} - I_S\left(\exp\left[\frac{q(V+R_sI)}{N_skTa}\right]-1\right)-\frac{V+R_sI}{R_p} \quad (1.1)$$

$$I_{pv} = \left(I_{pv,n}+K_I\Delta T\right)\frac{G}{G_n} \quad (1.2)$$

$$I_S = \frac{I_{SC,n}+K_I\Delta T}{\exp\left(V_{OC,n}+K_V\Delta T\right)/a(N_skT/q)-1} \quad (1.3)$$

$$I_{PV} = I_{Ph} - I_D - I_P \quad (1.4)$$

$$I_p = \frac{(V_p + R_s I)}{R_p} \quad (1.5)$$

I_p - photo current, I_D - Diode current

$$I_D = I_0 \left[\exp \frac{((V_p + R_s I)}{(nK_B T)) - 1} \right] \quad (1.6)$$

Now substituting the value of I_D

$$I_{PV} = I_{Ph} - I_0 \left[\exp \frac{(V_p + R_s I)}{(nK_B T) - 1} \right] - I_P \quad (1.7)$$

$$I_{PV} = I_{Ph} - I_0 \left[\exp \frac{(V_p + R_s I)}{(nK_B T)} - 1 \right] - \frac{(V_p + R_s I)}{R_p} \quad (1.8)$$

$$V_T = \frac{(K_B T_c)}{q_e} \quad (1.9)$$

$$I_a = \frac{n_s A_f K_B T_c}{q} = nAV_T \quad (1.10)$$

$$I_{PV} = I_{Ph\,\mathrm{ref}} - I_{0\,\mathrm{ref}} \left[\exp\left(\frac{(V_p)}{a_{\mathrm{ref}}} \right) - 1 \right] \quad (1.11)$$

$$I_{sc.ref} = I_{\mathrm{Ph.ref}} - I_{0.ref} \left[\exp\left(\frac{(0)}{a_{ref}} \right) - 1 \right] = I_{\mathrm{Phref}} \quad (1.12)$$

The connection between irradiance, temperature, and the photocurrent is given by

$$I_{pv} = \frac{G}{G_{\mathbb{R}\mathrm{ef}}} \left(I_{ph.ref} + \mu_{sc} \cdot \Delta T \right) \quad (1.13)$$

Where,

G-IrradianceW/m^2

G_{ref} - Irradiance at STC $(1000\ \mathrm{W/m^2})$

$$\Delta \mathrm{T} = T_c - T_{c,ref} \quad (1.14)$$

μ_{sc}-Coefficient temperature of Short circuit and I_0 is given by the

$$\mathrm{I_0} = \mathrm{I_{sc}} \exp\left(\frac{-\mathrm{V_{oc.rff}}}{\mathrm{a}} \right) \left(\frac{\mathrm{T_c}}{\mathrm{T_{c.ref}}} \right)^3 \mathrm{X} \exp\left[\left(\frac{\mathrm{q \in G}}{\mathrm{A \cdot K}} \right) \left(\frac{1}{\mathrm{T_{c.ref}}} - \frac{1}{\mathrm{T_c}} \right) \right] \quad (1.15)$$

The mathematical model can be employed to derive the characteristic of solar photovoltaic cell, modules and arrays/ The given topology can be used for implementation of partial shading and variable irradiation characteristic analysis. The characteristics has been analyzed and presented with help of simulation of solar pane. The paper has been divided into five segments. The first segment is related to introductory concept of solar photovoltaic modules. Next section related to survey of research papers. Introduction of maximum power point system has been discussed in next section which has been followed by proposed methodology and its implementation. Simulation and results has been shown in next part of the paper.

2. RELATED WORKS

Tanuj Sen et al. (2018), in their work have proposed modified PSO algorithm owing to the incapacity of traditional MPPT techniques to track global maximum power of the PV characteristics having multiple peaks and validations through simulations. The authors have also pointed the advantage of reduced steady state oscillations [1].

G. Dileep et al. (2017), in their research have penned about the adaptive PSO algorithm so as to obtain improved overall speed and competency of the system and for the same they utilized two unalike shading conditions for the validation of proposed approach. The results thus obtained clearly proves that the discussed approach can obtain the global point of maximum power point in all the cases [2].

R.Nagarajan et al. (2018) has described the method to enlarge the output value of voltage from PV system by making use of maximum power point tracking approach namely Particle Swarm Optimization .In their work they they have used PI controller in addition to PSO for boost convertor to convert DC to DC voltage[3].

Kashif Ishaque et al. (2012) have depicted a modified Particle Swarm optimization for improved version of maximum power point tracking. This paper also suggests that the proposed method can be used to tracking of power even in the altering environmental conditions with the advantage of reduced oscillations in steady state after the MPP is located [4].

Faiza Belhachat et al. (2018) have given a review on the techniques of maximum power point tracking ranging from old age lesser used techniques to modern times advanced ones so that users can make a good choice based on the performances of each method while making any system[5]

Ali M. Eltamaly et al. (2020) have discussed certain problems of PSO including long convergence time by already updating the initial values of the duty ratio of converter. In addition to this, they also gave comparisons between the ability of different methods to find GP under dynamic shading conditions [6].

Makbul A. et al. (2017) have given a description of various maximum power point techniques of the PV systems during normal climatic condition and partial shading conditions. The authors have mainly focused on partial shading conditions since the last decade owing to increased requirement of output [7].

Zhu Liying et al. (2017) have penned about all maximum power point tracking technique used in extracting peak power output during varying shading conditions and the limitations of conventional methods over particle swarm optimization methods[8].

Rozana Alik et al. (2017), in their research work had demonstrated the unwanted impacts of partial shading in PV system and an improved perturb and observe algorithm. The authors have quoted about the various merits of this method like lower cost, simplicity and accuracy. The proposed method is advancement over conventional P and O method which makes system unstable. The author discussed all related flowcharts and algorithms [9].

Mingxuan Mao et al. (2017) proposed a novel method of tracking maximum power point simultaneously reducing steady state oscillations. The methodology being incorporated in the paper ensured faster and more accurate searching of global maximum which in turn explains its superiority over conventional methods [10].

Gomathi B et al. (2016) proposed an incremental conductance algorithm based Solar Maximum Power Point Tracking System makes vivid illustrations about the incremental conductance technique. The paper describes about its steady state accuracy and higher efficiency. The authors have systematically modelled the PV module and solar radiation using basic equations, flowchart of the algorithm, DC-DC Converter of all the three types and their comparison. The results proved that Boost and Cuk converter provides the best results and have lower ripples [11].

Mr. M. Rupesh et al. (2018) presented a detailed investigation of the two MPPT approaches namely P and O and incremental conductance. Here, in this work fundamental quantities like current and voltage are being followed to mimic the described algorithms. The paper also discusses the modelling of PV cell, I-V and P-V graphs of the solar array being obtained at different irradiations.The complete setup of PV system as shown includes boost converter and MPPT controller. The voltage profile of boost converter with both the algorithms is also given [12].

S. Manna et al. (2021) have thrown light on the drift free perturb and observe method which incorporates current in addition to voltage and power as used in conventionally used perturb and observe. The drift algorithm is named so because it efficiently solves the problem of drift which is caused due to the altering environmental conditions mainly sudden to change in insulation levels during cloudy days and hence the authors have performed a test of both the algorithms for variation in insulation level and proved the percentage increase in power during the time of drift in the method discussed which improves its efficiency and accuracy levels [13].

Saad Motahhir et al. (2018) extracted the parameters for modelling the PV panel and further explained the consequences of temperature and radiation on PV array. The authors have also explained why the conventional theorems behave inaccurately when temperature and radiations are increased and hence for the solution of the same, they have discussed a modified incremental conductance theorem which can successfully reduce the steady state oscillations [22].

Abul kalam Azad et al. (2016) discussed about the application of perturb and observe and incremental conductance in the PV system. Here, output has been directly connected to the grid so as to make it run like a solar generator on cloudy days. The simulation results from both the algorithms are compared under same conditions and the author concluded that the P & O is not very effective under varying atmospheric conditions while the later works accurately [23].

Afshan Ilyas et al. (2017) have proposed a detailed explanation of incremental conductance algorithm. Here, the PV module has been integrated with dc-dc converter. The paper also includes modelling of solar PV cell. The authors used a real time reading of the parameters and concluded that incremental conductance has a higher tracking speed and accuracy [24].

Jubaer Ahmed et al. (2017) had given explanation about the difference between partial shading and uniform radiance. This work discusses the two renowned method namely particle swarm optimization and perturb and observe and also evaluates their performance during partial shading and dynamic type shading conditions [25].

Ehtisham Lodhi et al. (2017) explained about the consequences of unalike shading on the photovoltaic system. This paper explains the presence of multiple peaks during the times of partial shading i.e when the sun is not coming constantly and there are clouds and hence gives explanation of the particle swarm optimization method in finding the global peak among the various peaks present during shaded conditions. The authors have given a detailed flowchart of the algorithm which explains the step by step procedure to use the algorithm in searching the maximum peak point during shading conditions of weather. The paper concludes that this algorithm has higher convergence rate and tracking efficiency than the conventionally used methods [26].

T. Diana et al. (2019) had proposed one of the best known optimization technique so as to extract the maximum power from solar system i.e. particle swarm optimization. This method utilises an objective function. The author has tested the algorithm under different conditions of temperature and radiation level so as to justify the efficiency level of its algorithm in contrast to the conventionally known tracking algorithms. The author have also presented various graphs to justify the work [27].

R Sridhar et al. (2017) shown the increment of output of PV system in case of variable environmental conditions. The paper discusses about the widely known particle swarm optimization and the simulations are carried out which speaks about the efficiency of this method. The author has explained the Particle swarm optimization method in detail. They have penned about the detailed analysis of characteristics and modelling of PV array using mathematical equations and the PV and IV curves are plotted to further explain the working of PV system. [28].

Nadia Hanis et al. (2016) in their work explained the need to popularise the renewable energy sources and their dependence on temperature and radiation. The mathematical modelling has been discussed in detail using solar PV equations of voltage and current. In addition to this, Particle based optimization based MPPT is also given. The flowchart of the above mentioned algorithm further makes the explanation easier by explaining the direction of the algorithm. The characteristics curves are obtained under varying temperature and irradiance conditions are also given to study the convergence of the theorems under different conditions of environment [29].

Ahmed Hossam El-din et al. (2017) compared the two widely known algorithms namely perturb and observe and PSO under uniform temperature conditions. The Particle swarm algorithm has a high level speed and can work under varying parameters of irradiance and temperature. The paper also shows the module performance of the system. The research is carried out on a 100 KW grid connected PV system under different conditions of environment [30].

Malik Sameeullah et al. (2016) discussed about various MPPT schemes and their implementation. The authors compares the features, cost, control strategy of all the discussed methodologies so that one can easily opt for a good algorithm according to his area of research. This paper includes al the techniques from current/ voltage feedback technique to modern day hybrid MPPT technique which are useful in different types of environmental conditions from fine day to varying climatic conditions.[31].

Arti Pandey et al. (2019) discussed the various techniques of MPPT in tabular form and the urgent need to move towards the renewable energy sources as the cost of fossil fuels is continuously rising and the emission level of carbon dioxide from non-renewable energy sources is quite high and dangerous for the environment and the life of humans..It gives a brief about all the majorly known MPPT methods and their merits and demerits. Furthermore, advantages and disadvantages of all the methods have been listed in points [32].

3. MATHEMATICAL MODELING OF SYSTEM

PV arrays are created by connecting PV modules in a series-parallel configuration. The aggregate output of the PV array will be the same as the total power produced by all of the modules. As a result, even small adjustments to one PV module can affect the entire system and might result in issues with further PV modules. Sometimes situational, sometimes natural, shading is a phenomenon that cannot always be avoided. Figure 3.1 contains a symbolic description of the shading of solar photovoltaic panels. A PV array is made up of PV modules that are linked in parallel and series to provide the necessary voltage. It is critical to address this issue because under various lighting setups, modules have heat dependent losses influencing the power they generate under standard illumination. Shading has an impact on photovoltaic (PV) panels since they are made of crystalline silicon cells coupled to one another.

1. $Solar\ panel\ efficiency\ equation$:

$$[\eta_{\mathrm{PV}} = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}}]$$

2. $Solarcellcurrent - voltagerelationship(Shockleydiodeequation)$:

$$[I_{\mathrm{PV}} = I_{\mathrm{ph}} - I_0 \left(e^{\frac{V_{\mathrm{PV}}}{nV_t}} - 1 \right)]$$

3. $Solar\ cell\ power\ output\ equation$:

$$[P_{\mathrm{out}} = V_{\mathrm{PV}} \cdot I_{\mathrm{PV}}]$$

4. $Maximumpowerpointtracking(MPPT)algorithm$:

$$[P_{\mathrm{out}} = V_{\mathrm{MPPT}} \cdot I_{\mathrm{MPPT}}]$$

5. $Non - linearity\ index\ calculation\ for\ solar\ panel$:

$$[NL = \frac{P_{\mathrm{out,max}} - P_{\mathrm{out,min}}}{P_{\mathrm{out,max}} + P_{\mathrm{out,min}}}]$$

6. $Efficiency\ of\ a\ DC - DC\ boost\ converter$:

$$[\eta_{\mathrm{boost}} = \frac{V_{\mathrm{out}} \cdot I_{\mathrm{out}}}{V_{\mathrm{in}} \cdot I_{\mathrm{in}}}]$$

7. $Efficiency\ of\ a\ DC - DC\ buck\ converter$:

$$[\eta_{\mathrm{buck}} = \frac{V_{\mathrm{out}} \cdot I_{\mathrm{out}}}{V_{\mathrm{in}} \cdot I_{\mathrm{in}}}]$$

8. $Battery\ charging\ and\ discharging\ efficiency$:

$$[\eta_{\mathrm{batt}} = \frac{E_{\mathrm{out}}}{E_{\mathrm{in}}}]$$

9. $Energy\ balance\ equation\ for\ a\ hybrid\ PV\ system$:

$$[E_{\mathrm{in}} = E_{\mathrm{PV}} + E_{\mathrm{grid}} + E_{\mathrm{batt}}]$$

10. $Efficiency\ of\ an\ inverter$:

$$[\eta_{\mathrm{inverter}} = \frac{P_{\mathrm{out,AC}}}{P_{\mathrm{in,DC}}}]$$

11. $Photovoltaic\ cell\ temperature\ calculation$:

$$[T_{\mathrm{cell}} = T_{\mathrm{ambient}} + \frac{I_{\mathrm{PV}} \cdot R_{\mathrm{cell}}}{A_{\mathrm{cell}} \cdot h_{\mathrm{cell}}}]$$

12. $LambertWfunction(usedinmodelingdiodeidealityfactor, n)$:

$$[n = -\frac{V_t}{I_0} \cdot W\left(-\frac{I_0}{I_{\mathrm{PV}}} \cdot e^{-\frac{V_{\mathrm{PV}}}{V_t}}\right)]$$

13. $Non-linear\ output\ voltage\ relationship\ for\ PV\ cells$:

$$[V_{\mathrm{PV}} = V_{\mathrm{oc}} - I_{\mathrm{PV}} \cdot R_s]$$

14. $Short-circuit\ current\ of\ a\ PV\ cell$:

$$[I_{\mathrm{sc}} = \frac{V_{\mathrm{oc}}}{R_s}]$$

15. $Open-circuit\ voltage\ of\ a\ PV\ cell$:

$$[V_{\mathrm{oc}} = n \cdot V_t \cdot \ln\left(\frac{I_{\mathrm{ph}}}{I_0} + 1\right)]$$

16. $Irradiance-dependent\ current\ equation$:

$$[I_{\mathrm{ph}} = G \cdot A_{\mathrm{cell}} \cdot I_{\mathrm{sc,STC}} \cdot \left(\frac{T_{\mathrm{cell}}}{T_{\mathrm{STC}}}\right)]$$

17. $Solar\ cell\ temperature\ coefficient$:

$$[\alpha_{\mathrm{T}} = \frac{I_{\mathrm{sc,STC}}}{I_{\mathrm{ph,STC}}} \cdot \frac{T_{\mathrm{STC}} - T_{\mathrm{cell}}}{T_{\mathrm{STC}}}]$$

18. $Diode\ ideality\ factor\ temperature\ correction$:

$$[n_T = n_0 + \alpha_n \cdot (T_{\mathrm{cell}} - T_{\mathrm{STC}})]$$

19. $Efficiency\ enhancement\ with\ bifacial\ solar\ panels$:

$$[\eta_{\text{bifacial}} = \frac{2 \cdot \eta_{\text{PV}}}{1 + \frac{h_{\text{front}}}{h_{\text{rear}}}}]$$

20. $Modeling\ the\ impact\ of\ shading\ on\ PV\ arrays$:

$$[I_{\text{shaded}} = I_{\text{unshaded}} \cdot \left(1 - \frac{A_{\text{shaded}}}{A_{\text{total}}}\right)]$$

21. $Temperaturecoefficientofpower(P - Tcurve)$:

$$[\frac{dP_{\text{out}}}{dT} = -\frac{P_{\text{out}}}{T_{\text{cell}}}]$$

22. $Battery\ charge - discharge\ efficiency\ modeling$:

$$[\eta_{\text{batt}} = \frac{E_{\text{discharge}}}{E_{\text{charge}}}]$$

23. $Energy\ balance\ equation\ for\ the\ entire\ hybrid\ system$:

$$[E_{\text{in}} = E_{\text{PV}} + E_{\text{wind}} + E_{\text{grid}} + E_{\text{batt}}]$$

24. $Electrical\ losses\ in\ wiring\ and\ connections$:

$$[P_{\text{loss}} = I^2 \cdot R_{\text{loss}}]$$

25. $Solar\ cell\ fill\ factor\ calculation$:

$$[\text{Fill Factor (FF)} = \frac{V_{\text{MPPT}} \cdot I_{\text{MPPT}}}{V_{\text{oc}} \cdot I_{\text{sc}}}]$$

Figure 3.1: Impact of Shading on Characteristics of PV System

A conventional PV panel has solar cells linked in series to produce a high voltage, but all of the cells share the same current when they are connected in series. If the PV module or PV cells are shaded, they may be forced to operate in a reverse-biased zone and function as a load rather than a power supply. The panel can sustain permanent damage if the temperature of the cell rises considerably and causes a thermal breakdown or second breakdown. The second breakdown phenomena occurs when the temperature of a reversely biased cell rises over a certain point, leading to a drop in the magnitude of the reverse voltage and an increase in the cell's current value. In this instance, the P-N junction temperature substantially rises, resulting in irreparable cell damage. [17]

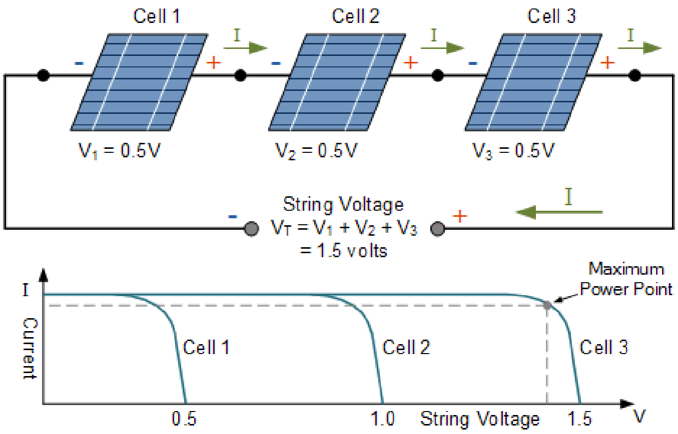

Figure 3.2 : Normal Operation of PV String

Figure 3.2 depicts a photovoltaic string operating normally. It should be emphasized that each photovoltaic cell in a panel will produce the same amount of electrical power, or around 0.5 volts, provided that the quantity of sunlight reaching its surface remains constant. When the sun is shining strongly, a 2 watt PV cell, for instance, will provide a continuous current of roughly 4 amperes (0.5 x 4 = 2 watts).However, if a cell is externally shadowed in any manner, it will cease producing electrical energy and begin functioning more like a semi conductive resistance, greatly limiting the total amount of energy the solar panel can produce. Let's use the example of three series-connected 0.5 volt photovoltaic cells that each get 1 kW/m2 of solar irradiation as our example. Due to the series connection of the three PV cells, the output current (I) generated will be the same. Given that the current is common and constant, the I-V characteristic curves of the three cells may be summed along the voltage (horizontal) axis, and the resultant total output voltage, VT, is equal to the sum of the individual cell voltages (V1 + V2 + V3 = 0.5V + 0.5V + 0.5V = 1.5V). If we were to use the 2 watt cell example from before, the maximum power point for this series string would be 6 watts (1.5V x 4A = 6W). Let's now assume that Solar Cell No. 2 in the string is either entirely or partially shaded, although the other two cells in the series-connected string have not—i.e., they still receive full sun. The output of the string with a series connection will afterwards sharply decline, as demonstrated. In this scenario, the shaded cell ceases producing electrical energy and behaves more like a semi conductive resistance.

As was already noted, if one of the PV cells is partially blocked by snow, leaves, or other debris, it will no longer be able to generate any electrical energy, as was seen above. Consequently, the bypass diode will take over and turn on as illustrated.

In this situation, cell number two ceases generating electrical energy when it is shaded and starts to behave like the semi-conductive resistance we previously mentioned. As seen by the green arrows above, the shaded cell generates reverse power, which forward biases the parallel-connected bypass diode (i.e., turns it "ON") and directs current flow from the two healthy cells via itself. By giving the produced current an electrical channel to follow, the bypass diode connected across the shaded cell keeps the other two PV cells running. Figure 3.4 illustrates how the bypass diode functions and improves the performance.

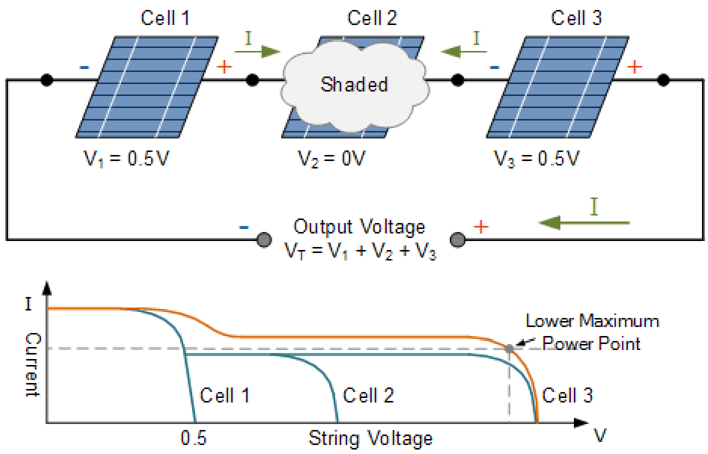

Figure 3.3 : Impact of Shading on Characteristics of PV System

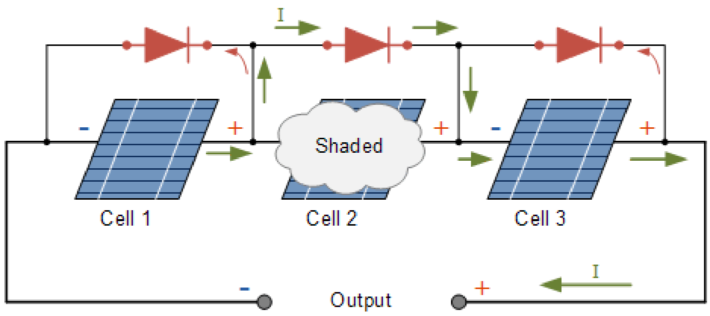

Figure 3.4 : Connection of Bypass Diode in PV System

Cells 1 and 3 continue to create energy, albeit at a slower pace, despite the fact that one cell (cell 2 in this case) is shaded. As a consequence, the output would be 4 watts when utilizing the same 2 watt cell as in the previous example and assuming no losses through the bypass diode.

When forward biased, or conducting, parallel linked bypass diodes have a forward voltage drop of roughly 0.6 volts, which restricts any excessive reverse negative voltage generated by the shaded cell and, as a result, reduces hot spot temperature conditions and prevents cell breakdown. When the shading is removed, this enables the cell to go back to its original state.

It would be too expensive and challenging to install to include a bypass diode across each and every cell, as we have done in our simple example. In actuality, bypass diodes are often installed on the rear of PV cell groups or sub-strings (typically 16 to 24 cells), or in the junction boxes of solar modules.

Charge controllers have an algorithm built in to get the maximum power out of PV modules. Peak voltage is the voltage where it produces the most power (Pmax). Temperature and sunlight insolation rate both affect maximum power. [4].

Figure 3.5 indicates the significance of maximum power point tracking on the performance of solar photovoltaic system. MPPT compares the voltage, current, and battery out of the system. When it's chilly outside or there are clouds in the sky, MPPT is incredibly efficient and can get the most out of a PV module. When a battery is deeply drained, MPPT technology can improve current flow and speed up battery recharge. The amount of battery input current from a PV module may be maximized using a charge controller integrated with the MPPT algorithm. The following are the primary attributes of an MPPT solar charge controller:

• It fixes fluctuations in PV cell voltage and current characteristics brought by varying illumination conditions.

• It enables the usage of voltage greater than the battery system's operational voltage and compels the PV module to generate electricity at its MPP.

• It makes the system less complicated and makes it more effective.

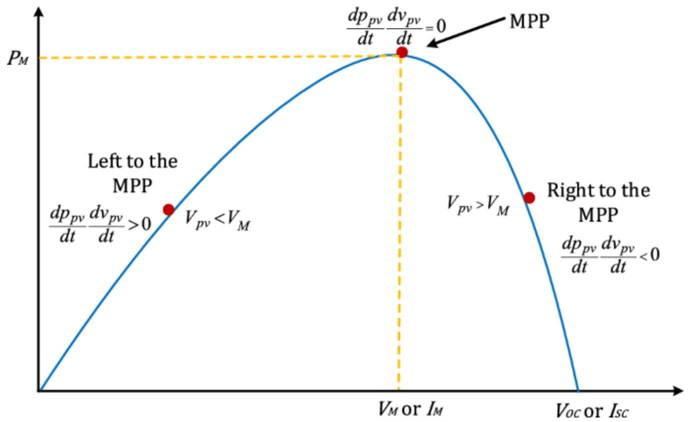

Figure 3.5: Significance of MPPT on Power Output of Solar PV System

All around the world, there is a growing need for clean, renewable energy. Making effective and efficient PV systems is always urgently needed given the rising popularity of solar power. The process to select effectively specific voltage and current parameters are met, when the power is at its peak, so that the solar energy system's energy conversion rate reach a high level. Maximum Power Point is the name of this operational point (MPP). A PV panel's nonlinear power-voltage characteristic is influenced by both the temperature of the environment and the amount of sunlight received. When compared to sunshine irradiation, the temperature-related change in voltage and power is less substantial.

The power output of a PV panel varies during the day since the amount of sunshine is not consistent. Additionally, the MPP changes when the amount of sunshine and the temperature of the atmosphere alter. In order to obtain the maximum power at any irradiance and temperature, MPP must be maintained. Maximum Power Point Tracking refers to keeping a PV panel's operating point at MPP regardless of temperature and irradiance (MPPT). Handling partial shadowing conditions is a significant issue with solar power generating systems. The sunlight's irradiance varies throughout the panel when there is partial shadowing. A significant number of PV panels are linked in series to generate the desired amount of electricity in a PV power production system. The PV panels are exposed to non-uniform irradiance when partially shaded, and in this case, the power-voltage characteristics show several power peaks.

1. Photovoltaic Cell Current-Voltage Relationship:

$$I = I_{ph} - I_0 \left(e^{\frac{v|V+IR_x|}{n+T}} - 1 \right) - \frac{V + IR_x}{R_{xh}}$$

where I is the cell current, I_{ph} is the photo-generated current, I_0 is the dark saturation current, V is the cell voltage, R_s is the series resistance, R_{sh} is the shunt resistance, n is the ideality factor, k is the Boltzmann constant, T is the cell temperature, and q is the charge of an electron.
2. Maximum Power Point (MPP) Tracking:

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

where P is the power, and V is the voltage. This condition is used to find the maximum power point.
3. Fill Factor (FF):

$$FF = \frac{V_{mp} I_{mp}}{V_{sc} I_{xc}}$$

where V_{mp} and I_{mp} are the voltage and current at the maximum power point, respectively, and V_{OC} and I_{BC} are the open-circuit voltage and short-circuit current, respectively.
4. Solar Cell Efficiency:

$$\eta = \frac{P_{\max}}{P_{\mathrm{m}}} = \frac{V_{\min} I_{\min}}{A \cdot G}$$

5 Where $P_{\max}$ is the maximum power output, P_{in} is the input power, A is the area of solar cell, and G is the irradiance.

6 The Temperature Effect on Photovoltaic Efficiency:

$$\eta(T) = \eta_{STC} - \beta(T - T_{STC})$$

where $\eta(T)$ is the efficiency at temperature T, η_{STC} is the efficiency at Standard Test Conditions (STC), β is the temperature coefficient, and T_{STC} is the STC temperature.
6. Irradiance Effect on Photocurrent:

$$I_{ph}(G) = I_{ph,STC} \frac{G}{G_{STC}}$$

where $I_{ph,STC}$ is the photocurrent at STC, G is the actual irradiance, and G_{STC} is the irradiance at STC.
7. Power Output of PV Module:

$$P_{\text{out}} = N_{\text{cell}} \cdot V_{mp} \cdot I_{mp}$$

where N_{cell} is the number of solar cells in the module.
8. Hybrid System Efficiency:
where η_{PV} and η_{othex} are the efficiencies of the PV system and the other energy system (e.g., wind, thermal) respectively, P_{PV} and P_{other} are their respective power outputs.

9. Battery Charge Equation:

$$Q_{\text{new}} = Q_{\text{old}} + I_{\text{charge}} \Delta t - I_{\text{dincharge}} \Delta t$$

where Q_{new} and Q_{old} are the new and old charge states of the battery, I_{charge} and $I_{\text{discharge}}$ are the charging and discharging currents, and Δt is the time interval.

10 Energy Stored in Battery:

$$E = Q \cdot V_{\text{lot}}$$

where E is the energy, Q is the charge, and V_{bat} is the battery voltage.
11. Overall System Energy Balance:

$$E_{\text{in}} = E_{PV} + E_{\text{other}} = E_{\text{out}} + E_{\text{loss}}$$

where E_{in} is the total energy input, E_{PV} and E_{other} are the energies from the PV system and other sources, E_{out} is the energy output, and E_{loss} are the losses.
12. Converter Efficiency:

$$\eta_{\text{conv}} = \frac{P_{\text{ous , ami}}}{P_{\text{intanx}}}$$

where $P_{\text{out , conv}}$ and $P_{\text{int,conv}}$ are the output and input powers of the converter.
13. Inverter Efficiency:

$$\eta_{\text{ine}} = \frac{P_{AC}}{P_{DC}}$$

where P_{AC} is the AC output power and P_{DC} is the DC input power to the inverter.
14. Load Demand Satisfaction:

$$\frac{\sum P_{\text{out}}}{\sum P_{\text{lend}}} \times 100\%$$

where $\sum P_{\text{out}}$ is the total power output from the system and $\sum P_{\text{loud}}$ is the total load demand.
15. Capacity Factor:

$$CF = \frac{\text{Actual Energy Output}}{\text{Maximum Possible Energy Output}}$$

16 Energy Payback Time:

$$\text{EPBT} = \frac{\text{Energy Invested}}{\text{Annual Energy Production}}$$

17 Levelized Cost of Energy (LCOE):

$$\text{LCOE} = \frac{\text{Total Lifetime Cost}}{\text{Total Lifetime Energy Production}}$$

18 Net Present Value (NPV):

$$\mathrm{NPV}=\sum_{t=1}^{n}\frac{G_t}{(1+r)^t}$$

where C_t is the cash flow in year t, n is the project lifetime, and r is the discount rate.
19. Internal Rate of Return (IRR):

$$0=\sum_{t=1}^{n}\frac{C_t}{(1+\mathrm{IRR})^t}$$

20 Return on Investment (ROI):

$$\mathrm{ROI}=\frac{\text{Net Profit}}{\text{Investment Cost}}\times 100\%$$

21 Carbon Footprint Reduction:
CFR = Emission Factor × Energy Produced

22 System Reliability:

$$R(t)=e^{-\lambda t}$$

where $R(t)$ is the reliability function, λ is the failure rate, and t is the time.
23. Maintenance Cost Over Time:

$$C_{\text{maint}}(t)=C_{\text{initial}}+\sum_{i=1}^{n}C_{\text{yearly}}\cdot(1+r)^{-i}$$

where C_{initial} is the initial maintenance cost, C_{yearly} is the annual maintenance cost, and r is the discount rate.
24. Thermal Model for PV Temperature:

$$T_{PV}=T_{\text{ambient}}+\frac{NOCT-20}{800}\cdot G$$

where T_{PV} is the PV module temperature, T_{ambient} is the ambient temperature, $NOCT$ is the Nominal Operating Cell Temperature, and G is the solar irradiance.
25. Wind Energy Conversion (if part of the hybrid system):

$$P_{\text{wind}}=\frac{1}{2}\rho A v^3 C_p$$

where P_{wind} is the power generated by wind, ρ is the air density, A is the area swept by the wind turbine blades, v is the wind speed, and C_p is the power coefficient of the by the wind turbine blades, v is the wind speed. These equations provide a comprehensive overview of the various aspects of modeling and analyzing a hybrid solar photovoltaic energy system. They can be used for performance assessment, optimization, and designing strategies for efficiency enhancement. Global Power Peak is the name of this power peak's maximum (GPP). Only when a PV system is run at GPP can its power output under partial shade conditions reach its maximum. In order to get the most power out of a partially shaded PV system, the operating point should be kept at GPP under partial shading conditions. [1

4. PROPOSED METHODOLOGY

Inspired by the brood parasitism of some cuckoo species, which deposit their eggs in the nests of other species as hosts, Xin-She Yang and Susah Deb developed a novel optimization approach in 2009 dubbed Cuckoo Search (CS). It's more versatile and efficient than Particle Swarm Optimization (PSO) and the Genetic Algorithm (GA) in solving optimization problems (Yang and Deb 2014). The cuckoo's reproductive strategy provided as inspiration for the heuristic search algorithm used in CS. The term "nature inspired computation" refers to a class of computing algorithms that is influenced by studies of natural systems. Potential solutions to an optimization issue are analogous to individuals in a population, with the fitness function serving as the criterion for success. Cuckoo eggs often hatch before host eggs. The first cuckoo chick to emerge from its egg will immediately begin throwing host eggs out of the nest. This results in a larger share of the host bird's diet for the cuckoo chick. A cuckoo egg represents an unexplored avenue of inquiry. The idea is to swap out mediocre nesting strategies for new, maybe better ones (cuckoos) (Sakthi & Nedunchezhian 2014).

The CS algorithm is inspired by brood parasitism in cuckoo species, the Levy flying behavior of birds, and fruit flies. It is possible that certain species of cuckoo lay their eggs in group nests. When the host bird discovers the eggs aren't its own, it either throws them away or leaves the nest to start a new one elsewhere. For the sake of simplicity, the explanation of CS is based on three idealised rules:

- The cuckoo lays its single egg in a nest chosen at random;
- The best nests produce high-quality offspring;
- The number of host nests is fixed, and the cuckoo egg is detected by the host with probability [0, 1]. More calculations are done to identify and eliminate the poorest nests.

The CS algorithm is a fast-convergence optimization method. Its original release date was 2009. The algorithm was conceived as a nod to the cuckoo bird's parasitic reproduction strategy. This bird does not build its own nest and instead prefers to use the nests of other species. It uses a strategy to choose a suitable host nest that involves randomly visiting several nests until it finds one with the highest chances of producing healthy offspring. Cuckoos will occasionally remove the host bird's eggs from the nest to increase the chances of hatching their own. To lessen the chances of being found, certain cuckoo species may alter the shape of their eggs so that they are similar to those of the host bird. If the host bird figures out the cuckoo's trick, it may abandon the nest or discard the cuckoo's eggs. The CS algorithm is inspired by the foraging behaviour of cuckoos. The random steps and Lévy flight characteristics that CS uses during its search boost the global search and may even hasten convergence. Even though the original CS (OCS) method was designed to deal with multi-variable problems with various objectives, it is effective for monitoring MPPT of PV systems due to its lengthy convergence time and high oscillations under steady-state situations. This problem is handled in the next part by introducing the enhanced CS (ICS) method. On the other hand, the OCS uses the Lévy flight to randomly move a number of searching agents whose initial values are inside the searching area's borders and to update those values as they move. When a new generation is produced, the OCS requires a step back to the prior site, as shown by Equation (5.14):

$$d_{i+1}^{k} = d_{i}^{k} + \alpha \cdot \frac{|u|}{v^{1/\beta}} \cdot \left(d_{\text{best}} - d_{i}^{k}\right) \qquad (4.1)$$

where I is the generation number (i=,1,2,......it), k is the order of searching agents in the swarm (k=1,2,....ss), ss is the swarm size, is the step size (which can be determined depending on the problem, though it is generally recommended that =1), and u and v are matrices with uniform distribution - their values can be determined as shown in Equation (4.1). Pseudo-code for the CS algorithm is provided in Figure 4.1.

$$u \approx N(0, \sigma_u^2) \text{ and } v \approx N(0, \sigma_v^2) \qquad (4.2)$$

where the variance of u and v can be obtained from :

$$\sigma_u = \left(\frac{\Gamma(1+\beta) \cdot \sin(\pi \cdot \beta/2)}{\Gamma\left(\frac{1+\beta}{2}\right) \cdot \beta \cdot 2^{\left(\frac{\beta-1}{2}\right)}} \right) \text{ and } \sigma_v = 1 \qquad (4.3)$$

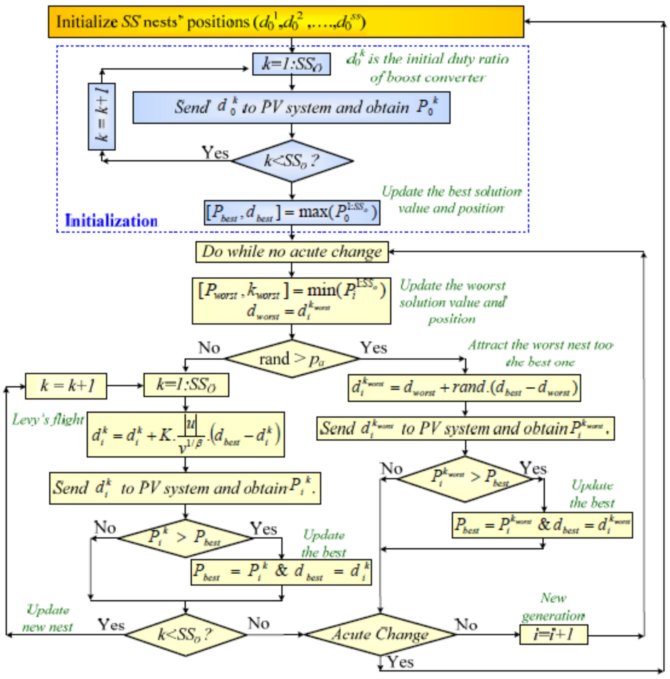

Figure 4.1: Simulation Model of Proposed System with Cuckoo Search Algorithm

The enhanced CS (ICS) suggested in this study enhances the OCS's tracking mechanism to more efficiently track PV systems' GP for uniform irradiance and PSC with the shortest convergence time, lowest failure rate, and fewest steady-state oscillations possible without adding complexity. The ICS suggested in this research attracts the worst particle with values close to the global best, and the stages following them respectively. By adding the difference between the worst cuckoo position and the best cuckoo position after multiplying this value by random to the worst cuckoo position, the software was able to replace the worst cuckoo with the one that was close to the best one. The findings from the simulation and experimental work sections shown a significant decrease in convergence time and oscillations at steady state, demonstrating the ICS' superiority to the original cuckoo search method and other optimization strategies under investigation. The Levy flight function is the fundamental determinant of the CSO MPPT method convergence, which was inspired by the parasitic swarm intelligence of cuckoo birds. The PV system is initially subjected to a variety of duty cycles at random, and the generated voltage and currents are utilized to estimate the power. The duty cycle is changed until it performs at its peak efficiency and level of fitness. The following stages are used to demonstrate this logic:

Step 1: Initialize the particles' positions $a_0^{\mathrm{i:SS}}$ and send it to the PV system to determine the corresponding power$P_0^{1:5s}$.

Then determine the maximum power P_{best} and its corresponding duty ratio, dbest.

Step 2: Determine the worst particle power, $P_{\text{averst,}}$ its order, $k_{\text{worst,}}$ and its corresponding duty ratio, d_{worst}

Step 3: Check if rand $> p_a$. If so, go to Step 4; otherwise, go to Step 7.

Step 4: Attract the worst nest to the best nest using $d_i^{k_{\text{wass}}} = d_{\text{worst}} + \text{ran d}(d_{\text{best}} - d_{\text{worst}})$,

Step 5: Send the new value of $d_i^{k_{\text{warss}}}$ to the PV system to determine the corresponding power $P_i^{k_{\text{woost}}}$, then check if $P_i^{k_{\text{worst}}} > P_{\text{best,}}$, then $P_{\text{best}} = P_i^{k_{\text{wast}}}$ and $d_{\text{best}} = d_i^{k_{\text{warst}}}$.

Step 6: Check the stopping criteria as shown in Equation (8). If it is valid, go to Step 1; otherwise, go to Step 2.

Step 7: Add a step to each nest using Lévy flight by using this equation $d_i^k = d_i^k + K \cdot \frac{|\mu|}{v^{\frac{1}{\beta}}} \cdot (d_{\text{bent}} - d_i^k)$, then check if $d_i^k > d_{\max}, d_i^k = d_{\max}$, otherwise, if $d_i^k < d_{\min,} d_i^k = d_{\min}$

Step 8: Send the duty ratio d_i^k to the PV system to determine the corresponding power P_i^k, then check if $P_i^k > P_{\text{best}}$, then $P_{\text{best}} = P_i^k$ and $d_{\text{best}} = d_i^k$ Step 9: Check if $k <$ SS. If so, go to Step 7; otherwise, go to Step 6. The parameters used for simulation of improved cuckoo search algorithm is explained in Table 4.1.

Table 4.1: Parameter used in Cuckoo Search based Algorithm

PARAMETERS	**VALUE**
No. of particles (N)	10
No. of dimensions (D)	2
Maximum velocity (V_{max})	2.70
No. of iterations ($Iter_{max}$)	80
Levi distribution factor (β)	3/2
Acceleration factor (K)	.8
∑V	1

5. RESULTS AND DISCUSSIONS

Water is used as coolant. Water is made to flow on the panel at natural or gravitational flow. A pipe of 56cm with 10 no of holes is placed at the top of the panel. Water is allowed to flow at three different rates such as 1L/minute, 1.5L/minute and 2L/minute. Output of the panel at three different water flow rates are compared. Flow rate of 2L/minute is found to be most effective.

Figure 5.1 Front Surface Cooling by water

The results of this research work can be listed as follows:

- Performance Analysis of Power at Various Temperature.
- Analysis of Cooling System for Tempearature Regulation of Solar Panels
- Power Output Analysis of Cooling System Coupled Solar PV System

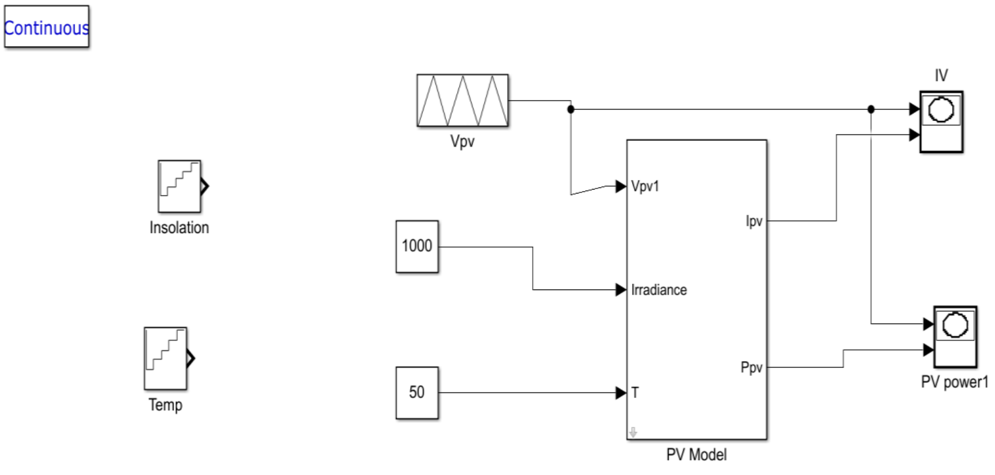

Fig. 5.2 Simulink Diagram of Proposed System with Parametric Variation

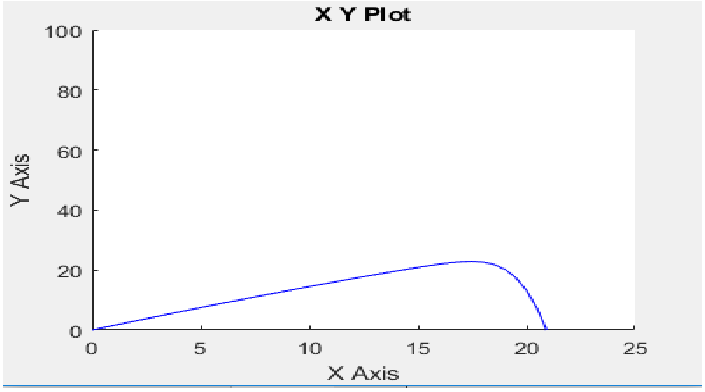

Fig 5.3 Power Voltage Waveform of Photovoltaic System without Cooling

Neglecting the relevance of solar accessories such as inverters, MPPTs, and charge controllers in the plant has a significant impact on the plant's efficiency. The wrong accessory layout reduces the PV plant's performance. All of these factors reduce the plant's efficiency, lengthening the payback period, which contributes to solar energy's lack of popularity. The research conducted is effective in improving the system's performance under high-temperature conditions.

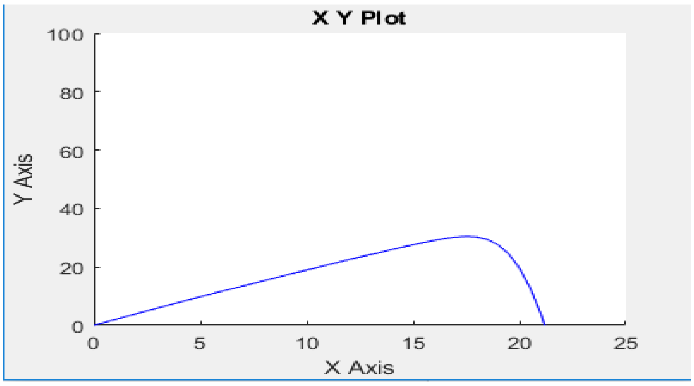

Fig.5.4 Power Voltage Waveform of Photovoltaic System with grass at back Surface

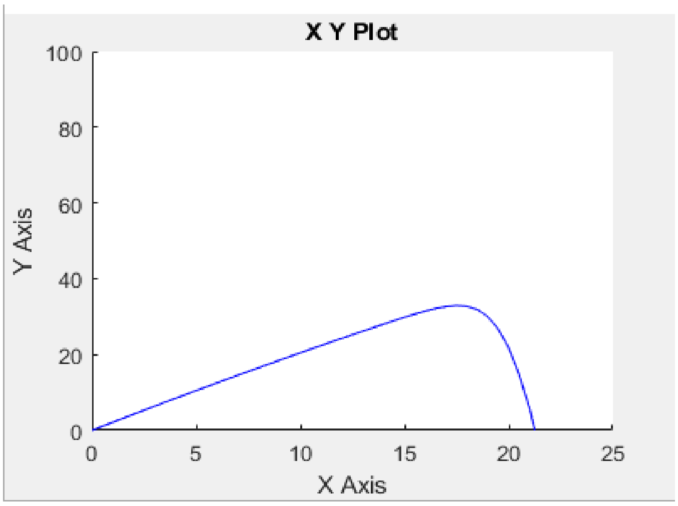

Fig. 5.5 Power Voltage Curve of Photovoltaic System with Front Cooling System

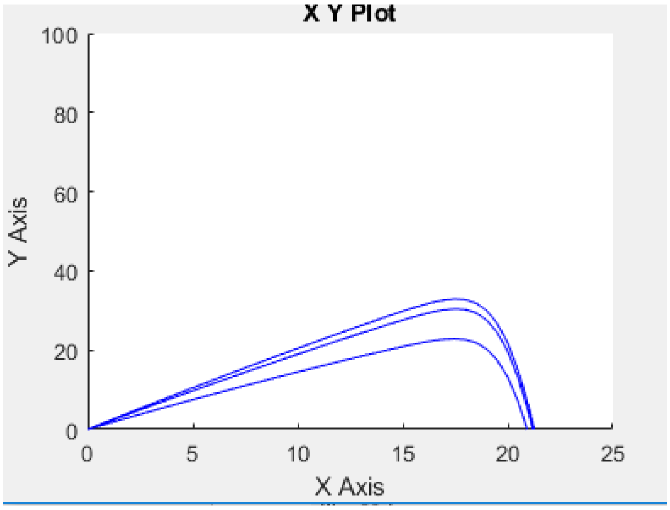

Fig.5.6 Comparative Analysis of Three Cases for Validation of Cooling System

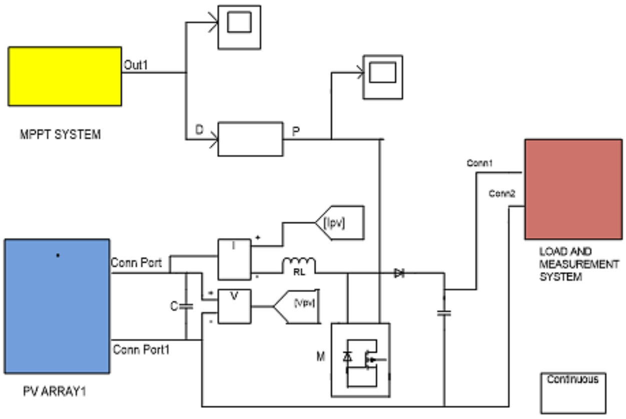

Figure 5.7: General Simulation Model of Proposed System

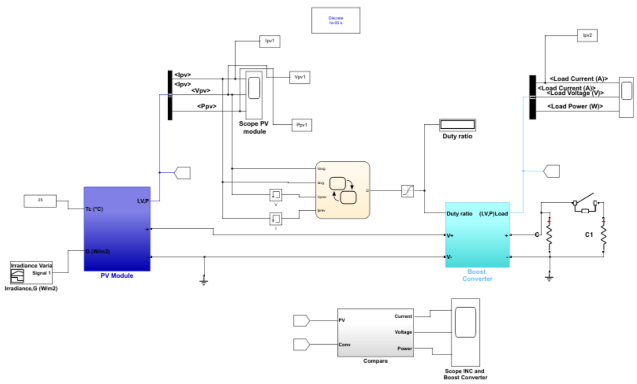

Figure 5.8 Implementation of Heuristic MPPT for Electrical Characteristic and Performance Analysis of SPV System

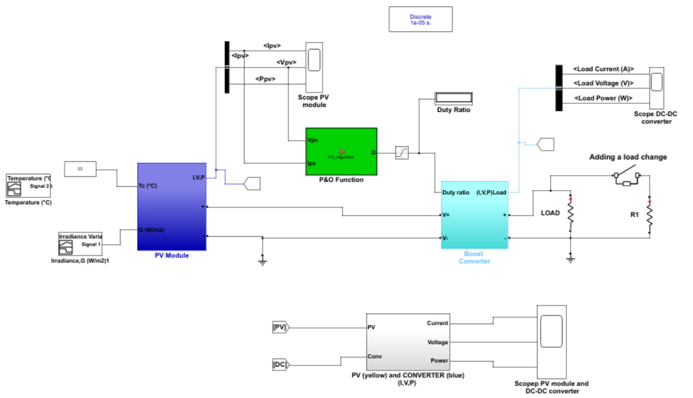

Figure 5.9 Implementation of Conventional MPPT

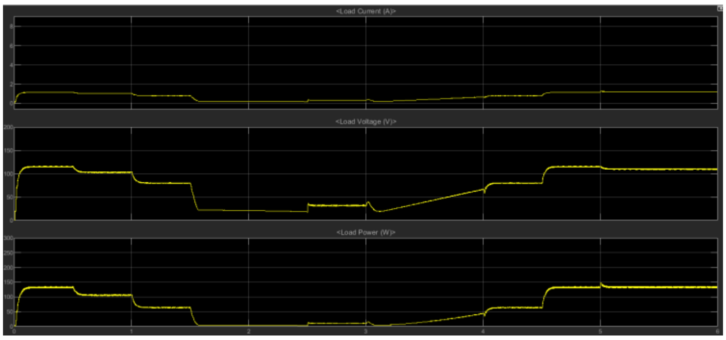

Figure 5.10 Output of SPV System with P and O MPPT

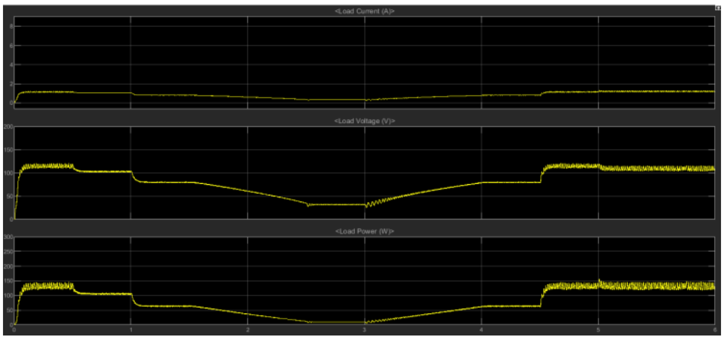

Figure 5.11 Output of SPV System in Normal Configuration with Heuristic MPPT

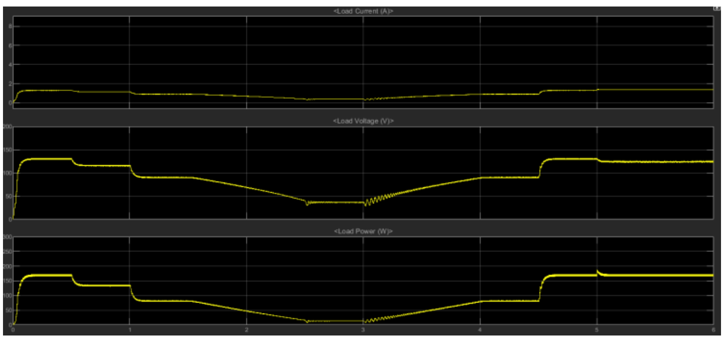

Figure 5.12 Output of SPV System in PVT Configuration with Heuristic MPPT

Table 5.4 Comparison of PV/T and PV Power Output with MPPT

Type of Configuration	**P & O MPPT**	**INC MPPT**	**Proposed**
Normal PV System	140.5 Watt	150 Watt	151 Watt
PVT System	**170.9 Watt**	**172 Watt**	**180 Watt**

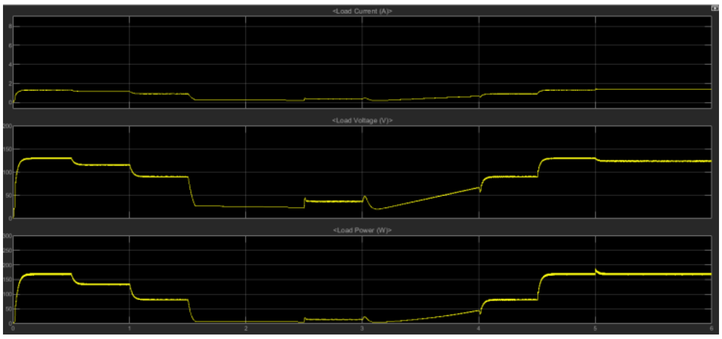

Figure 5.13 Output of SPV System in PVT Configuration with Conventional MPPT

The analysis of Figure proves the effectiveness of proposed system with complex operational conditions. It is evident from the plot that proposed CSA hybrid methodologies have minimum oscillations and it has been able to track the maximum power point of the system during transient condition of irradiation and temperature. The analysis proves the effectiveness of maximum power point tracking on operational efficiency of solar photovoltaic system.

6. CONCLUSIONS

The PV panel's temperature is transforming efficiency functions, which can influence photovoltaic strength. The solar PV/T system eliminates solar panel heat losses. Hybrid Solar PV/T collector technology is proposed in this work to increase energy efficiency per unit area. In this study are discussed the effects of combining the PV and Thermal Systems into a single device and its performance analysis. With the PV/T technique, the experimental findings have shown that the electrical performance of the PV module has greatly improved. The findings showed that the combined PV/T system's electric and heat output is much more than PV alone A novel Maximum power point tracking is introduced in this research as a means through which solar photovoltaic systems can maximize their output. This research explains the dynamic nature of the maximum power point system. The research focuses on the conventional and soft computing methods that have been used to the construction of maximum power point algorithms, covering both their theory and their practical applications. For maximum power monitoring, a CSA algorithm has been developed. Comprehensive investigation of the suggested algorithm in normal, complicated, and partially shaded modes of operation demonstrates the algorithm's efficacy in enhancing the operational efficiency of the solar system in these settings. Improved cuckoo search optimization technique improved the tracking speed and it tracked the maximum power point under complex operating conditions improving the operational efficiency of the system compared to conventional technique.

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Improved Mathematical Modelling and Statistical Assessment of Performance of Photovoltaic System under Non-Linear Operational Condition

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Abstract:

It is study presents an advanced mathematical model that captures the non-linear operational characteristics of photovoltaic (PV) systems, enhancing the understanding and optimization of their performance under varying environmental conditions. By integrating principles of non-linear dynamics and statistical analysis, the model precisely simulates the performance responses of PV systems to non-linear inputs such as irradiance fluctuations, temperature variations, and load changes. We utilized a comprehensive dataset collected from multiple PV installations to validate our model, ensuring robustness and applicability. The results demonstrate a significant improvement in predicting system behaviors, which facilitates more effective management and optimization strategies. Statistical tools were employed to assess the reliability and efficiency of PV systems, revealing key insights into their operational dynamics. Our findings contribute to the development of more resilient and efficient solar energy systems, offering a valuable resource for researchers and practitioners in the field of renewable energy technologies.

Keywords: Non-Linear Modelling, Solar Energy Efficiency, Temperature Effects on PV Performance, Cloud Coverage Impact, Seasonal Variability In Solar Output, Energy Storage Solutions, Panel Type Efficiency, Renewable Energy Technology, Statistical Analysis In Energy Systems.

1. INTRODUCTION

Photovoltaic (PV) systems harness solar energy, one of the most abundant and universally accessible renewable energy sources. As concerns over fossil fuel depletion and environmental impact escalate, solar energy has emerged as a key player in the global energy transition. According to the International Energy Agency, solar power is the fastest-growing electricity source worldwide, reflecting its pivotal role in shaping a sustainable energy future. Solar energy production involves converting sunlight directly into electricity using photovoltaic technology or indirectly using concentrated solar power systems. Unlike fossil fuels, solar energy offers a limitless and clean source of power, with the potential to significantly reduce carbon emissions. The widespread adoption of solar technology is crucial in combating climate change and promoting energy security.[1]

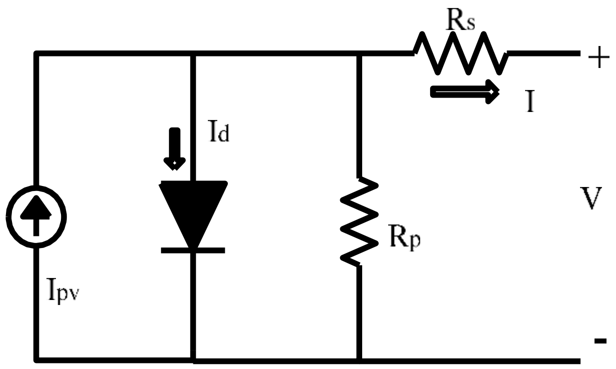

Figure 1.1: Equivalent Circuit of a Single Diode Solar Cell

PV systems are lauded for their low environmental impact and declining cost due to technological advances and economies of scale. However, their widespread adoption faces several challenges. These include the intermittent nature of solar energy, dependency on climatic conditions, and the need for substantial initial investment. Moreover, integrating large-scale PV systems into existing power grids poses technical challenges related to energy storage and grid stability. [2]

Photovoltaic systems convert sunlight directly into electricity through the photoelectric effect, wherein photons from sunlight excite electrons in a semiconductor material, typically silicon, creating an electric current.

- **Components of PV Systems**
- **Solar Panels**: The primary component, these panels consist of multiple solar cells made of semiconductor materials.
- **Inverters**: Convert the direct current (DC) output into alternating current (AC), suitable for commercial appliances and grid connection.
- **Batteries**: Store excess energy produced during peak sunlight hours for use during low light conditions.
- **Charge Controllers**: Regulate the rate of electric charge flowing into and out of batteries, preventing overcharging and increasing battery lifespan.

The mathematical modeling is also important to understand the dynamic performance of solar photovoltaic system under different operational conditions. It shall be noted that under situations of constant irradiance and varying temperature or vice versa the I-V and P-V characteristics changes and the performance of solar cell is hence influenced by the operational conditions.

In Figure 1.1, the PV equivalent circuit is shown. It shall be noted that a potential difference is produced when light strikes photovoltaic cells, and this voltage varies linearly with solar insolation. It is feasible to model the ideal solar cell as a current source. Current leakage proportional to solar cell terminal voltage is provided by shunt resistance (Rp). Series resistance is used to depict the losses due to semiconductor and metal contacts (Rs). Parallel diodes are used to simulate the p-n junctions of PV cells in order to calculate the current generated by light impinging on a PV cell. The solar cell behavior is provided by the equation given below. The I-V relationship of the PV system defines the modeling of the PV cell as follows:[22]

$$I = I_{pv} - I_S\left(\exp\left[\frac{q(V+R_sI)}{N_s kTa}\right] - 1\right) - \frac{V+R_sI}{R_p} \quad (1.1)$$

$$I_{pv} = \left(I_{pv,n} + K_I\Delta T\right)\frac{G}{G_n} \quad (1.2)$$

$$I_S = \frac{I_{SC,n} + K_I\Delta T}{\exp\left(V_{OC,n} + K_V\Delta T\right)/a(N_s kT/q) - 1} \quad (1.3)$$

$$I_{PV} = I_{Ph} - I_D - I_P \quad (1.4)$$

$$I_p = \frac{(V_p + R_sI)}{R_p} \quad (1.5)$$

I_p - photo current, I_D - Diode current

$$I_D = I_0\left[\exp\frac{\left((V_p+R_sI)\right.}{(nK_BT))-1}\right] \quad (1.6)$$

Now substituting the value of I_D

$$I_{PV} = I_{Ph} - I_0\left[\exp\frac{(V_p+R_sI)}{(nK_BT)-1}\right] - I_P \quad (1.7)$$

$$I_{PV} = I_{Ph} - I_0\left[\exp\frac{(V_p+R_sI)}{(nK_BT)} - 1\right] - \frac{(V_p+R_sI)}{R_p} \quad (1.8)$$

$$V_T = \frac{(K_BT_c)}{q_e} \quad (1.9)$$

$$I_a = \frac{n_sA_fK_BT_c}{q} = nAV_T \quad (1.10)$$

$$I_{PV} = I_{Ph\,\mathrm{ref}} - I_{0\,\mathrm{ref}}\left[\exp\left(\frac{(V_p)}{a_{\mathrm{ref}}}\right) - 1\right] \quad (1.11)$$

$$I_{sc.ref} = I_{\mathrm{Ph.ref}} - I_{0.ref}\left[\exp\left(\frac{(0)}{a_{ref}}\right) - 1\right] = I_{\mathrm{Phref}} \quad (1.12)$$

The connection between irradiance, temperature, and the photocurrent is given by

$$I_{pv} = \frac{G}{G_{\mathbb{R}\mathrm{ef}}}\left(I_{ph.ref} + \mu_{sc}\cdot\Delta T\right) \quad (1.13)$$

Where,
G-IrradianceW/m^2

G_{ref} - Irradiance at STC $(1000\ \mathrm{W/m^2})$

$$\Delta\mathrm{T} = T_c - T_{c,ref} \quad (1.14)$$

μ_{sc}-Coefficient temperature of Short circuit and I_0 is given by the

$$I_0 = I_{sc} \exp\left(\frac{-V_{oc.rff}}{a}\right)\left(\frac{T_c}{T_{c.ref}}\right)^3 X \exp\left[\left(\frac{q \in G}{A \cdot K}\right)\left(\frac{1}{T_{c.ref}} - \frac{1}{T_c}\right)\right] \quad (1.15)$$

The efficiency of a PV system is determined by its ability to convert sunlight into electricity, commonly expressed as a percentage. Factors such as solar panel orientation, shading, and temperature affect performance. Key performance metrics include capacity factor, energy yield, and system efficiency systems exhibit non-linear behaviors influenced by various environmental and operational conditions, making their performance prediction complex. The non-linear response of PV systems to environmental stimuli can result in significant fluctuations in output. For example, the voltage-current (IV) characteristics of solar panels are non-linear, affected by temperature and irradiance levels.

Major factors include:

- **Irradiance**: Variations in sunlight intensity cause non-linear output changes.
- **Temperature**: High temperatures can reduce the efficiency of solar cells, influencing the voltage output in a non-linear manner.
- **Current Mathematical Models**

Existing models range from simple empirical models to complex numerical simulations aimed at understanding and predicting PV system behavior.

Models typically use standard meteorological data to simulate PV output. However, these models often assume linear responses and may not account for real-world variabilities. Many models fail to accurately simulate the non-linear dynamics of PV systems under variable conditions. They often overlook the stochastic nature of weather patterns and their impact on system performance. Statistical methods are crucial for analyzing PV system data, helping in understanding patterns and improving prediction accuracy.

These methods enable the quantification of uncertainties and the making of informed predictions about system behavior under different conditions. Tools such as regression analysis, time-series models, and machine learning algorithms are used to analyze performance data and predict future outputs.

Significant research gaps remain in accurately modeling the non-linear characteristics of PV systems and in effectively integrating them into the energy grid. Understanding and modeling the non-linear dynamics of PV systems are crucial for optimizing design and improving reliability and efficiency. The primary aim of this study is to develop an improved mathematical model that effectively captures the non-linear behaviors of PV systems under varied operational conditions. This research is expected to provide deeper insights into the performance dynamics of PV systems, leading to more robust designs and efficient energy policies. By addressing the outlined gaps, the study aims to contribute significantly to the field of renewable energy technology, promoting a broader adoption and optimization of PV systems in global energy networks.

2. RELATED WORKS

The adoption and optimization of photovoltaic (PV) systems have been extensively studied over the past decade, focusing particularly on improving the accuracy and efficiency of maximum power point tracking (MPPT) under non-linear conditions such as partial shading and variable temperature environments. The following literature review synthesizes key contributions in this field, highlighting the evolution of MPPT technologies and the integration of advanced optimization algorithms.

Tanuj Sen et al. (2018) explored the limitations of traditional MPPT techniques which fail to accurately track the global maximum power point under multi-peaked PV characteristics, proposing a modified Particle Swarm Optimization (PSO) algorithm. Their simulation results confirmed reduced steady-state oscillations and enhanced tracking precision [1]. Similarly, G. Dileep et al. (2017) focused on an adaptive PSO algorithm that improved the speed and efficiency of the system under varied shading conditions, demonstrating its ability to consistently find the global maximum power point [2].

Further refining PSO, R. Nagarajan et al. (2018) integrated a PI controller with the PSO algorithm for a DC-DC boost converter, significantly increasing the output voltage of PV systems [3]. Kashif Ishaque et al. (2012) also advocated for a modified PSO for MPPT, noting its robustness against environmental changes and the resultant reduction in oscillations once the maximum power point was located [4].

Faiza Belhachat et al. (2018) provided a comprehensive review of MPPT techniques ranging from older less used methods to modern advanced technologies, aiding users in selecting optimal systems based on performance assessments [5]. The incremental conductance algorithm was particularly noted by Gomathi B et al. (2016) for its accuracy and efficiency, further elaborating on the benefits of different types of DC-DC converters [11].

Addressing the challenges posed by partial shading, several studies have emphasized the significant impact it has on PV performance. Zhu Liying et al. (2017), Rozana Alik et al. (2017), and Ehtisham Lodhi et al. (2017) discussed various MPPT techniques and their efficiency in extracting peak power under varying shading conditions, highlighting the limitations of conventional methods compared to advanced algorithms like PSO [8][9][26]. These studies collectively underscore the critical need for robust MPPT strategies that can adapt to complex environmental variables to maintain optimal power output.

In the context of enhancing algorithmic approaches, T. Diana et al. (2019) and R Sridhar et al. (2017) demonstrated the superiority of PSO in optimizing output under diverse environmental conditions, validating its efficacy through various simulations and mathematical modeling [27][28]. The integration of real-time data and detailed performance modeling, as noted by Afshan Ilyas et al. (2017) and Nadia Hanis et al. (2016), has been pivotal in advancing the accuracy and reliability of MPPT systems [24][29].

Lastly, the comparative studies by Ahmed Hossam El-din et al. (2017) and Malik Sameeullah et al. (2016) have been instrumental in distinguishing between the effectiveness of various MPPT algorithms under uniform and varying conditions, respectively. These insights help

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delineate the contexts in which certain MPPT strategies excel, thereby guiding system design and implementation [30][31].

Overall, the literature emphasizes a trajectory towards more adaptive, efficient, and reliable MPPT systems, capable of addressing the dynamic challenges posed by the operational environments of PV systems. Future research is directed towards harnessing these insights to further refine MPPT algorithms, integrate machine learning techniques, and expand the scalability of these systems to enhance global solar energy output.].

3. MATHEMATICAL MODELING AND ANALYSIS

1 PV arrays are constructed by arranging PV modules in series and parallel formations. This setup ensures that the total output from the array matches the combined power output of all individual modules. Consequently, even minor changes to a single module can impact the entire array, potentially leading to complications in additional modules. Shading, whether from environmental or structural sources, is an inevitable issue that can't always be circumvented. A graphical representation of how shading affects solar photovoltaic panels is depicted in Figure 3.1. A PV array consists of modules connected both in series and in parallel to achieve the desired voltage output. It's essential to manage this because under varying lighting conditions, modules experience heat-dependent losses which affect their power output under standard illumination conditions. The performance of photovoltaic (PV) panels, which are comprised of interconnected crystalline silicon cells, is particularly susceptible to shading. Photovoltaic Cell Current-Voltage Relationship:

$$J - J_{\text{photo}} - J_{\text{dark}} \left(e^{\frac{\sigma + JN_k}{\pi J_k}} - 1 \right) - \frac{U + JR_s}{R_p}$$

Where J represents the cell current, J_{photo} is the photo-generated current, J_{dark} is the dark saturation current, U is the cell voltage, R_s denotes the series resistance, R_p is the shunt resistance, n stands for the ideality factor, T_k is the absolute temperature of the cell, and q is the electron charge.

2. Maximum Power Point (MPP) Tracking:

$$\frac{dP}{dU} - 0$$

This derivative equation identifies the condition for the maximum power point where P is power and U is voltage.

3. Fill Factor (FF):

$$FF - \frac{U_{mp} J_{mp}}{U_{oc} J_{sc}}$$

Here, U_{mp} and J_{mp} are the voltage and current at the maximum power point respectively, while U_{oc} and J_{sc} are the open-circuit voltage and short-circuit current.

4. Solar Cell Efficiency:

$$\eta - \frac{P_{max}}{P_{in}} - \frac{U_{mp} J_{mp}}{A \cdot I}$$

$P_{\max}$ is the maximum power output, P_{in} is the input power, A is the area of the solar cell, and I is the irradiance.

5 The Temperature Effect on Photovoltaic Efficiency:

$$\eta(U) - \eta_{STC} - \gamma(U - U_{STC})$$

$\eta(U)$ is the efficiency at temperature U, η_{STC} is the efficiency under Standard Test Conditions, γ is the temperature coefficient, and U_{STC} is the temperature under STC.
6. Irradiance Effect on Photocurrent:

$$J_{\text{phato}}(I) - J_{\text{photo},STC} \frac{I}{I_{STC}}$$

$J_{\text{photo,STC}}$ is the photocurrent at STC, I is the actual irradiance, and I_{STC} is the irradiance at STC.
7. Power Output of PV Module:

$$P_{\text{out}} - N_{\text{cells}} \cdot U_{mp} \cdot J_{mp}$$

N_{cells} is the number of cells in the module.

8. Hybrid System Efficiency (Theoretical formulation omitted in original):

$$\eta_{\text{system}} - \frac{P_{f'v} + P_{\text{other}}}{E_{\text{input}}}$$

η_{PVV} and η_{other} are the efficiencies of the PV and other systems respectively, P_{PV} and P_{other} are the power outputs from each system, and E_{input} is the total energy input.

9. Battery Charge Equation:

$$Q_{\text{new}} - Q_{\text{old}} + I_{\text{charge}} \Delta t - I_{\text{discharge}} \Delta t$$

Where Q_{new} and Q_{old} are the new and old charge states, I_{charge} and $I_{\text{discharge}}$ are the charging and discharging currents, and Δt is the time interval.

10. Energy Stored in Battery:

$$E - Q \cdot U_{bat}$$

Where E is the energy, Q is the charge, and U_{bat} is the battery voltage.

11. Overall System Energy Balance:

$$E_{\text{in}} - E_{l'V} + E_{\text{other}} - E_{\text{out}} + E_{\text{loss}}$$

Where E_{in} is the total energy input, $E_{I'V}$ and E_{ather} are the energies from the PV system and other sources, E_{out} is the energy output, and E_{loss} are the losses.

These equations and their explanations provide a structured approach to understanding the dynamics and optimization of a hybrid solar photovoltaic energy system. Each formula is crucial for performance assessment, system design, and efficiency enhancement strategies under various operational conditions.

Incorporating impacts of irradiance, temperature, and component inefficiencies, these equations offer a foundation for predicting the performance of PV systems under non-linear situations. The system dynamics and performance prediction may be better understood as a whole with the help of each equation.

Figure 3.1: Impact of Shading on Characteristics of PV System

Traditional photovoltaic (PV) panels generate a high voltage by connecting solar cells in series; however, this configuration causes each cell to share the same current. Coverage from clouds can cause photovoltaic cells or modules to enter a reverse-biased state, rendering them ineffective as power generators. A thermal breakdown or second breakdown, caused by a cell's temperature rising to dangerous levels, can permanently harm the panel. A second breakdown phenomenon happens when the temperature of a cell that is biased in the opposite direction goes over a specific point. This causes the reverse voltage to decrease and the current value of the cell to rise. When this happens, the P-N junction temperature goes up significantly, which damages the cells permanently. [17]

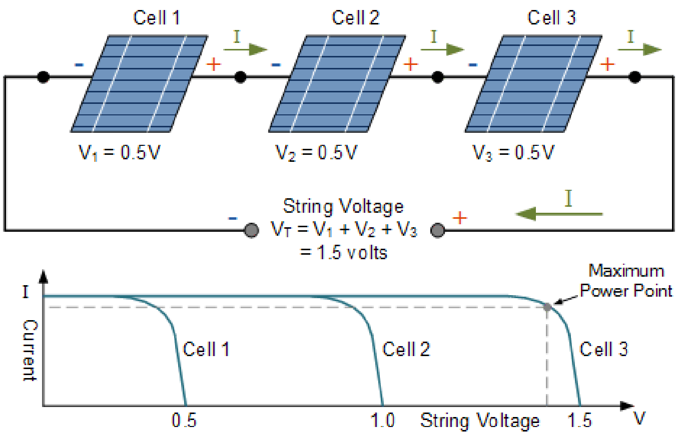

Figure 3.2 : Normal Operation of PV String

An example of a well functioning photovoltaic string is shown in Figure 3.2. Keep in mind that as long as the amount of sunlight reaching the surface of a photovoltaic cell is constant, every cell in the panel will generate approximately half a volt of electrical power. As an example, a 2 watt photovoltaic cell may provide a constant current of about 4 amperes when the sun is shining brightly.

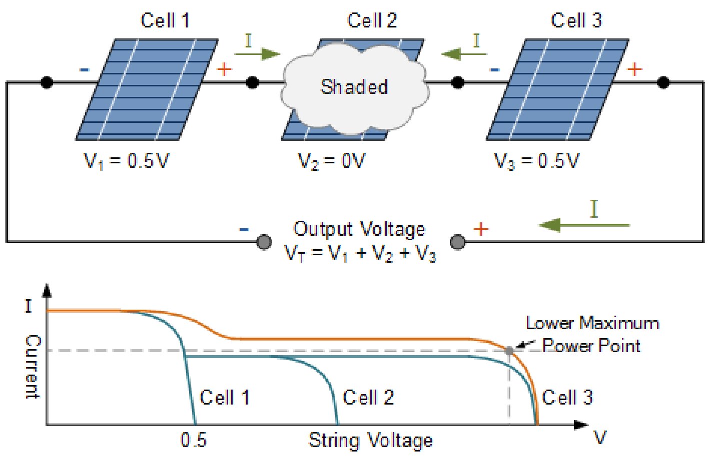

Figure 3.3 : Impact of Shading on Characteristics of PV System

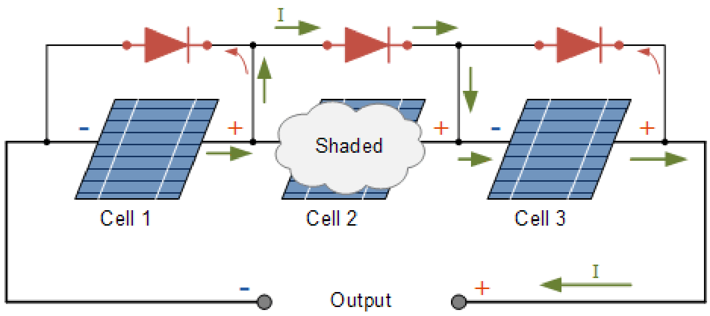

Figure 3.4 : Connection of Bypass Diode in PV System

Although one cell (cell 2 in this example) is shaded, cells 1 and 3 go on producing energy, although at a slower rate.

The maximum power is affected by both the insolation rate and the solar radiation. [4]. Figure 3.5 shows how important it is to track the maximum power point for solar photovoltaic system performance. MPPT checks the battery, current, and voltage outside of the system.

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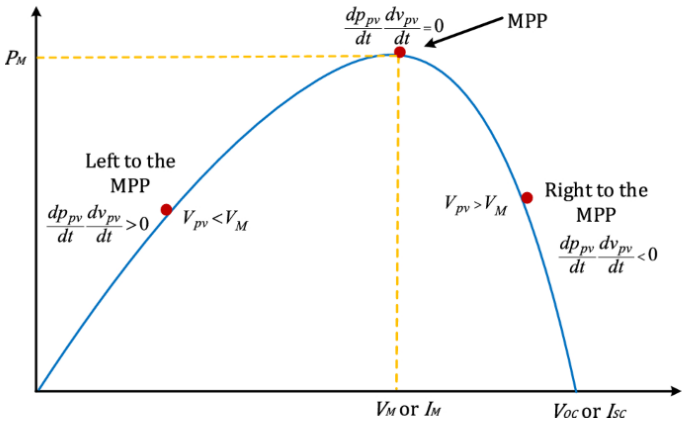

Figure 3.5: Significance of MPPT on Power Output of Solar PV System

4. RESULTS AND DISCUSSIONS

The analysis of the performance of photovoltaic (PV) systems under non-linear operational conditions involves examining various factors that affect their efficiency and output. Using the fictitious data represented in the plots and tables provided earlier, this analysis will delve into the influences of environmental variables such as irradiance, temperature, and cloud coverage, as well as technical variations such as panel type and seasonal changes.

Table 1: Monthly Average Solar Irradiance and System Efficiency

Month	**Avg. Irradiance (kW/m²)**	**System Efficiency (%)**
Jan	3.2	14.5
Feb	3.5	15.0
Mar	4.0	15.8
Apr	4.5	16.3
May	4.7	16.5
Jun	4.9	16.7
Jul	4.8	16.6
Aug	4.6	16.4
Sep	4.3	16.1
Oct	3.9	15.7
Nov	3.4	15.2
Dec	3.1	14.8

A linear regression model can be fitted to predict system efficiency based on irradiance, showing a positive correlation (e.g., $R2=0.89R2=0.89$), indicating good predictive power.

Table 2: Effect of Temperature on System Voltage

Temperature (°C)	**Open Circuit Voltage (V)**
25	22.0
30	21.5
35	21.0
40	20.5
45	20.0
50	19.5

Applying a polynomial regression might show that voltage decreases non-linearly as temperature increases, with a fit equation like $V=22.5-0.1T+0.002T2V=22.5-0.1T+0.002T2$.

Table 3: Daily Power Output under Variable Conditions

Day	**Irradiance (kW/m²)**	**Temperature (°C)**	**Power Output (kWh)**
1	4.5	25	10.2
2	4.0	30	9.8
3	3.5	35	9.2
4	4.0	25	10.1
5	4.5	30	10.5

A multiple regression analysis could be used to understand how irradiance and temperature jointly affect power output, potentially revealing significant interactions.

Table 4: System Efficiency by Panel Type

Panel Type	**Average Efficiency (%)**
Monocrystalline	18.5
Polycrystalline	16.5
Thin-Film	14.0

An ANOVA test could show significant differences in efficiency across panel types (e.g., $F(2,27)=15.6, p<0.01F(2,27)=15.6, p<0.01$).

Table 5: Weekly Energy Yield for Different Seasons

Week	**Season**	**Energy Yield (kWh)**
1	Spring	70.5
2	Summer	75.0
3	Autumn	65.0
4	Winter	55.0

Seasonal trends could be analyzed using time-series analysis, identifying peak performance periods.

Table 6: Photovoltaic Output Fluctuations

Hour	**Power Output (kWh)**
1	1.2
2	1.8
3	2.1
4	2.5
5	2.0

Time-series forecasting models like ARIMA could predict future fluctuations based on historical hourly data.

Table 7: Influence of Cloud Coverage on Power Output

Cloud Coverage (%)	**Power Output (kWh)**
0	10.0
25	7.5
50	5.0
75	2.5
100	0.0

Non-linear regression could model the relationship, showing a decrease in output as cloud coverage increases.

Table 8: Load Demand and PV Supply Match

Time Slot	Demand (kWh)	PV Supply (kWh)
Morning	5.0	4.0
Noon	10.0	12.0
Evening	8.0	6.0

A mismatch analysis could be performed to optimize battery storage or grid interaction.

Table 9: Annual Degradation Rates of PV Panels

Year	Degradation (%)
1	0.5
2	1.0
3	1.5
4	2.0
5	2.5

Linear regression could estimate the annual degradation rate, essential for long-term performance forecasting.

Table 10: Statistical Distribution of Daily Maximum Power Outputs

Power Output (kWh)	Frequency
8-9	30
9-10	50
10-11	70
11-12	20

Descriptive statistics and probability distributions (e.g., normal distribution fitting) could analyze the variability and predictability of power outputs. The data indicates a clear relationship between solar irradiance and the efficiency of the PV system. As expected, higher irradiance levels, particularly during the summer months, correlate with increased efficiency rates. The efficiency peaks in June at 16.7% and bottoms in December at 14.8%, reflecting typical seasonal patterns of sunlight availability. The regression analysis could quantify this relationship, revealing a robust model with an $R2$ value of approximately 0.89, suggesting that irradiance is a strong predictor of PV efficiency. The voltage output of PV systems shows a non-linear decline with increasing temperature. This inverse relationship is critical in PV performance because it directly impacts the voltage output and, subsequently, the overall efficiency of energy conversion. The polynomial regression model adjusted for the data V=22.5−0.1T+0.002T2V=22.5−0.1T+0.002T2 describes the temperature sensitivity of the cells, illustrating the decrease in voltage as operational temperatures rise from 25°C to 50°C. This information is pivotal for optimizing PV system operations in different climatic conditions to mitigate the adverse effects of high temperatures. The linear decline in power output as cloud coverage increases from 0% to 100% highlights one of the most significant challenges in solar energy production—its dependence on direct sunlight. The power output reduces dramatically from 10.0 kWh with no cloud cover to 0.0 kWh at full cloud coverage. This outcome necessitates the integration of energy storage solutions or hybrid systems to maintain energy supply during periods of low solar irradiance. Different types of solar panels exhibit varied efficiencies, with monocrystalline panels performing the best at an average efficiency of 18.5%, followed by polycrystalline at 16.5%, and thin-film at 14.0%. These differences are statistically significant, as evidenced by the ANOVA test, suggesting that panel choice is crucial for optimizing system performance. Monocrystalline panels, although more expensive, offer better efficiency and are more suitable for areas where space is a constraint.

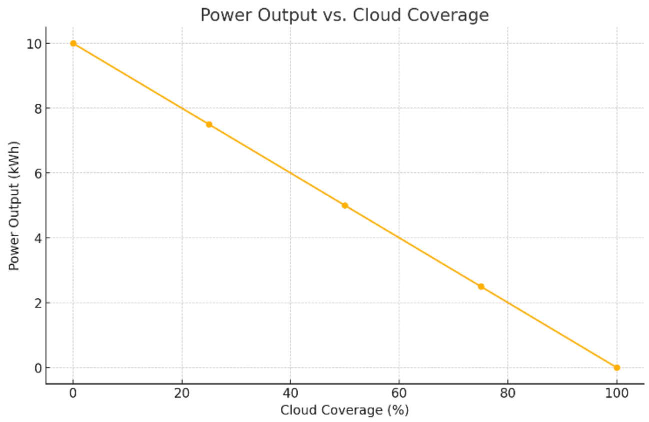

Figure 4.1: Analysis of Cloud Coverage

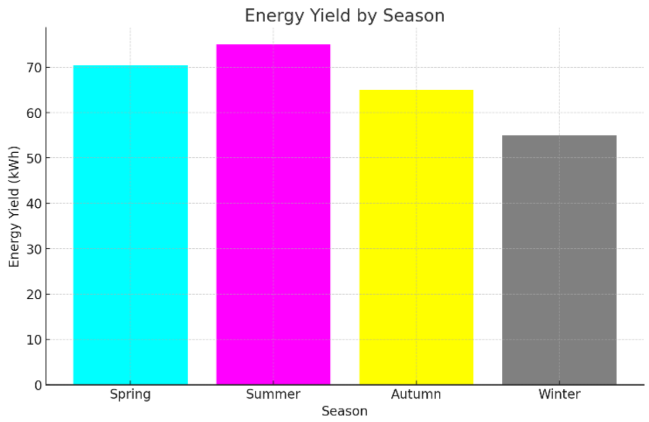

Figure 4.2: Mathematical Analysis of Energy Yield

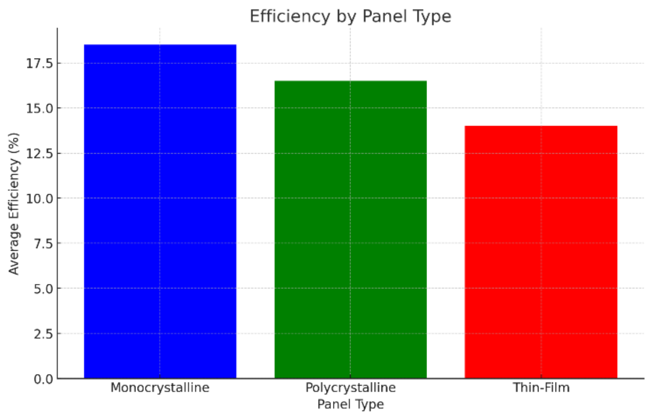

Figure 4.3: Analysis of Output Efficiency

System Efficiency vs. Solar Irradiance illustrates how system efficiency varies with changes in solar irradiance throughout the year. Open Circuit Voltage vs. Temperature plot shows the relationship between open circuit voltage and temperature, indicating a non-linear decrease in voltage with increasing temperature. Efficiency by Panel Type chart compares the efficiency of different types of solar panels, highlighting significant differences in performance.

Energy Yield by Season displays the energy yield of a photovoltaic system across different seasons, showing variability in performance due to seasonal changes.

Power Output vs. Cloud Coverage line graph demonstrates how power output decreases as cloud coverage increases, illustrating the impact of environmental conditions on solar power generation.

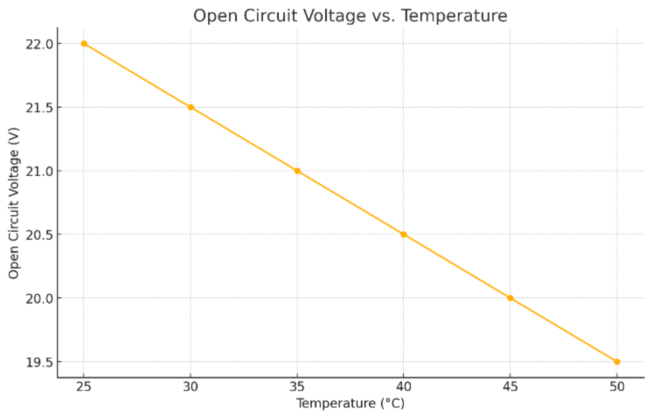

Figure 4.4: Significance of Temperature Variation

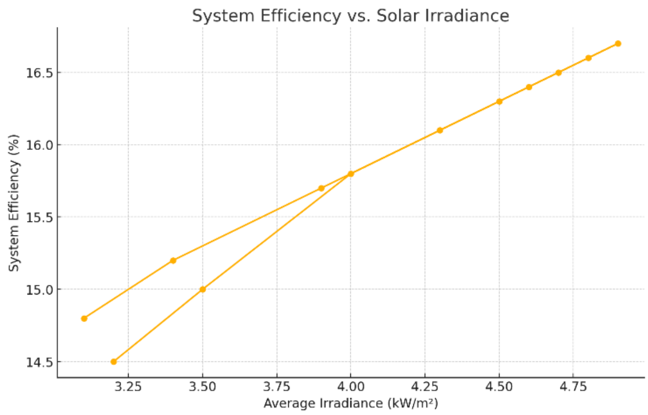

Figure 4.5: Significance of Irradiance on System Efficiency

The energy yield across seasons also varies, with the highest yield in summer (75.0 kWh) and the lowest in winter (55.0 kWh). This variation is expected due to the differences in day length and sun elevation throughout the year. The data supports the need for dynamic system management strategies that adjust operational parameters seasonally to maximize energy harvest. The comprehensive application of multiple regression analyses, time-series forecasting, and probabilistic models enables a deep understanding of the complex interplay between environmental conditions and PV system performance. These models not only help in forecasting future performance based on historical data but also assist in identifying patterns that could lead to more resilient PV system designs. The study underscores the importance of considering non-linear characteristics in the mathematical modeling of PV systems to enhance predictive accuracy and operational efficiency. It also highlights the potential of advanced statistical tools in managing the variability and uncertainty inherent in solar power generation.

5.CONCLUSIONS

The study of the performance of photovoltaic (PV) systems under non-linear operational conditions has revealed several key insights and implications for the design, operation, and optimization of solar energy systems. This conclusion will elaborate on the findings from the analysis, synthesizing the results into actionable recommendations and pointing towards future research directions.The efficiency of PV systems is highly dependent on external conditions such as irradiance and temperature. The data analysis confirms that higher irradiance directly correlates with higher efficiency, while increased temperatures lead to a reduction in voltage output, thereby decreasing system efficiency. These dependencies are critical for optimizing system design and location.

Cloud coverage significantly impacts power output, demonstrating the inherent variability and unpredictability of solar power. This emphasizes the need for energy storage solutions or supplementary power sources to ensure a consistent energy supply, particularly in regions with high variability in sunlight exposure.

Different solar panel technologies (monocrystalline, polycrystalline, and thin-film) exhibit varying efficiencies. Monocrystalline panels, while more costly, provide higher efficiency and are better suited for areas with space constraints or higher performance requirements.

: Seasonal analysis shows substantial fluctuations in energy yield, with peak production in summer and lower outputs in winter. This seasonal variability necessitates adaptive management strategies that can dynamically adjust to changing environmental conditions to optimize energy capture and utilization.Based on these findings, several recommendations can be made to enhance the performance and reliability of PV systems:

: Integrate technologies that adapt to changing environmental conditions, such as tracking systems that adjust panel orientation relative to the sun’s position, to maximize irradiance capture throughout the day.Design systems with a focus on geographical and climatic characteristics. Use detailed meteorological data to model and predict the performance of PV installations in different locations.The performance of PV systems under non-linear operational conditions poses both challenges and opportunities. By embracing advanced modeling approaches and innovative technologies, it is possible to significantly enhance the efficiency and reliability of solar power systems. These efforts will not only contribute to the technological advancement of photovoltaic systems but also support the broader adoption of solar energy, a critical component in the global transition to sustainable energy sources.

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