Power System Frequency Stability Simulation for Solar Power System using MATLAB.

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APPROVAL

The project titled “Power System Frequency Stability Simulation for Solar Power System using MATLAB” submitted by to the Department of Electrical and Electronics Engineering has been accepted as satisfactory for the partial fulfillment of the requirements for the degree of Bachelor of Science in Electrical and Electronics Engineering and approved as to its style and contents.

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DECLARATION

We, hereby, declare that the work presented in this report is the outcome of the investigation performed by us under the supervision of **Mohammad Ali sir, Lecturer** Department of Electrical and Electronics Engineering, **Uttara university**, Bangladesh on **14 January 2026**. We reaffirm that no part of this project has been or is being submitted elsewhere for the award of any degree or diploma.

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ABSTRACT

With the increasing penetration of renewable energy sources, particularly solar photovoltaic (PV) systems, maintaining power system frequency stability has become a major technical challenge. Conventional power systems rely on synchronous generators that inherently provide rotational inertia, which helps stabilize system frequency during load disturbances. However, solar PV systems are connected to the grid through power electronic inverters and do not naturally contribute inertia, making the system more vulnerable to frequency deviations. This thesis investigates the frequency stability performance of a power system with integrated solar PV generation using MATLAB/Simulink. Mathematical modelling of the power system, solar PV system, inverter control, and frequency response dynamics is developed. Various load disturbance scenarios are simulated to analyze frequency deviation, frequency nadir, and rate of change of frequency (RoCoF). The simulation results demonstrate that high solar penetration significantly affects frequency stability. Furthermore, improvement techniques such as droop control and virtual inertia are discussed. The findings of this research provide valuable insights into maintaining frequency stability in modern renewable-dominated power systems.

ACKNOWLEDGEMENT

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This thesis gratefully acknowledges the importance of the solar power system as a clean, renewable, and sustainable energy source. Solar energy plays a significant role in reducing environmental pollution, enhancing energy security, and supporting modern power systems.

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CHAPTER 1
INTRODUCTION:

1.1 Background of Power System Frequency Stability

Frequency stability becomes crucial when supply fails to match demand across the grid. In Bangladesh, like many regions, grids target a standard rate - usually 50 cycles per second. Sudden shifts, whether from equipment loss, spikes in consumption, or variable solar and wind output, challenge consistent operation. When production lags behind usage - or exceeds it - the rhythm of the network begins to drift. Maintaining balance ensures that the flow stays close to its intended pace.

Inertia once came easily - big spinning turbines in coal, gas, hydro, or nuclear stations kept voltage steady through physical momentum. Now, sunlight feeds more electricity into grids via solar panels that lack moving parts. Because these inverters respond instantly, they do not slow sudden shifts like traditional machines did. As a result, networks feel disturbances faster than before.

Fig 1.1: solar system connected

1.2 Impact of Solar Power Integration on Frequency Stability

Solar PV systems are typically connected to the grid through power electronic inverters rather than synchronous machines. While solar energy offers environmental and economic benefits, inverter-based generation does not inherently provide rotational inertia. As a result, high penetration of solar PV can cause:

i. Increased frequency deviations
ii. Faster Rate of Change of Frequency (RoCoF)
iii. Lower frequency nadir after disturbances
iv. Reduced system stability margin

These challenges make frequency stability analysis essential for modern power systems with high solar penetration.

1.3 Problem Statement

The rapid growth of grid-connected solar PV systems has introduced new challenges in maintaining power system frequency stability. Conventional frequency control methods are not fully effective for inverter-based generation systems. Without proper control strategies, high solar penetration can lead to unacceptable frequency deviations and even system collapse. Therefore, it is necessary to analyze and understand the frequency stability behaviour of power systems with integrated solar PV using accurate simulation tools.

1.4 Solar PV and Power System Challenges

High penetration of solar PV introduces challenges such as reduced system inertia, increased frequency fluctuations, power variability due to weather conditions, and greater reliance on inverter-based control for maintaining grid stability.

Solar PV introduces unique technical challenges:

Challenge	Description
Variability	Cloud movement causes rapid power fluctuations
Zero inertia	Inverter-based systems do not support frequency stabilization
Reverse power flow	Excess solar at distribution level flows backward
Reduced fault current	Impacts protection coordination
Power quality issues	Causes sags, swells, flicker

Table 1: Solar PV introduces unique technical challenges

These challenges make frequency control more complicated than in traditional systems.

1.5 Power System Stability Overview

Power system stability refers to the ability of an electric power system to maintain a state of operating equilibrium under normal conditions and to regain an acceptable operating condition after being subjected to a disturbance. Disturbances may include sudden changes in load, generator outages, transmission line faults, or fluctuations in renewable energy sources. A stable power system ensures continuous supply of electricity with acceptable voltage and frequency levels, thereby maintaining system reliability and security.

Power system stability is broadly classified into rotor angle stability, voltage stability, and frequency stability, each associated with different system dynamics and time scales. Rotor angle stability concerns the synchronous operation of generators following large or small disturbances. Voltage stability relates to the system's ability to maintain acceptable voltage levels under changing load and generation conditions. Frequency stability focuses on maintaining system frequency within permissible limits after an imbalance between generation and load.

With increasing integration of renewable energy sources such as solar PV and wind, the dynamic behavior of power systems has changed significantly due to reduced inertia and increased reliance on power electronic interfaces. As a result, maintaining power system stability has become more challenging and requires advanced control strategies, accurate modeling, and coordinated operation of conventional and renewable resources.

classified into:

i. Rotor angle stability
ii. Voltage stability
iii. Frequency stability

Rotor angle stability mainly concerns synchronous generators, while voltage stability focuses on maintaining acceptable voltage levels. Frequency stability, which is the focus of this thesis, refers to the system's ability to maintain nominal frequency following large disturbances such as sudden load changes or generation loss.

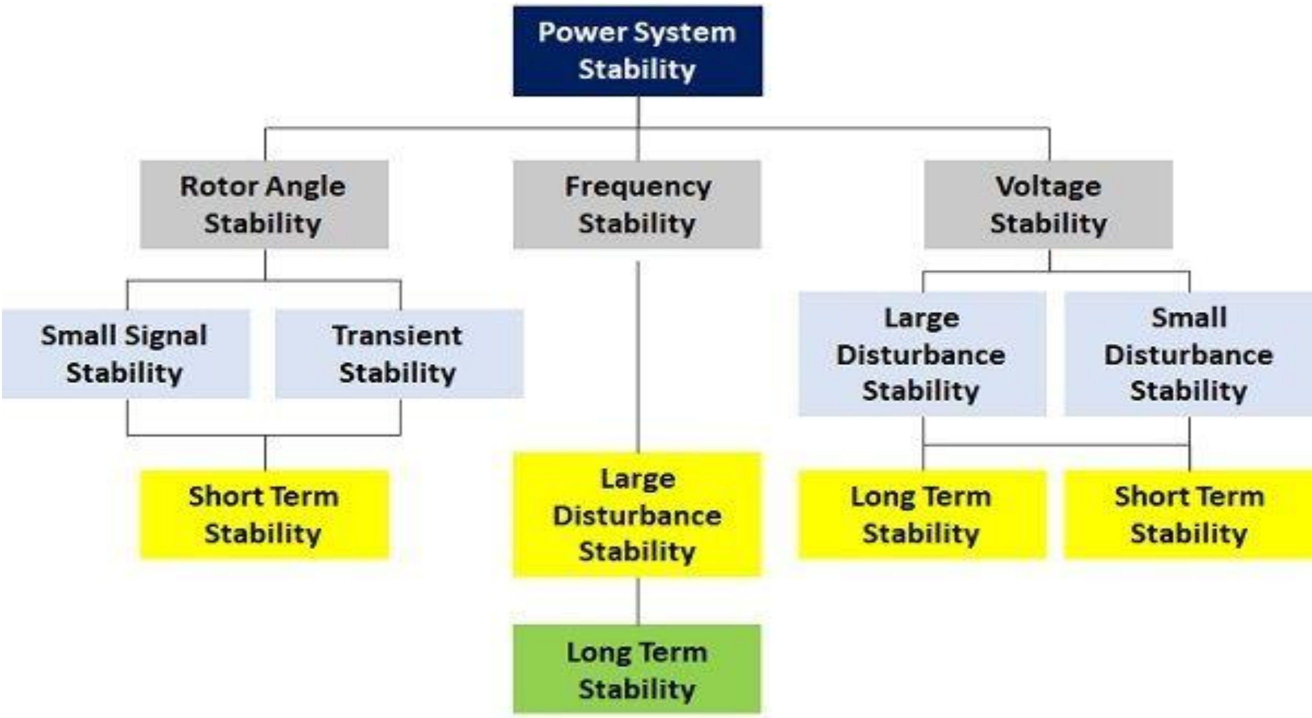

Fig 1.2: Classification of stability

1.6 Motivation of the Study

This research is motivated by:

i. The rapid growth of solar energy in Bangladesh and globally.
ii. Increasing need for frequency stability analysis.
iii. Lack of detailed local research on inverter-based power system stability.
iv. Need for new frequency control strategies such as:
v. Virtual inertia.
vi. Fast frequency response (FFR).
vii. Improved inverter control.

1.7 Methodology Overview

Although we are not using MATLAB code here, the thesis follows a standard methodology:

i. Literature Review
ii. Study existing research on frequency stability.
iii. Review behavior of inverter-based solar systems.
iv. Model Development (Conceptual)
v. Represent a typical power system with solar PV.
vi. Identify load, grid, and inverter characteristics.
vii. Frequency Stability Analysis

viii. Evaluate inertia reduction.
ix. Analyze frequency deviations from disturbances.
x. Result Discussion (Conceptual)
xi. Compare low-inertia vs high-inertia conditions.
xii. Recommendations
xiii. Possible solutions like synthetic inertia, improved control loops, storage system

1.8 Objectives of the Thesis

One focus here involves examining how often frequency remains stable within electrical networks that include large amounts of solar energy production. A separate direction looks at ways to manage fluctuations through different regulation methods. Mathematical representations, built inside MATLAB/Simulink, serve as tools for replicating grid conditions involving photovoltaics. Under shifts caused by demand changes or inconsistent supply, behavior patterns emerge worth exploring. As spinning mass decreases across the network, consequences appear in delayed stabilization. Techniques mimicking rotational inertia and those adjusting output based on speed differences undergo testing. Performance comparisons arise when these controls exist versus when they do not. Measures like maximum swing in frequency, its acceleration, and duration until steady state offer clarity. Insight grows regarding dependable operation where traditional mechanical momentum fades.

1.9 Scope of the Work

The scope of this work is to analyze and improve the frequency stability of a power system with significant integration of solar photovoltaic (PV) generation using MATLAB/Simulink. The study involves developing mathematical and simulation models of conventional generation units, solar PV systems, loads, and disturbances to examine system frequency dynamics under various operating conditions. Frequency deviations caused by load changes and renewable power fluctuations are investigated using the swing equation–based dynamic model. Various frequency stability enhancement techniques such as virtual inertia and droop control are implemented and evaluated. The performance of the system is assessed in terms of frequency deviation, rate of change of frequency (RoCoF), and settling time. This work is limited to simulation-based analysis and aims to provide a clear understanding of frequency stability challenges and mitigation methods in solar-integrated power systems.

CHAPTER 2
LITERATURE REVIEW:

Power system frequency stability has been a fundamental research area for several decades. Kundur [1] provided a comprehensive explanation of power system stability and emphasized the role of system inertia and power imbalance in frequency dynamics. His work forms the theoretical foundation for modern frequency stability analysis.

With the increasing integration of distributed and renewable energy sources, new operational challenges have emerged. Bollen and Hassan [2] discussed the impact of distributed generation on power system operation and highlighted the reduced controllability and inertia issues associated with renewable integration. Similarly, Ackermann [4] analyzed renewable-based power systems and pointed out that converter-interfaced generation lacks inherent inertia.

The IEEE Task Force on Frequency Control [3] investigated frequency response requirements in low-inertia power systems and concluded that reduced inertia leads to higher RoCoF and deeper frequency nadirs. Their study emphasized the urgent need for fast frequency response mechanisms in renewable-dominated grids.

Several researchers have proposed control-based solutions to improve system stability. Abido [5] demonstrated the effectiveness of optimization-based control strategies for power system stabilization, while recent studies such as Yadav et al. [6] specifically focused on frequency stability challenges in renewable-dominated power systems and highlighted the importance of energy storage systems.

MATLAB/Simulink has been widely adopted as a simulation platform for power system stability studies. According to MathWorks documentation [7], Simulink-based modeling allows effective analysis of system-level frequency dynamics without requiring detailed electrical component modeling.

Based on the reviewed literature, it is evident that low inertia caused by renewable energy integration significantly affects frequency stability. Battery Energy Storage Systems (BESS) have emerged as a promising solution due to their fast response capability. However, there remains a need for simplified and clear simulation models to demonstrate frequency dynamics and BESS effectiveness, which is addressed in this study.

CHAPTER 3
FUNDAMENTALS OF SOLAR PV SYSTEM:

3.1 Introduction

Sunlight-powered cells now shape much of today's electricity networks. When fossil fuels step back, renewables move forward - solar panels lead that shift. Because they scale easily, demand little upkeep, yet cut emissions, these systems fit large plants just as well as small local setups. Their rise continues at a pace few predicted.

Frequency stability sits at the heart of this work, given that adding solar PV to major grids often brings notable technical and operational hurdles along with it.

To grasp what comes next, one must first know how solar PV systems operate at their core.

3.2 Solar Energy Basics

Fueled by daylight, solar power captures sunshine using photovoltaic panels made of silicon cells that generate direct current when exposed to light. This flow shifts into alternating current thanks to inverters before reaching household circuits. While best known for producing electricity, the technology applies just as well to warming spaces and water through thermal systems. A steady supply hinges on exposure, yet it remains one among few truly sustainable options available today.

3.2.1 Solar Radiation and Irradiance

From within the core of the Sun, electromagnetic energy moves outward into space. This flow reaches our planet as what is known as solar radiation. Measured across a defined area, its strength appears as solar irradiance. Expressed in watts per square meter, it reflects incoming power at any point. As rays advance toward Earth's surface, they pass through layers of air. Within these layers, some light gets taken in, redirected, or bounced back. What finally arrives varies widely based on when and where you observe. Time of day plays a role, just as latitude does. Seasons shift exposure levels throughout the year. Air clarity and cloud presence also influence results. Even the tilt of the receiving surface alters how much strikes it.

With sunlight intensity shaping electricity production in solar panels, its measurement becomes central to photovoltaic assessments. Instead of broad terms, distinctions appear through direct beam exposure, scattered light across flat surfaces, and total incoming radiation at ground level. Because these components influence how much energy systems generate, their behavior must

be captured precisely. When forecasting output or reviewing efficiency, small errors in estimation can shift outcomes noticeably. Even grid-level responses to changing solar inputs rely heavily on correct interpretation of these patterns.
Irradiance (W/m^2) measures the power density of sunlight falling on a surface.

Typical values:

Condition	Irradiance
Clear sunny day	800–1000 W/m^2
Cloudy	200–400 W/m^2
Very cloudy	<150 W/m^2

Table 2: Solar PV performance is heavily dependent on irradiance.

3.3 Photovoltaic Effect

Light hitting certain materials kicks electrons into motion, producing electricity directly. Such energy shifts occur inside devices called solar cells. These units rely on joined sections of specially treated matter to split apart energized particles and their gaps. Movement of these components builds up power potential across the structure. Once linked to an external pathway, flow begins steadily. The entire shift from sunlight to current takes place without mechanical steps. What emerges is steady, one-directional output ready for use.

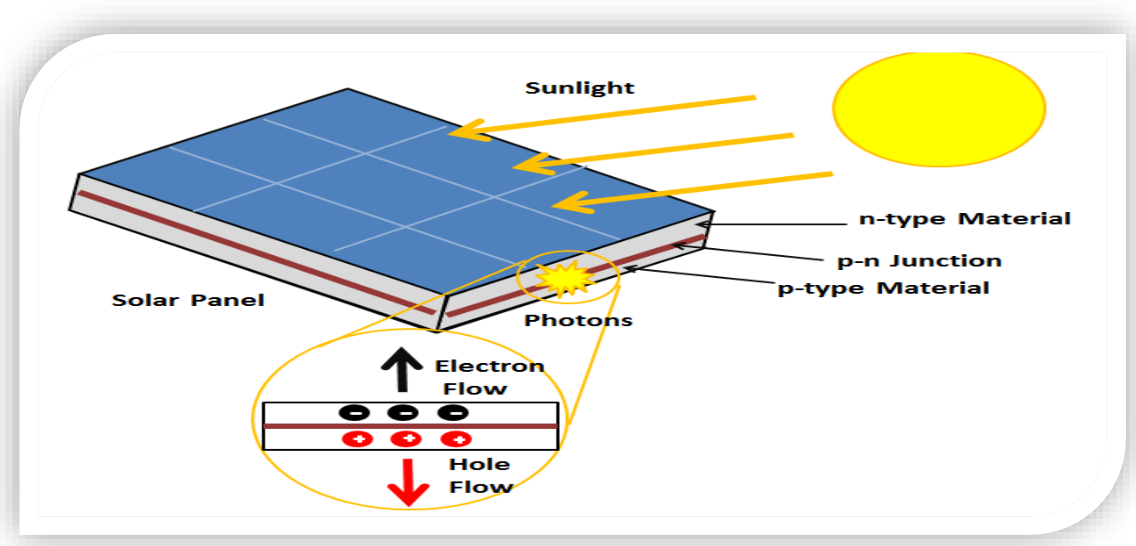

Fig 3.1: Photovoltaic effect

The photovoltaic effect is the basic principle behind solar electricity generation. When photons from sunlight strike a semiconductor material, such as silicon, their energy is absorbed and excites electrons from the valence band to the conduction band, creating electron–hole pairs. An internal electric field, formed by the p–n junction of the semiconductor, separates these charge carriers by driving electrons toward the n-type region and holes toward the p-type region. This separation prevents recombination and creates a potential difference across the junction. When an external electrical circuit is connected, the flow of electrons through the circuit produces direct current (DC) electricity.

Materials commonly used:

Materials commonly used in photovoltaic (PV) cells include silicon-based semiconductors, which dominate the commercial market due to their reliability and efficiency. Monocrystalline silicon offers high efficiency and long lifespan, while polycrystalline silicon provides a lower-cost alternative with slightly reduced efficiency. Amorphous silicon, a thin-film material, is used in applications requiring flexibility and lower material consumption. In addition to silicon, compound semiconductors such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) are widely used in thin-film PV technologies because of their good light absorption properties. Emerging materials, including perovskites, are also gaining attention due to their high efficiency potential and low manufacturing cost, although long-term stability remains a challenge.

3.4 Solar Cell Characteristics

Electrical traits of a solar cell reflect its response across varying operational settings. What matters most appears in how current shifts relative to voltage, under set sunlight and heat levels. This pattern, known as the I–V behavior, forms the foundation for extracting essential values. Among these values, one finds the current when voltage drops to zero - called short-circuit current. Voltage reaches peak value when no current flows, identified as open-circuit voltage. Power output peaks where voltage multiplied by current hits its highest level. That specific operating spot determines the greatest energy delivery possible. Performance hinges on identifying this optimal position along the curve.

A key feature lies in the power–voltage relationship, showing where peak power delivery takes place. What defines the fill factor is how much of the theoretical power limit a cell can reach, calculated using open-circuit voltage and short-circuit current. Performance shifts noticeably under changing sunlight intensity - greater light levels boost current output. Heat plays a contrasting role, often lowering both voltage output and overall effectiveness. Understanding these behaviors supports accurate simulation of photovoltaic arrays, development of control strategies for optimal operation, along with assessment of solar integration effects on grid behavior.

3.4.1 Current-Voltage (I-V) Characteristics

The I-V curve demonstrates how current and voltage vary with load.

Important points:

i. Short-circuit current (Isc): Maximum current when voltage is zero.
ii. Open-circuit voltage (Voc): Maximum voltage when current is zero.
iii. Maximum power point (MPP): Operating point with maximum output.
iv. Fill Factor (FC)

a) Short Circuit Current (I_sc):

1. Current when output terminals are shorted
2. Proportional to **solar irradiance**
3. Slightly affected by temperature

b) Open Circuit Voltage (V_oc):

1. Voltage when circuit is open.
2. Strongly dependent on cell temperature**.**
3. Decreases with temperature rise.

c) Maximum Power Point (MPP):

Point where output power is maximum

$$P_{max} = V_{mp} \times I_{mp} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 1$$

d) Fill Factor (FF):

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 2$$

1. Indicates PV cell quality.
2. Typical value: 0.7 – 0.85.

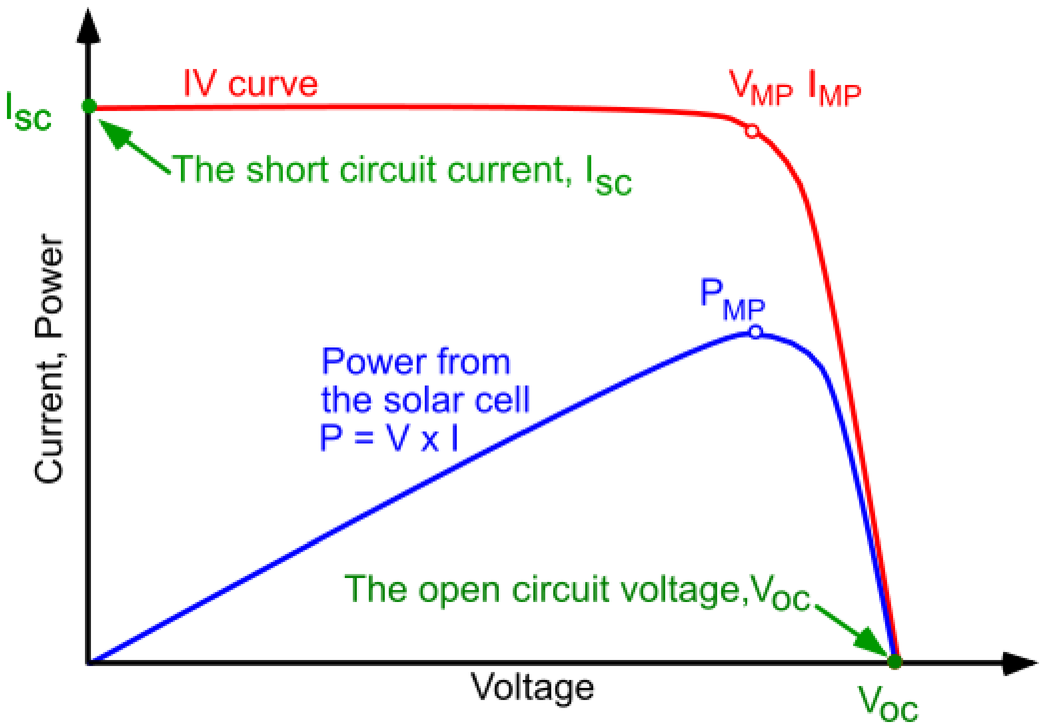

Fig 3.2: Current-voltage (i-v) characteristics

3.4.2 Mathematical Model of I–V Characteristics

Single-Diode Model

$$I = I_{ph} - I_0 \left(e^{\frac{q(V+IR_s)}{nkT}} - 1 \right) - \frac{V + IR_s}{R_{sh}} \dots\dots\dots\dots\dots\dots\dots\dots .3$$

Where:

I_{ph}= Photocurrent

I_0= Diode saturation current

R_s= Series resistance

R_{sh}= Shunt resistance

n= Ideality factor

3.4.3 Power-Voltage (P-V) Curve

The P-V curve identifies the maximum power the cell can deliver.

The MPP varies with:

i. Irradiance.

ii. Temperature.

iii. Cell degradation.

iv. Partial shading.

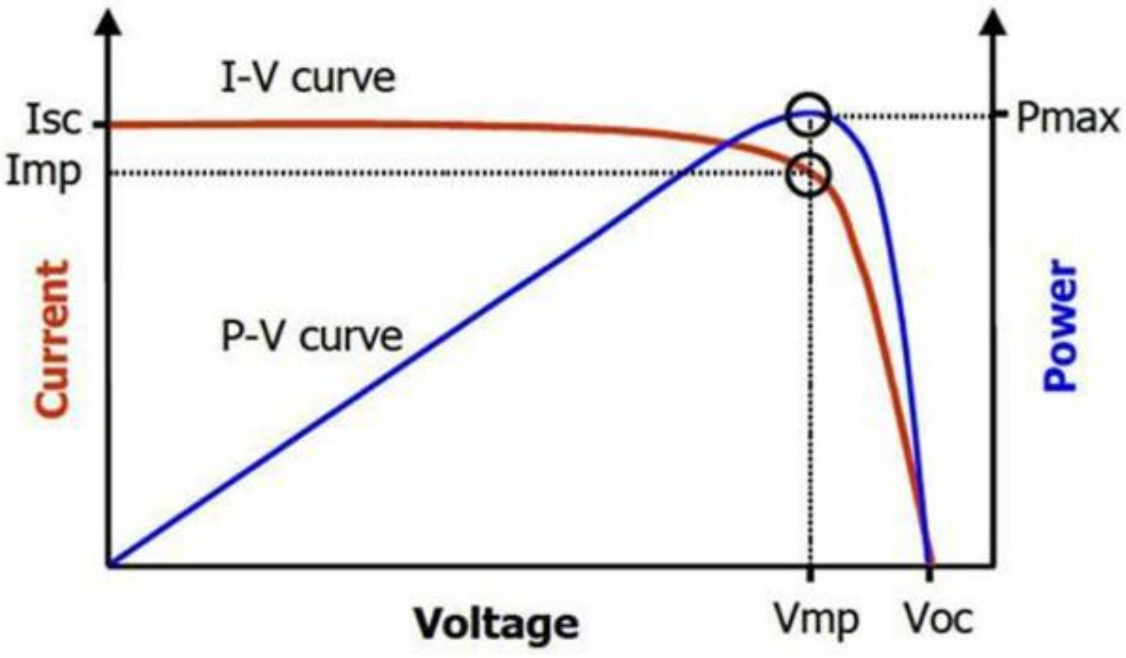

Fig 3.3: Power-voltage (p-v) curve

3.5 PV Modules, Arrays, and Strings

3.5.1 PV Module

A PV (Photovoltaic) module, commonly called a solar panel, is an assembly of interconnected solar cells that convert sunlight into direct current (DC) electricity using the photovoltaic effect, typically made of silicon cells protected by a glass front, back sheet, and aluminum frame for outdoor use. These modules are the fundamental building blocks of solar energy systems, with multiple modules forming a larger PV array for increased power generation, and are available in various types like monocrystalline or polycrystalline

Several solar cells are connected in series and/or parallel to form a module. Typical module power range: 200–450 W

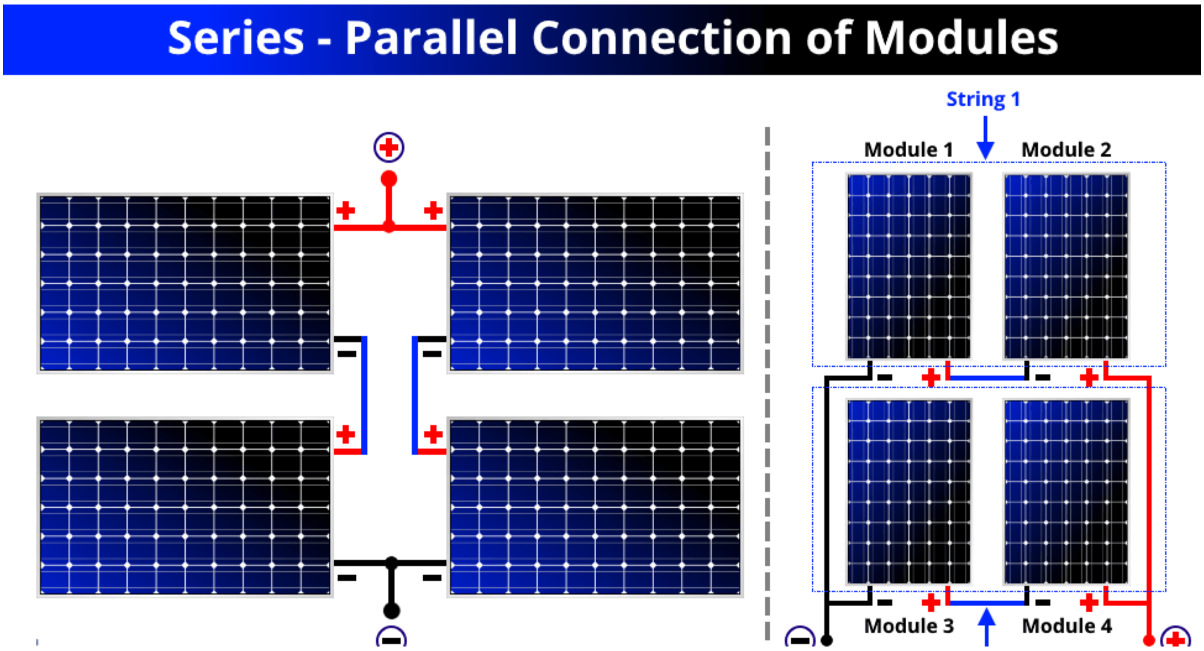

Fig3.4: Series and parallel connection module

3.5.2 PV String

A PV String is a series of solar panels (photovoltaic modules) connected in a chain (positive to negative) to increase voltage, forming a single electrical circuit for a solar system, crucial for efficient power delivery to the inverter; the number of panels is carefully sized to match the inverter's voltage limits, preventing damage and optimizing performance, often with strings combined in parallel for higher current.

Multiple modules connected in series create a string Series connection increases voltage.

3.5.3 PV Array

A PV array (Photovoltaic array) is a collection of interconnected solar panels (PV modules) wired together to generate significant solar electricity, forming a complete power-producing unit for residential, commercial, or utility-scale use, converting sunlight into DC power that is then often converted to AC by inverters for grid use. The number of panels determines the array's size and power output, allowing for scalability from small rooftop systems to vast solar farms.

A combination of several strings connected in parallel or series forms the array. Parallel connection increases current.

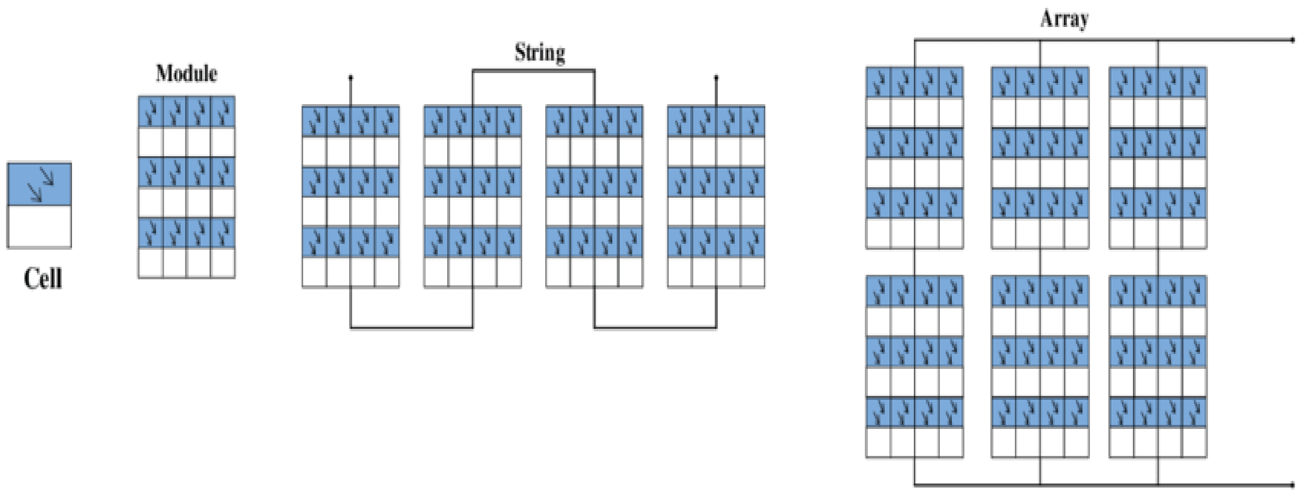

Fig 3.5: PV modules, arrays, and strings

3.6 Environmental Effects on PV Performance

When sunlight hits a solar panel, its power response depends heavily on surrounding conditions. Though electric current may rise just a bit in warmer cells, voltage drops enough to lower total output. Power levels tend to follow light intensity closely, dropping fast when clouds block the sun. Dust buildup or shadows across panels cuts production without delay. Even small changes in how much light reaches the surface can shift performance noticeably. Efficiency slips as heat builds up inside the module structure.

Especially under uneven lighting, partial shading stands out by creating mismatches that lead to energy loss, localized heating, even irregular spikes across the P–V graph - making it harder to pinpoint peak efficiency. Dust or grime buildup tends to block incoming light, a common issue where rainfall is scarce or air quality poor. Cooling gets a boost when airflow increases, helping panels stay closer to optimal operating temperatures. When moisture lingers, combined with constant sun and wet cycles, materials slowly wear down over years of exposure. Predicting how each of these elements affects output supports better planning, consistent function, along with steadier integration into electricity networks powered by photovoltaics.

3.6.1 Effect of Irradiance

Sunlight strength shapes how well a solar panel works. Measured in watts per square meter, it shows how much energy hits the panel's surface. When more light arrives, more particles of light hit the semiconductor material inside the cell. This process frees additional electrons, creating greater electric current. Power production climbs steadily because of this stronger flow. Yet voltage at zero load changes very little even under brighter sun. That response follows a slow, curved pattern rather than a straight rise. When sunlight is weak, solar panels produce less efficiently due to greater proportional losses and fewer charge carriers being created. As a result, changes in light intensity - whether from clouds, shadows, or daily cycles - affect how consistently power comes out of photovoltaic installations. This variability then impacts how smoothly electricity integrates into the network and maintains steady frequency.

3.6.2 Effect of Temperature

When sunlight hits solar cells, heat begins to build up - this warmth directly affects how well they work. Higher temperatures tend to shrink the energy gap inside semiconductors, which in turn lowers voltage output. Even though current flow sees a minor rise when it gets hotter, that gain does little to balance the sharp decline in open-circuit voltage. Because of this imbalance, total available power drops just as efficiency takes a hit. Cooler conditions reverse the trend: voltages climb back up, supporting stronger electricity production. When sunlight lasts long and surroundings get hot, solar cells heat up beyond lab-test levels, leading to clear drops in output. Because of this, keeping panels cool through smart setup and airflow matters a lot - it slows wear and supports steady performance over time.

Typical temperature coefficient: −0.3% to −0.5% per °C

3.6.3 Partial Shading

Shading on part of a photovoltaic setup happens when something - like trees, buildings, or dirt - blocks sunlight unevenly across the panels. Clouds or debris may also limit how much light reaches certain areas. Because solar cells linked in series share the same flow of current, any drop in one section pulls down performance everywhere else. If some cells receive less sun, they produce less electricity, dragging the whole chain toward weaker output. Power levels fall more sharply than expected under such conditions. The relationship between voltage and power gets messy, showing several peaks instead of one clear high point. Finding that peak becomes harder for control systems trying to maximize energy harvest. When sunlight is uneven, some solar cells heat up because they run backward, creating spots that harm the panel. Because of this issue, engineers install bypass diodes so current finds another path. Instead of letting shadows control performance, systems use smart tracking methods to keep power steady. Some layouts arrange panels differently on purpose, reducing losses when shade moves across them.

3.7 Maximum Power Point Tracking (MPPT)

PV panels operate at a single point of maximum efficiency known as the maximum power point (MPP).

MPPT is an algorithm used in PV inverters or charge controllers to track this point continuously.

Common MPPT Techniques:

i. Perturb and Observe (P&O).
ii. Incremental Conductance (INC).
iii. Fuzzy Logic Control.
iv. Neural Network Based MPPT.
v. Hill-Climbing Method.

MPPT ensures highest efficiency regardless of weather conditions.

Method	Complexity	Response Speed	Implementation
1. Perturb & Observe (P&O)	Low	Slow	Very Easy (Simple logic)
2. Incremental Conductance	Medium	Medium	Hardware/Software
3. Fuzzy Logic Control	High	Fast	Microcontroller
4. Neural Network	Very High	Very Fast	High-end Processor
5. Hill-Climbing	Low	Slow	PWM duty cycle control

Table 3: Comparison of MPPT Techniques

3.8 Solar Inverters and Their Role

A key piece of any photovoltaic setup sits quietly doing heavy lifting: the solar inverter. Instead of merely changing DC into AC, it fine-tunes performance across shifting sunlight and heat levels through intelligent tracking methods. Output stays consistent because built-in controls manage both voltage and frequency within tight boundaries. When linked to the utility network, these devices act like watchful guards - spotting irregularities such as sudden spikes or dips and stepping in when safety demands isolation. Even during normal operation, some models contribute behind the scenes by adjusting reactive flow or mimicking inertia-like responses. As more solar feeds into the mix, their quiet balancing acts grow even more significant.

3.8.1 Types of Inverters

1. String Inverters
2. Central Inverters
3. Microinverters

Feature	String Inverter	Central Inverter	Microinverter
Typical Use	Residential / Small Commercial	Utility / Solar Farms	Residential/ Complex Roofs
Shade Impact	High (affects whole string)	High	Minimal (affects 1 panel)
Monitoring	System-wide	System-wide	Panel-by-panel
Upfront Cost	Lowest	Lowest (per kW)	Highest
Lifespan	10–15 years	10–20 years	25 years

Table 4: Inverter role

3.9 Grid-Connected Solar PV System

Most sunlight gets turned into electricity using panels wired directly to the main power network. These setups rely on arrays of cells that produce direct current when exposed to daylight. To get the most out of changing light conditions, electronics adjust voltage through constant monitoring. That steady flow moves next to a device boosting efficiency before heading toward conversion. Matching the grid's rhythm matters - timing, wave height, and alignment must line up precisely. Equipment like isolators and relays guard against mismatches or sudden surges. When production exceeds local needs, surplus flows outward into the wider system. Yet when skies dim or demand spikes, the connection pulls needed support from external lines. This setup removes reliance on massive energy storage while boosting how well the whole system operates. Still, smarter inverters tied to the grid also help manage voltage, handle reactive power, and keep frequency steady - key traits when adding substantial solar PV to today's electrical networks.

A grid-connected PV system consists of:

i. PV array.
ii. DC/DC converter.
iii. MPPT unit.
iv. DC/AC inverter.
v. Transformer.
vi. Protection equipment.
vii. Grid interface

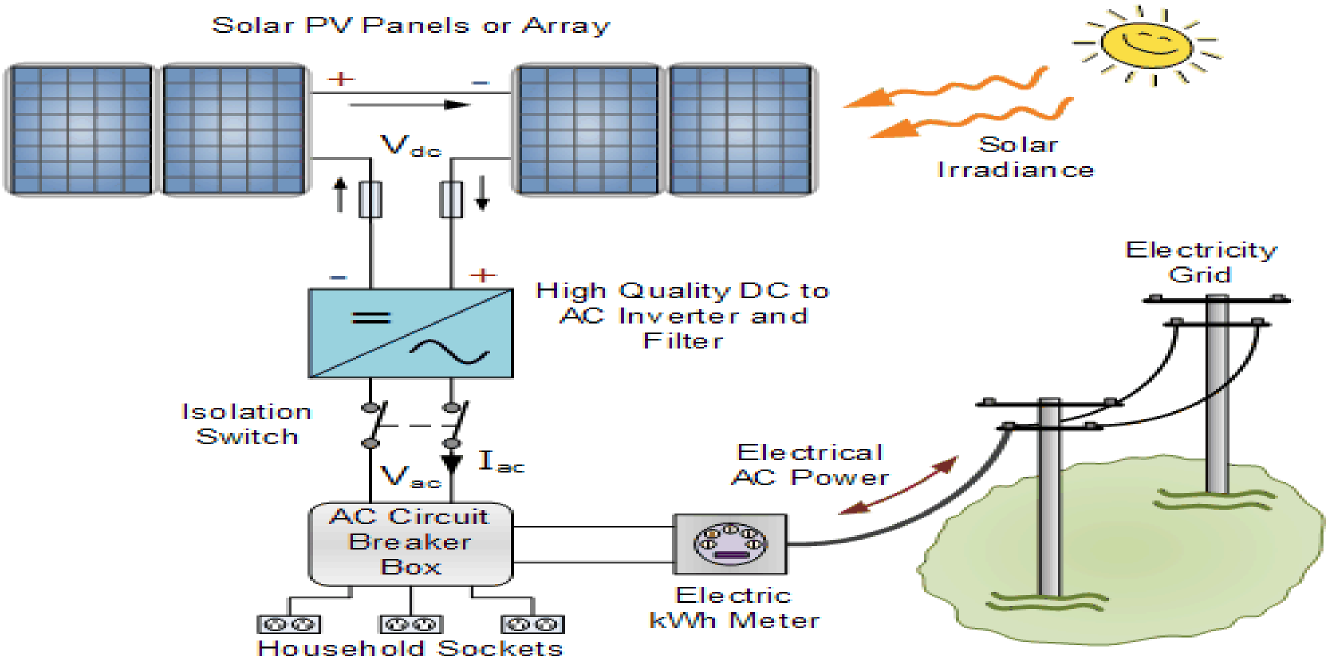

Fig 3.6: Grid-connected solar PV system

3.9.1 Working Principle

Sunlight hitting solar panels triggers a flow of electrons through the photovoltaic effect, producing direct current. Inside each cell, light energy separates charges in the semiconductor layer, pushing them apart via an internal field to generate usable power. From there, the raw DC moves into a converter that fine-tunes performance using MPPT logic - adapting instantly when weather shifts alter sun exposure or heat levels. Once stabilized, this adjusted DC enters an inverter designed to match the rhythm of the public electricity network. Matching voltage, timing, and wave alignment allows seamless transfer of clean energy straight into household circuits or beyond. Once protected and filtered, AC power reaches nearby users or flows into the network. This setup allows solar photovoltaic systems tied to the grid to turn sunlight into electricity effectively, ensuring smooth integration without disrupting supply balance.

3.10 Role of Inverters in Frequency Stability

Nowadays, solar photovoltaic setups contribute significantly to keeping electricity networks stable when it comes to frequency. Instead of relying on mechanical rotation like traditional power sources, these systems connect through electronics that separate them from immediate grid shifts. Because of this separation, they cannot naturally resist sudden imbalances in supply and demand. When disruptions happen, the speed at which frequencies drift tends to increase. However, newer inverters now apply smart methods to help correct such fluctuations quickly. One method adjusts power output based on how much frequency moves away from its normal value. Others mimic the stabilizing effect of spinning mass or react within milliseconds to stabilize conditions. So while lacking physical moving parts, these devices still influence grid behavior effectively. When frequency shifts occur, inverters respond fast by adding or removing power, which slows how quickly frequency changes while boosting system resilience. Because of this behavior, well-managed solar inverters contribute to steadier grid frequencies and aid dependable energy delivery where traditional inertia is limited.

3.11 Challenges of Solar PV Integration

Challenge	Description
Variability	Highly dependent on weather
Lack of inertia	No rotating mass
Protection issues	Low short-circuit current
Reverse power flow	Distribution grids become stressed
Frequency instability	High RoCoF under disturbances
Voltage flicker	Caused by cloud movement

Table 5: Challenges of Solar PV Integration

3.12 Chapter Summary

Here begins an outline of solar photovoltaic setups tied to electrical networks. When sunlight levels shift, so does electric current, while heat changes mainly affect voltage strength. Shadows falling across panels create uneven power drops, disrupting normal function. Instead of simply turning direct current into alternating current, devices known as inverters adjust output to capture peak efficiency. Connection methods link rooftop arrays or ground-mounted fields to neighbourhood circuits through standardized interfaces. System behaviour under fluctuation depends heavily on smart response from these electronic managers. Frequency shifts in the grid prompt corrective actions from inverters without delay. Stability emerges not just from hardware design, but from precise, rapid signal adjustments made continuously. High reliance on sun-produced electricity reshapes how central grids manage supply consistency. Thus, intelligent controls become part of everyday regulation behind the scenes.

CHAPTER 4

POWER SYSTEM FREQUENCY STABILITY THEORY :

4.1 Introduction

When something disrupts a power grid - like a quick shift in demand, a generator failing, or swings in wind or solar output - the system must hold steady at its normal frequency. This steadiness shows how well supply matches consumption across the network. If production and usage do not line up, the frequency shifts right away. Equipment on both ends - from large turbines down to household appliances - relies on that frequency staying inside safe boundaries. Over time, spinning masses in conventional generators have helped absorb shocks, their physical momentum slowing rapid changes. Their automatic speed controls also adjust output when needed. Fewer spinning parts in today's grids come from relying more on solar panels and similar tech, which weakens natural resistance to speed changes. Because of this shift, knowing how frequencies stay steady becomes essential when studying reactions, shaping responses, and keeping electricity networks running without disruption.

4.2 Concept of Frequency in Power Systems

The frequency of an alternating current (AC) power system represents the rate at which the system voltage and current oscillate. In most countries, including Bangladesh, the nominal system frequency is 50 Hz. Frequency is a global parameter and remains almost the same throughout an interconnected power system.

The system frequency is directly related to the rotational speed of synchronous generators and is given by:

$$f = \frac{PN}{120} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

where:

f= system frequency (Hz)

P= number of poles

N= rotor speed (rpm)

Any disturbance that affects the balance between mechanical input power and electrical output power causes a change in rotor speed, which leads to frequency deviation.

4.3 Generation–Load Imbalance and Frequency Deviation

A shift in power system frequency reflects how closely production aligns with consumption. Exact alignment keeps the rate steady at its standard level. Deviation appears once supply and demand fall out of sync. Too much output compared to need pushes the rate upward beyond normal. The extent of imbalance shapes the direction of change. When demand outpaces supply, frequency begins to fall, leading to a downward shift. How fast and how far it falls relies heavily on how much inertia exists within the network along with how quickly primary controls react - like those built into traditional generator turbines. Systems with little stored energy or heavy reliance on solar panels see these shifts happen faster, sometimes nearing dangerous levels without timely intervention. Grasping how mismatches between production and consumption affect frequency becomes vital when shaping responses that support balance, steady performance, and consistent delivery across today's electrical networks.

4.4 Role of Inertia in Frequency Stability

Inertia refers to the stored kinetic energy in the rotating masses of synchronous generators and turbines. The kinetic energy acts as a buffer that resists sudden changes in frequency.

The inertia constant H is defined as:

$$H = \frac{\text{Stored kinetic energy at rated speed}}{\text{Rated power of the machine}}$$

In conventional power systems, high inertia slows down the rate of frequency change. However, solar PV systems connected through inverters do not contribute mechanical inertia, resulting in low-inertia systems with faster frequency deviations.

4.5 Swing Equation of Synchronous Generator

The swing equation describes the dynamic behavior of a synchronous generator rotor following a disturbance. It is the fundamental equation used in frequency stability analysis.

$$2H\frac{d^2\delta}{dt^2} = P_m - P_e \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .5$$

where:

H= inertia constant (seconds)

δ= rotor angle (rad)

P_m= mechanical input power (pu)

P_e= electrical output power (pu)

For frequency stability studies, the swing equation is often expressed in terms of frequency deviation:

$$2H\frac{df}{dt} = P_m - P_e - D\Delta f + P_{bess} \quad \text{......} 6$$

where:

D= damping coefficient

Δf= frequency deviation

P(BESS) =Battery PowerPower injected by a Battery Energy Storage System to stop the drop. This equation shows that the rate of change of frequency (RoCoF) is inversely proportional to system inertia.

4.6 Rate of Change of Frequency (RoCoF)

RoCoF is defined as the speed at which system frequency changes following a disturbance:

$$RoCoF = \frac{df}{dt} \quad \text{......} 7$$

High RoCoF values are dangerous because:

i. Protection relays may malfunction.
ii. Generators may trip.
iii. Load shedding may be triggered unnecessarily.

Low-inertia systems with high solar penetration typically experience higher RoCoF compared to conventional systems.

4.7 Frequency Nadir

Frequency nadir is a critical parameter in power system frequency stability analysis and refers to the minimum frequency value reached following a disturbance such as a sudden load increase, generator outage, or loss of renewable generation. It occurs after the initial inertial response and before primary frequency control mechanisms fully restore the system balance. The depth of the frequency nadir indicates how severely the system frequency is affected by the disturbance and is strongly influenced by system inertia, the magnitude of the disturbance, and the speed of control responses.

In low-inertia power systems with high solar PV penetration, frequency nadir tends to be lower because inverter-based resources do not naturally provide inertial support. A deeper frequency nadir increases the risk of triggering under-frequency protection schemes or load shedding, which can compromise system reliability. Advanced inverter control strategies, such as droop control and virtual inertia, play an important role in improving the frequency nadir by injecting active power rapidly during frequency decline. Therefore, maintaining an acceptable frequency nadir is essential for ensuring stable and secure operation of modern power systems.

4.8 Primary Frequency Control Modeling

Primary frequency control is the immediate response provided by generator governors. The governor adjusts the turbine input based on frequency deviation using a droop characteristic.

The governor droop equation is:

$$\Delta P = -\frac{1}{R}\Delta f \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..8$$

where:

R= speed regulation (droop constant)

Governor and turbine dynamics are typically modelled using first-order transfer functions in MATLAB/Simulink.

4.9 Secondary Frequency Control (AGC)

Secondary frequency control restores frequency to its nominal value by adjusting generator setpoints. Automatic Generation Control (AGC) operates over a longer time scale and minimizes steady-state frequency error.

The Area Control Error (ACE) is defined as:

$$ACE = \Delta P_{tie} B\Delta f \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.9$$

where:

B= frequency bias constant

In this thesis, AGC is not implemented to keep the model suitable for undergraduate-level analysis.

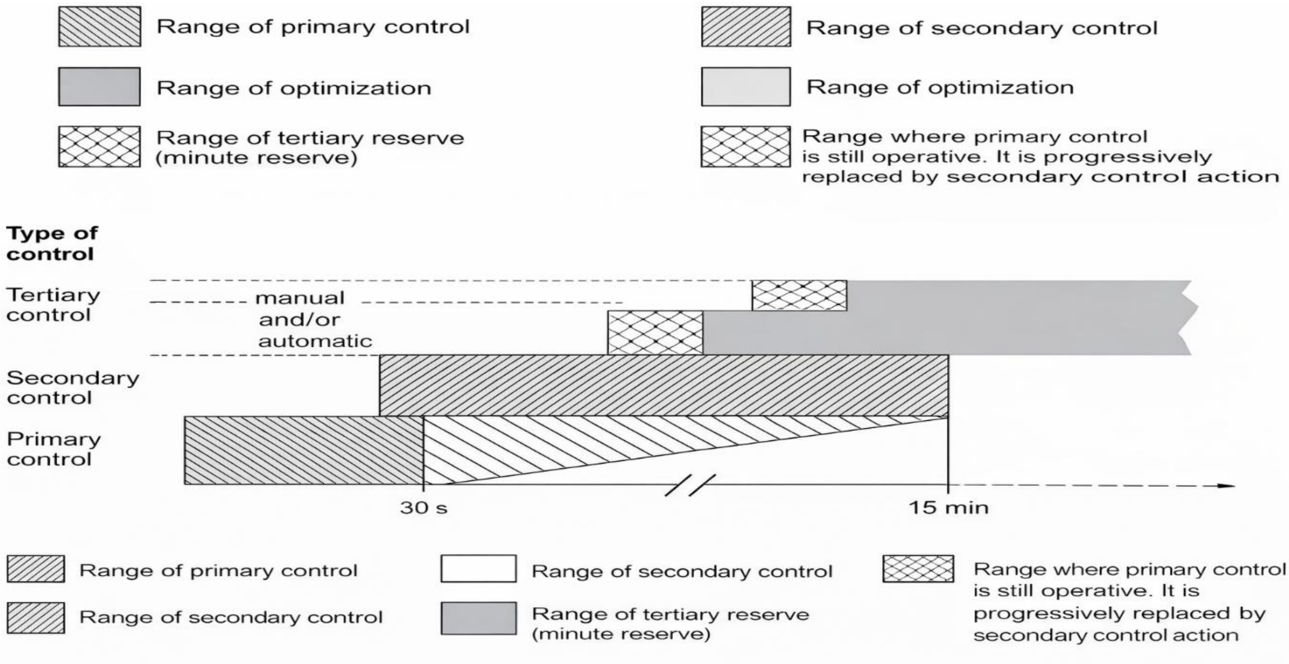

Fig 4.1: Timing of the various (partially overlapping) ranges of action of primary, secondary and tertiary control

4.10 Power System Frequency Behavior

Despite disturbances like abrupt load shifts or lost generation units, a power network's frequency response shows how quickly it reacts. Close to standard levels - say, 50 hertz - the grid holds steady when supply matches demand. Should that balance break, any gap between mechanical energy supplied and electricity consumed directly affects frequency movement. Resistance to fast swings comes first from rotating mass within machines, slowing the rate of change. Afterward, turbine governors step in automatically, countering drift through immediate adjustments. Over minutes rather than seconds, secondary systems fine-tune output settings across plants to return frequency fully to target. When solar panels connect deeply into today's grids, spinning mass drops. This causes grid frequency to shift more quickly. Sudden shifts mean the rate at which frequency changes rises sharply. Because of this behavior, new ways to manage responses become necessary. Control methods like simulated inertia help mimic traditional dynamics. Rapid reactions from inverter systems also play a role. Stability depends on how well these elements respond. Reliable operation hinges on precise adjustments over time.

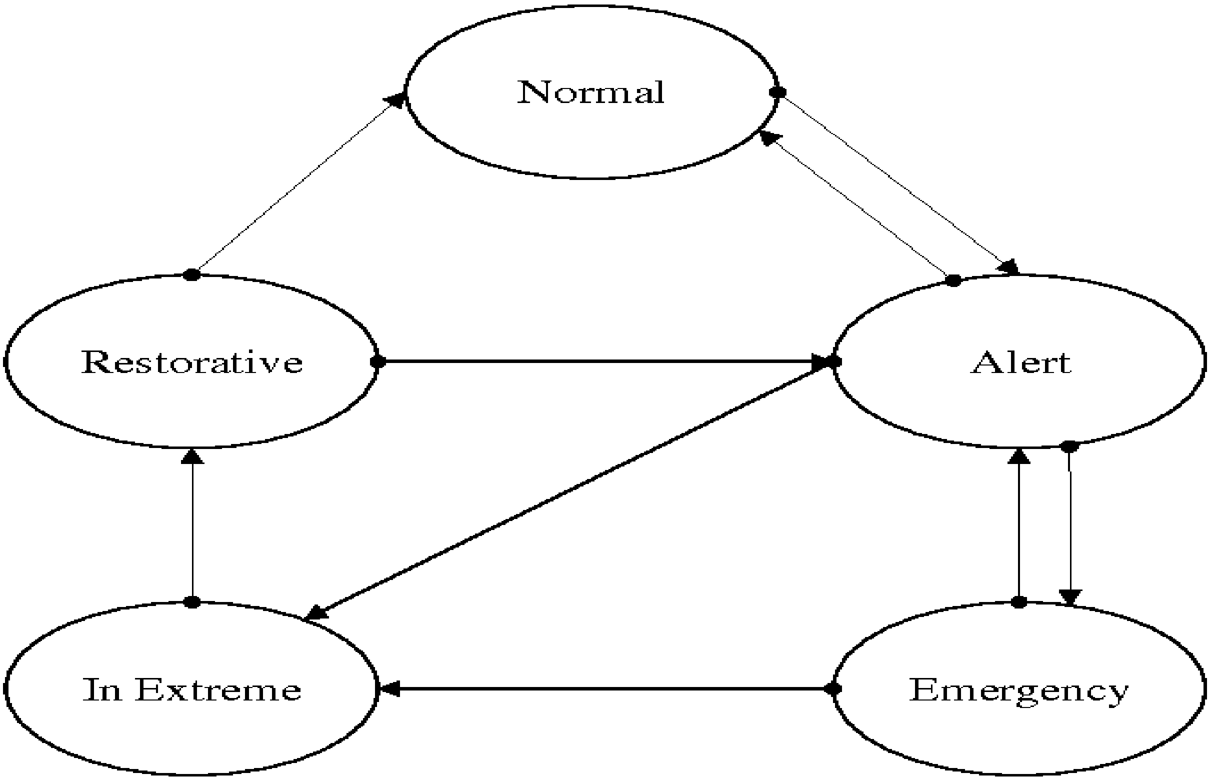

Fig 4.2: Example of frequency response after a frequency event. Source scientific paper impact of distributed energy resources on frequency regulation of the bulk power system

4.11 Impact of Solar PV on Frequency Dynamics

With more solar photovoltaic units connecting to the network, how fast electricity frequency responds begins shifting noticeably. Because these setups link via inverters rather than rotating machines, they bring no natural inertia into play. This absence means less resistance forms against speed shifts when imbalances occur across supply and demand. Sudden drops in output or abrupt usage spikes now prompt sharper swings compared to earlier designs. Sunlight flickering under passing clouds introduces brief surges or dips, adding strain to regulation tasks. If left unmanaged, rising shares of solar feed-in tend to accelerate frequency drift while narrowing safety buffers during events. Still, modern inverter methods - like simulated inertia, slope-based regulation, or rapid reaction to grid shifts - allow solar installations to help stabilize frequency. With correct setup, photovoltaic systems deliver more than emission-free power; they enhance stability where system inertia is weak.

4.12 Frequency Stability Indices

Frequency stability indices are essential metrics used to evaluate the ability of a power system to maintain its nominal frequency following disturbances such as sudden load changes, generator outages, or fluctuations in renewable energy generation. These indices provide insight into the system's dynamic behavior and help in designing effective control strategies. The rate of change of frequency (RoCoF) indicates how rapidly the system frequency changes immediately after a disturbance and reflects the level of system inertia. The frequency nadir, or minimum frequency reached during a disturbance, is a critical indicator of how close the system comes to under-frequency limits. Steady-state frequency deviation measures the final frequency difference from the nominal value after the system has stabilized, highlighting the effectiveness of secondary control. Additionally, the system inertia constant (H) represents the stored kinetic energy in rotating machines, which inherently resists rapid frequency changes, while the primary frequency control response shows how effectively generators and inverter-based resources can arrest frequency deviations. Together, these indices provide a comprehensive understanding of frequency behavior and are vital for ensuring reliable and stable operation of modern power systems, especially those with high penetration of solar PV and other renewable energy sources.

To quantify frequency behavior, researchers use:

Index	Meaning
Frequency deviation	Difference from nominal frequency
Nadir	Lowest value reached after disturbance
RoCoF	Speed of frequency drop
Settling time	Time to return to stable frequency
Overshoot	Excess rise after recovery

Table 6: Frequency Stability Indices

4.13 International Standards and Grid Codes

Countries have different frequency response requirements:

1. Australia
    i. Mandatory fast frequency response (FFR) for PV.

2.Germany

i. PV disconnection rules upgraded.

ii. Synthetic inertia required.

3.USA (California)

i. Inverters must support grid stability.

4.Bangladesh

i. Grid code still evolving.

ii. Inertia concerns rising as solar capacity increases.

Aspect	Bangladesh Grid Code (BGC)	IEEE 1547 (USA)	IEC / EN (Europe)
Nominal Frequency	50 Hz	60 Hz (configurable)	50 Hz
Normal Frequency Operating Range	49.5 – 50.5 Hz	59.3 – 60.5 Hz	49.8 – 50.2 Hz
Extended / Time-Limited Range	Limited provision; mainly protection-based	Mandatory defined ride-through ranges	Clearly defined time-based ranges
Frequency Ride-Through (FRT)	Not explicitly mandatory for PV (legacy grid focus)	Mandatory	Mandatory
Primary Frequency Response	Via governors (mainly synchronous generators)	Required for DERs (frequency–watt)	Required (droop-based response)
Secondary Control (AGC)	Not specified for DERs	Supported	Supported
RoCoF Withstand Capability	Not clearly defined	Explicitly defined	Explicitly defined
Synthetic / Virtual Inertia	Not mandated	Allowed / encouraged	Increasingly required
Anti-Islanding Protection	Mandatory	Mandatory	Mandatory
Harmonic Limits	As per IEC/IEEE references	IEEE 519	IEC 61000
Voltage & Frequency Support by PV Inverters	Limited	Advanced inverter functions required	Advanced inverter functions required

Table 7: Bangladesh Grid Code Comparison with International Standards (Solar PV & Frequency Stability)

4.14 Chapter Summary

This chapter presented the theoretical foundation of power system frequency stability, including generation–load imbalance, inertia, swing equation, RoCoF, frequency nadir, and frequency control mechanisms. These concepts are essential for modelling and simulation in MATLAB/Simulink. The next chapter focuses on the modelling of solar PV systems and inverter-based generation for frequency stability analysis.

CHAPTER 5

SOLAR POWER SYSTEM MODELING FOR FREQUENCY STABILITY ANALYSIS:

5.1 Introduction

With solar photovoltaic (PV) capacity expanding quickly, today's power grids face shifts in both layout and how they respond to change. Although it delivers electricity without emissions and supports local production, widespread solar adoption brings fresh concerns about keeping frequency steady. Instead of connecting directly like traditional plants, PV units link via electronic converters this design separates their operation from the grid's frequency swings. Because of that separation, these systems contribute little inertial response or automatic adjustment after disruptions, functions once taken for granted. For reliable assessments of frequency resilience, precise models capturing solar behavior have now grown necessary.

Starting with sunlight conversion, the photovoltaic array's response shifts under changing light and heat conditions, shaping how much energy becomes available. Instead of treating panels as static sources, models reflect their varying output based on environmental inputs. Moving to conditioning stages, voltage levels get adjusted via DC–DC converters that respond dynamically to maintain peak efficiency. To track optimal performance, algorithms guide these adjustments by detecting real-time changes in generation capacity. Once power moves toward the grid, inverters take charge - translating direct current into synchronized alternating current. Their operation hinges on precise timing mechanisms that lock onto grid frequency using feedback systems. Beyond basic conversion, modern controls embedded within inverters influence how quickly they react when grid frequency wavers. Features like synthetic inertia mimic traditional generator responses during sudden imbalances. By adjusting power delivery rates in proportion to frequency deviations, certain methods help stabilize the network. How well these techniques perform depends on accurate representation of each component's behavior under fluctuating loads.

Starting with a mix of traditional generators, solar setups need connection to loads and grid behavior for realistic testing. When things shift - like demand jumps, plants fail, or sunlight flickers - simulations running over time show how the system reacts. Instead of isolated parts, combined models track effects across full events. These tools measure what happens to frequency swings, lowest points reached, and how fast things settle down. From these results, patterns emerge about limits and responses tied to growing solar share. Understanding such shifts helps shape better controls without assuming smooth outcomes.

5.2 Structure of a Grid-Connected Solar PV System

Connected to the electricity network, a solar photovoltaic setup relies on linked parts turning sunlight into usable electric power. Sunlight strikes the PV array first - many panels joined in series or parallel - to produce direct current. From there, the DC moves through a DC–DC converter regulated by an MPPT method, adjusting dynamically when light or heat shifts. That adjusted flow reaches an inverter tied to the grid, transforming current type from DC to AC while matching grid standards closely. Matching happens across voltage, cycle rate, and waveform alignment before delivery occurs. Harmonics get minimized because filtering takes place right after inversion, smoothing what enters public infrastructure. Power quality improves simply due to this built-in cleanup stage near generation. Power from the solar array often moves through a transformer first, adjusting it to fit the required grid level prior to reaching the connection point. At that junction, safety gear like relays, meters, and switches helps maintain stable performance while meeting operational standards. Sometimes faults occur - these components act fast when they do.

A typical grid-connected solar PV system consists of the following main components:

i. Solar PV array.
ii. DC–DC converter.
iii. Maximum Power Point Tracking (MPPT) controller.
iv. DC link capacitor.
v. Voltage Source Inverter (VSI).
vi. Grid interface filter.

Unlike conventional generators, solar PV systems do not directly contribute to system inertia and are fully controlled by power electronic converters.

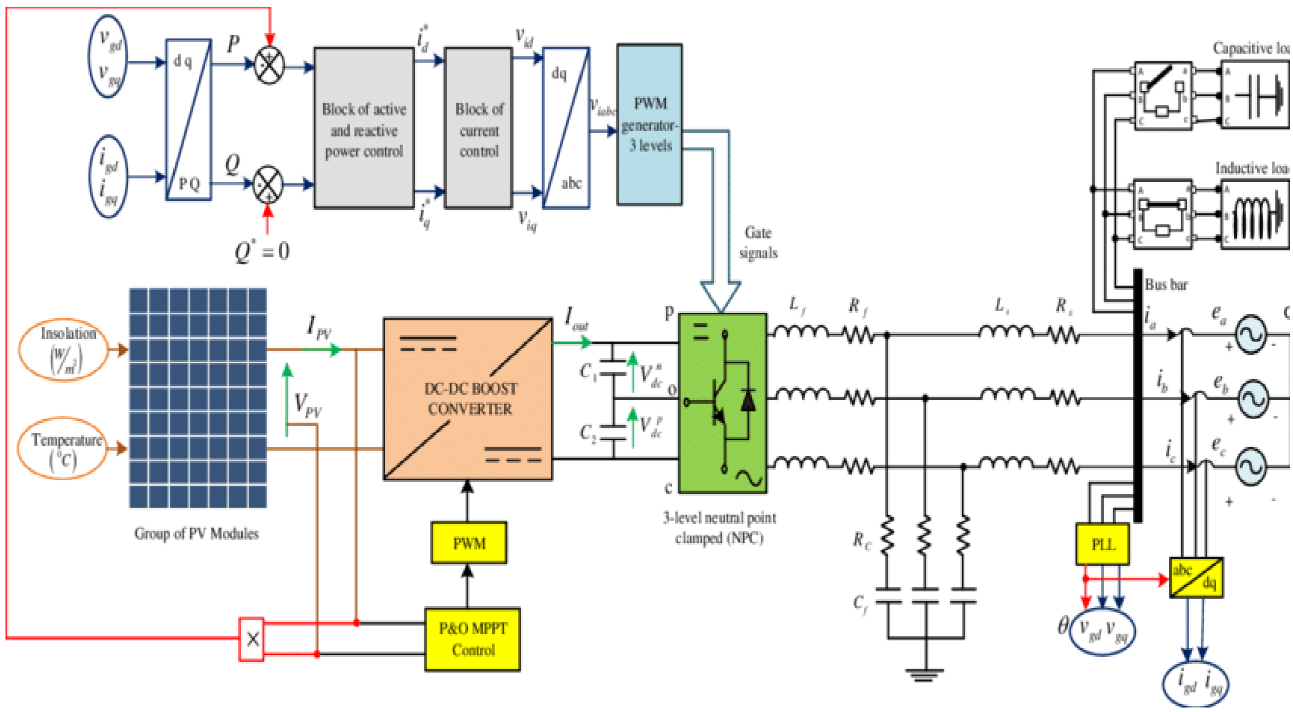

Fig 5.1: Grid-connected solar PV system

5.3 Solar Photovoltaic Cell Modeling

Solar PV cell modeling represents the electrical behavior of a solar cell using an equivalent circuit to capture its nonlinear I–V characteristics and the effects of irradiance and temperature on performance.

5.3.1 Equivalent Circuit of PV Cell

A model that mirrors how a solar cell behaves electrically comes into play when analyzing performance across varying conditions. One common approach uses a single-diode setup to reflect this behavior, involving a current supply, a diode, alongside two resistances - one in sequence, one parallel. Sunlight hitting the device generates current, captured by the source element, scaling linearly with light intensity. What governs the core semiconductor interaction lies in the diode, capturing the curved relationship between voltage and current. Resistance along the conduction path emerges from materials, connections, and contact points, quietly reducing usable voltage while shaping efficiency traits. A small amount of current can escape through flaws in the material or along the edges of the p–n junction, captured by what is called shunt resistance - this becomes more significant when voltages are low. Representing real-world operation well, the model built around this idea helps study how current and power change with voltage, supports simulations, guides design choices, while also enabling checks on how actual solar setups perform.

A solar PV cell is modelled using an equivalent circuit consisting of:

i. A current source representing photo-generated current.
ii. A diode.
iii. Series resistance.
iv. Shunt resistance.

This model accurately represents the electrical behavior of a PV cell under varying irradiance and temperature conditions.

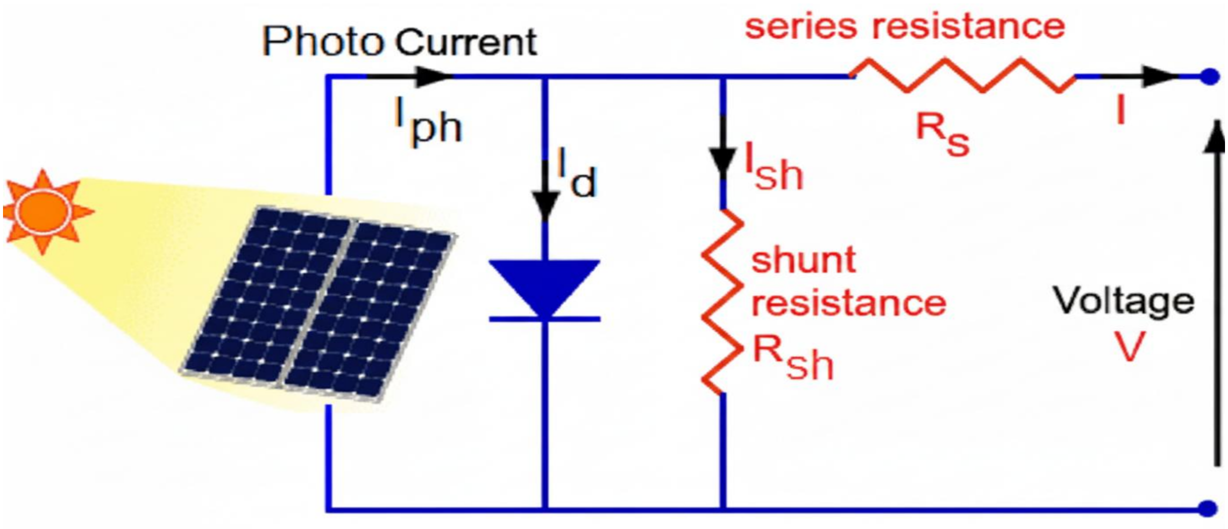

Fig 5.2: Solar photovoltaic cell

5.4 PV Array Modeling

A closer look at how sunlight turns into electricity begins with understanding grouped solar units. These groupings, called arrays, link many small cells and larger panels in lines and branches to match needed power outputs. Instead of starting fresh each time, engineers build on a basic electronic layout - the single-diode setup - to represent one cell's behavior before expanding it across the full structure. Changes in light strength and heat around the panel shift key internal values: what drives current flow, how much leaks through junctions, even the final voltage sent out. Each connection pattern adjusts these responses differently depending on sun and warmth. From the model, nonlinear current–voltage and power–voltage curves help examine how peak power shifts under varying conditions while influencing overall performance. Because environmental fluctuations directly affect output, precise photovoltaic array simulation matters most when testing transient responses or grid frequency response. Such models reflect real-world power shifts, supporting better decisions in controller design even when sunlight or temperature change rapidly.

A PV array is formed by connecting multiple PV cells in series and parallel to achieve the desired voltage and current levels. The output power of a PV array depends on:

i. Solar irradiance.
ii. Cell temperature.
iii. Load conditions.

In this thesis, a simplified PV array model is used to focus on frequency stability rather than detailed semiconductor behavior.

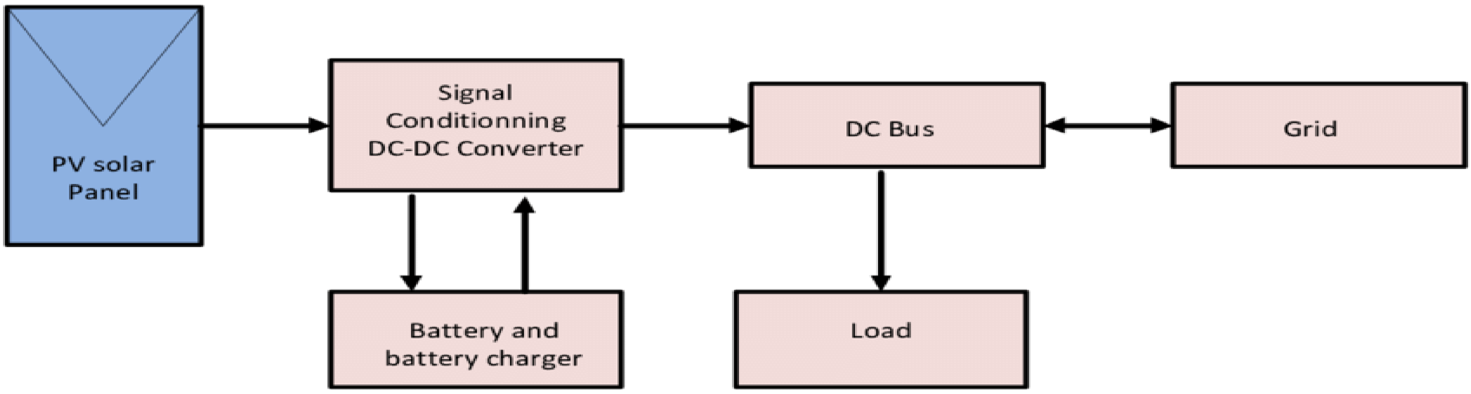

Fig 5.3: General block diagram of PV system

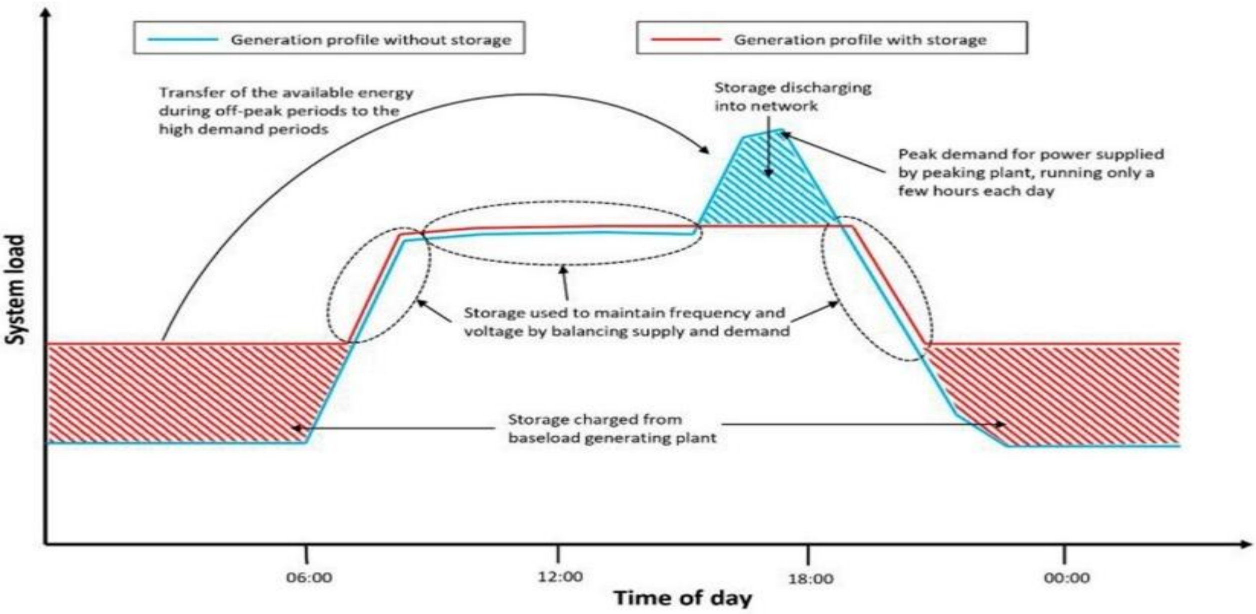

Fig 5.4: Load conditions

5.5 Maximum power point tracking (MPPT) charge controller

5.5.1 Need for MPPT

Solar photovoltaic (PV) systems produce varying amounts of power depending on sunlight intensity, temperature shifts, and how they are operated. At any given moment, one specific spot on the power–voltage curve allows the panel to reach peak output - this is called the maximum power point (MPP). If unregulated, operation often drifts from this ideal position, leading to wasted energy. To prevent loss, tracking methods adapt the electrical load dynamically, keeping production near the MPP despite fluctuating inputs. Because of these adjustments, more usable electricity enters the system over time. Panels work closer to their real potential, especially when shadows pass across them or temperatures jump unexpectedly. Efficiency gains matter most when weather changes fast. Though small in concept, the effect adds up during daily cycles. Performance stays high even when surroundings stay unpredictable. Ultimately, consistent alignment with peak output shapes long-term results. While invisible to users, internal regulation defines how much light becomes useful power. Such control makes a difference where sun exposure lacks stability. Even modest improvements per hour influence total generation by day's end. With constant tuning, resources meet demand more directly than fixed settings ever could. This balance between environment and response keeps supply aligned with what panels can realistically deliver. Not every change shows immediately; yet over weeks, outcomes reflect smarter management beneath the surface. Behind steady flows lies an ongoing search for better ratios between voltage and output. What matters most happens quietly, without user effort. As conditions shift, hidden corrections maintain flow close to theoretical limits. Small but frequent decisions shape whether incoming radiation gets used fully - or lost needlessly. Precision does not guarantee perfection. Still, it reduces gaps between possible and actual harvest. When clouds come and go, resilience comes not from strength - but responsiveness. In that flexibility rests much of modern solar reliability.

5.5.2 MPPT Techniques

Several MPPT techniques are available, including:

i. Perturb and Observe (P&O).
ii. Incremental Conductance.
iii. Fractional Open Circuit Voltage.

In this work, the Perturb and Observe (P&O) method is selected due to its simplicity and wide acceptance in academic research.

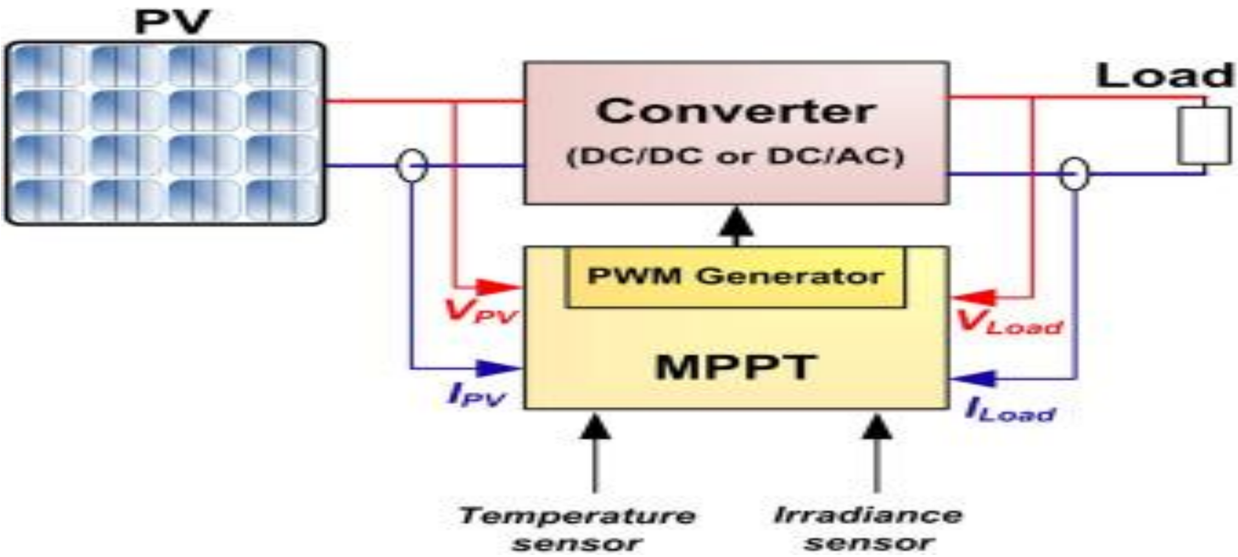

Fig 5.5: MPPT technique of a solar module

5.6 DC–DC Converter Modeling

DC-DC converter modeling involves creating mathematical representations and circuit simulations to analyze and design converters (buck, boost, buck-boost) for voltage conversion, focusing on dynamics (transient/steady-state) and control strategies (PWM, average current mode) for applications like renewable energy systems. These models help in understanding component behavior, deriving control laws, and optimizing performance for efficiency and stability.

Converter Type	Solar Panel Voltage (Vin)	Battery Voltage (Vout)	Common Solar Application
Buck	Higher than Battery	Lower than Panel	Standard 12V/24V charging
Boost	Lower than Battery	Higher than Panel	Micro-grids, small portable panels
Buck-Boost	Variable (High or Low)	Fixed / Regulated	MPPT Controllers (Best for all-weather)

Table 8: DC–DC Converter Modeling

5.7 Inverter Modeling for Grid Connection

Inverter modeling is a critical component in the analysis of grid-connected solar photovoltaic (PV) systems, as the inverter governs the interaction between the DC-side PV source and the AC power grid. The grid-connected inverter converts DC power from the PV array or DC-link into synchronized AC power with controlled voltage, frequency, and phase. Its model typically consists of a power electronic switching stage, a DC-link capacitor, an output filter (usually an L, LC, or LCL filter), and control systems. For system-level and frequency stability studies, detailed switching models are often simplified into average-value models to reduce computational complexity while preserving dynamic behavior. The control structure generally includes an inner current control loop, an outer DC-link voltage or active power control loop, and a phase-locked loop (PLL) for grid synchronization. Accurate inverter modeling enables the assessment of active and reactive power control, dynamic response during disturbances, and the capability of inverter-based resources to support grid frequency and voltage stability.

5.7.1 Voltage Source Inverter (VSI)

A typical setup for connecting solar panels to the power grid relies on what is called a Voltage Source Inverter. This type of system keeps the incoming direct current stable using a capacitor linked across the DC side. Instead of varying wildly, the voltage stays fairly steady during operation. On the output end, alternating current forms with adjustable strength, timing, and alignment. Built around electronic switches like IGBTs or MOSFETs, these units usually take shape as a bridged layout. To form a smooth wave resembling household electricity, they apply pulse width modulation methods. From flat input, rhythmic switching carves out something close to a sine curve. In grid-connected mode, synchronization between the VSI and the utility occurs through a phase-locked loop and reactive power. Fast dynamics, adaptable control features, combined with support for methods like current-based regulation, droop mechanisms, or synthetic inertia, allow the VSI to contribute significantly. Power networks rich in renewable generation rely on these traits for maintaining stable frequency and voltage levels.

The Voltage Source Inverter converts DC power from the PV system into AC power suitable for grid connection. The inverter is modeled using:

i. PWM control.
ii. Phase-locked loop (PLL).
iii. Current control loops.

The inverter plays a critical role in determining the frequency response of the solar PV system.

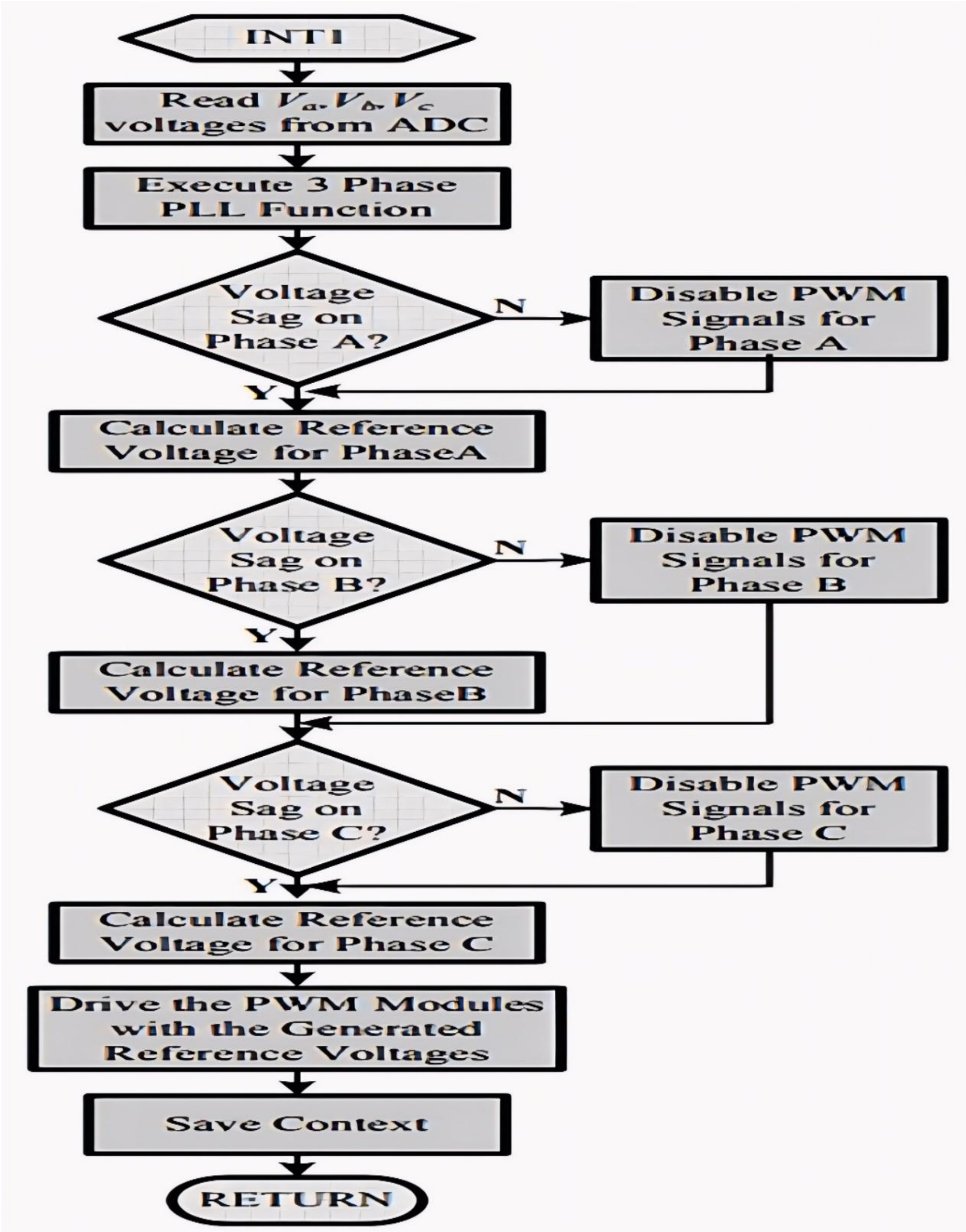

Fig 5.6: Flow chart Voltage Source Inverter (VSI)

5.7.2 Active Power Control

The active power output of the inverter is controlled to regulate power injection into the grid. The active power reference is generated based on system requirements and frequency deviation.

5.8 Frequency Control of Solar PV Inverter

Frequency regulation in a solar photovoltaic (PV) inverter means adjusting how much electricity it delivers when the grid's frequency shifts, helping keep supply stable. While traditional power sources naturally respond due to rotating mass, PV units lack this physical link since they connect via electronics instead. So their reaction depends on smart software built into the device. As long as it stays tied to the network, the unit tracks frequency constantly through a synchronization method and updates its target output based on that signal. Methods like P–f droop, simulated inertia, or rapid adjustment allow it to push more energy if frequency drops too low - or pull back when it rises too high. When designed well, solar PV inverters slow down rapid shifts in grid frequency while also lifting the lowest point it reaches during disturbances, contributing to smoother recovery. Their ability to manage these changes becomes more critical as traditional generators decline and renewable sources take up larger shares of electricity supply**.**

5.8.1 Droop Control Implementation

To enable solar PV participation in frequency regulation, a droop-based control strategy is implemented. The active power reference is adjusted according to frequency deviation:

$$\Delta P = -K_f \Delta f \ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 10$$

where:

K_f= frequency droop coefficient

This control allows the inverter to mimic the behavior of conventional generators.

5.8.2 Virtual Inertia Concept

Virtual inertia control adds a derivative term of frequency to emulate inertial response:

$$P_{vi} = -K_{vi} \frac{df}{dt} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .11$$

Meaning of Each Term:

Parameter	Symbol	Description	Unit	Effect on System
Virtual inertia power	(P_{vi})	Power injected/absorbed by inverter due to virtual inertia control	MW / pu	Supports frequency stability
Virtual inertia gain	(K_{vi})	Controls strength of inertia emulation	MW·s/Hz	Higher value → stronger frequency support
Rate of Change of Frequency	$\frac{df}{dt}$	Speed of frequency variation	Hz/s	Indicates severity of disturbance
Negative sign	−	Provides opposing action to frequency change	—	Stabilizes frequency

Virtual inertia improves frequency nadir and reduces RoCoF in low-inertia systems.

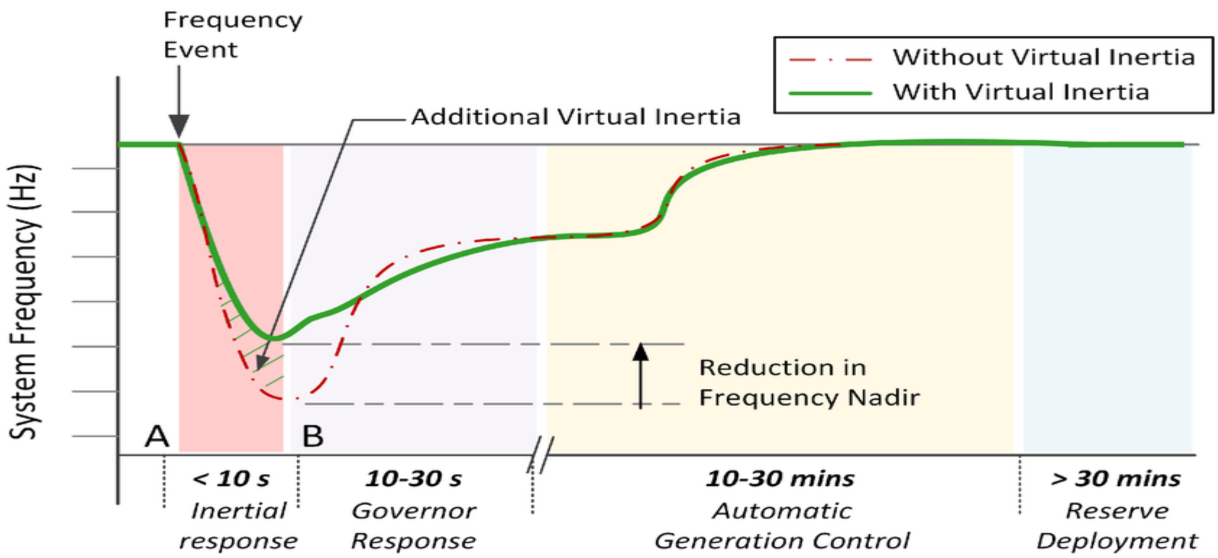

Fig 5.7: Virtual inertia concept

5.9 MATLAB/Simulink Implementation

One way to study how solar power affects grid frequency is through MATLAB/Simulink, which supports simulation and analysis of connected photovoltaic setups. Inside this software, parts like the solar panel group, voltage adjuster, peak power tracker, current converter, filtering unit, and network link are built either with ready-made elements or unique equations. A common method uses a one-diode setup to mimic the solar panel's behavior under different sunlight and heat conditions. Instead of fixed designs, engineers often pick adjustable circuits - like step-up, step-down, or dual-mode converters - that respond to control signals. These signals come from methods such as tweaking observation values or measuring conductance changes, both aiming to capture optimal energy output without direct commands in code structure. A voltage source setup stands at the core, modeling the grid-linked inverter through pulse-width modulation along with a phase-detection mechanism to match grid timing. Connected elements - filter circuits, safeguards, and connection points - are present to mirror actual operating setups. With time-step simulations via Simulink, shifts like sudden demand swings, loss of generation units, or variations in sunlight intensity get applied. Response patterns then emerge: how fast frequency moves, its swing rates, and related measures come into view. Through this method, experts explore regulation methods, refine output behavior, while assessing photovoltaic effects on network frequency under controlled digital conditions. The complete solar PV system model is implemented in MATLAB/Simulink using:

i. Simscape Electrical.
ii. Control blocks.
iii. Power electronics blocks.

Subsystems are created for:

i. Input.
ii. Summation Blocks.
iii. Gain Block.
iv. Feedback Loop.
v. Scope.
vi. System Function.

The modular structure allows easy integration with the power system frequency model.

5.10 Assumptions and Simplifications

Though simulations aim for accuracy, shortcuts shape how solar power ties into the grid. A lone diode stands in for entire panels, treating sunlight and heat as if they never flicker across surfaces. Instead of tracking every switch flip inside converters, engineers lean on smoothed approximations that skip tiny cycles. Wires and demand points get compressed into single blocks - no fine threads stretched over miles. When things run smoothly, voltage hums at its set point, steady and even. Only when testing begins does imbalance enter, slipped in by design. Starting with how controllers behave, their changing patterns - like those in MPPT and inverter loops - are often smoothed near a set condition to examine minor fluctuations. Because of this approach, scientists can track broad shifts in frequency response and stability without losing sight of key links among solar output, inverter behavior, and grid conditions.

5.11 Chapter Summary

This chapter looked into how grid-tied solar photovoltaic setups are modeled and simulated when studying frequency stability. Since solar power plays a bigger role in today's electricity networks, concerns about maintaining stable frequency have grown - particularly due to the lack of inherent inertia from inverter-driven sources compared to traditional plants. A typical setup includes several components: panels that capture sunlight, circuits that adjust voltage levels, control methods aimed at harvesting peak output, inverters converting current type, filtering elements smoothing waveforms, alongside connections feeding into the main network. One part explained modeling methods for different parts of solar systems. A single-diode approach works well for photovoltaic panels. Instead, DC–DC converters use averaged representations when simulating maximum power tracking. For inverters, voltage regulation plus phase alignment help connect to the electrical network. Getting the most energy depends heavily on efficient tracking strategies. These devices also support steady grid performance under varying conditions. Simulations in MATLAB and Simulink demonstrate reactions to disruptions like abrupt demand shifts or changing sunlight levels. Some typical approximations in these models reduce complexity without losing essential response traits. Simplified structures still reflect core system dynamics during transient events.

This chapter outlines how solar photovoltaic setups connect to electrical grids, shaping frequency behavior. Insights into these interactions form a base for examining, building, efficient control of inverter-driven renewables within today's lower inertia networks.

CHAPTER 6

MATLAB/SIMULINK SIMULATION AND FREQUENCY STABILITY ANALYSIS:

6.1 Introduction

This chapter presents the MATLAB/Simulink-based simulation of a power system integrated with a solar photovoltaic (PV) system to analyze frequency stability. The developed model is used to study the system frequency response under different operating conditions and load disturbances. The simulation results demonstrate the impact of solar PV penetration on system frequency behavior and evaluate the effectiveness of frequency control strategies.

6.2 Description of the Test Power System

For frequency stability analysis, a representative test power system is used to study the dynamic interactions between conventional generators, loads, and grid-connected solar photovoltaic (PV) units. The system is designed to capture essential behaviors while keeping the model manageable for simulation. It typically consists of conventional synchronous generators, which provide the system's inertia and primary frequency control, combined with variable loads that represent realistic power consumption patterns. The load may include both constant power and frequency-dependent components to accurately reflect how the system responds to frequency deviations.

A solar PV generation unit is integrated into the system through a voltage source inverter (VSI), which ensures that the PV output is synchronized with the grid in terms of voltage, frequency, and phase. The PV array is connected to a DC–DC converter with a Maximum Power Point Tracking (MPPT) controller, which continuously adjusts the operating voltage to extract maximum power under varying irradiance and temperature conditions. The inverter is modeled with an inner current control loop, DC-link voltage regulation, and a phase-locked loop (PLL) for grid synchronization, allowing it to contribute to active and reactive power control.

The network connections in the test system, including transformers and transmission lines, are represented using lumped-parameter models. This simplification captures the electrical interactions between generation and load without introducing unnecessary complexity. Protective devices, such as circuit breakers and relays, are included to ensure safe operation in simulation studies.

In MATLAB/Simulink, the test system is implemented using a combination of prebuilt blocks and custom models. Synchronous generators are represented using standard machine and governor blocks, while the PV array, DC–DC converter, and VSI are implemented using detailed or average-value models depending on the simulation requirements. Disturbances such as sudden load changes, generator outages, or rapid fluctuations in solar irradiance are introduced to evaluate the system's frequency response. Key performance metrics, such as rate of change of frequency (RoCoF), frequency nadir, and settling time, are observed to analyze system stability.

This test power system provides a practical and flexible platform for studying the impact of solar PV integration on frequency dynamics. It also allows the testing and validation of advanced inverter-based control strategies, such as virtual inertia or droop control, aimed at enhancing the frequency stability of modern low-inertia power systems.

6.3 MATLAB/Simulink Model Development

The development of a MATLAB/Simulink model is a crucial step for analyzing the frequency stability of grid-connected solar photovoltaic (PV) systems. The model integrates all major components of the test power system, including conventional synchronous generators, variable loads, the PV array, DC–DC converter, voltage source inverter (VSI), and the grid interface, to create a realistic simulation environment.

The PV array is modeled using the single-diode equivalent circuit, which accounts for the effects of irradiance and temperature on current and voltage output. This ensures that variations in environmental conditions are accurately reflected in the PV output. The DC–DC converter is implemented using a boost or buck-boost topology, controlled by a Maximum Power Point Tracking (MPPT) algorithm—typically Perturb & Observe (P&O) or Incremental Conductance (INC)—to ensure the PV array always operates at its maximum power point.

The grid-connected inverter is modeled as a voltage source inverter (VSI) with PWM-based control and a phase-locked loop (PLL) for synchronization with the utility grid. The inverter control includes an inner current loop and an outer voltage or active power loop, which enables precise regulation of power injection into the grid and allows the simulation of advanced frequency support strategies such as droop control and virtual inertia. Filters, transformers, and network lines are included using lumped-parameter models to emulate realistic grid behavior while keeping the simulation computationally efficient.

In Simulink, the system is constructed by connecting these components into a modular structure. The synchronous generators and loads are modeled using standard Simulink blocks for machine dynamics, governor response, and frequency-dependent loads. The PV system and inverter are represented using a combination of prebuilt blocks and custom models, allowing flexible control strategy implementation and disturbance testing.

Once the model is developed, various disturbance scenarios—such as sudden load changes, generator outages, and variations in solar irradiance—are simulated to observe the system's frequency response. Key indices, including rate of change of frequency (RoCoF), frequency nadir, and settling time, are recorded to evaluate system stability and the effectiveness of inverter-based control strategies.

This MATLAB/Simulink model provides a robust and flexible platform for studying the dynamic behavior of grid-connected PV systems and their impact on frequency stability, offering insights for the design of advanced control strategies in modern low-inertia power systems.

6.3.1 Overall System Block Diagram

The complete Simulink model is divided into the following subsystems:

i. Conventional power generation unit.
ii. Load and disturbance block.
iii. Solar PV generation unit.
iv. Frequency control and measurement.

Each subsystem is developed independently and then integrated to analyze system-level frequency response.

6.3.2 Conventional Generator Model

When analyzing how well a grid keeps steady frequency, traditional spinning generators matter - they deliver real power along with built-in momentum that fights abrupt shifts after disruptions occur. Found within standard setups, these units combine three core elements: the rotating electrical part, the engine driving it, and the speed regulator. Voltage and current come from the rotating component itself, whose mass naturally resists fast swings when demand or supply jumps unexpectedly. Mechanical energy enters through the driver unit, reacting over time to guidance inputs sent its way. Frequency dips or rises trigger adjustments via the controller, altering incoming force according to what the network's rhythm shows. Although the swing equation links rotor speed changes to imbalances between mechanical input and electrical output power, it serves as a common mathematical description of generator dynamics. With built-in machine and governor components, MATLAB/Simulink allows modeling of synchronous generators. These models capture how generators react to disruptions while connecting with inverter-driven sources like solar PV. Because they reflect real-world interactions, such simulations play an essential role in assessing frequency stability.

6.3.3 Load Model

The load is modeled as a combination of:

i. Constant power load.
ii. Frequency-dependent load component.
iii. A step increase in load is applied to simulate a disturbance and observe system frequency response.

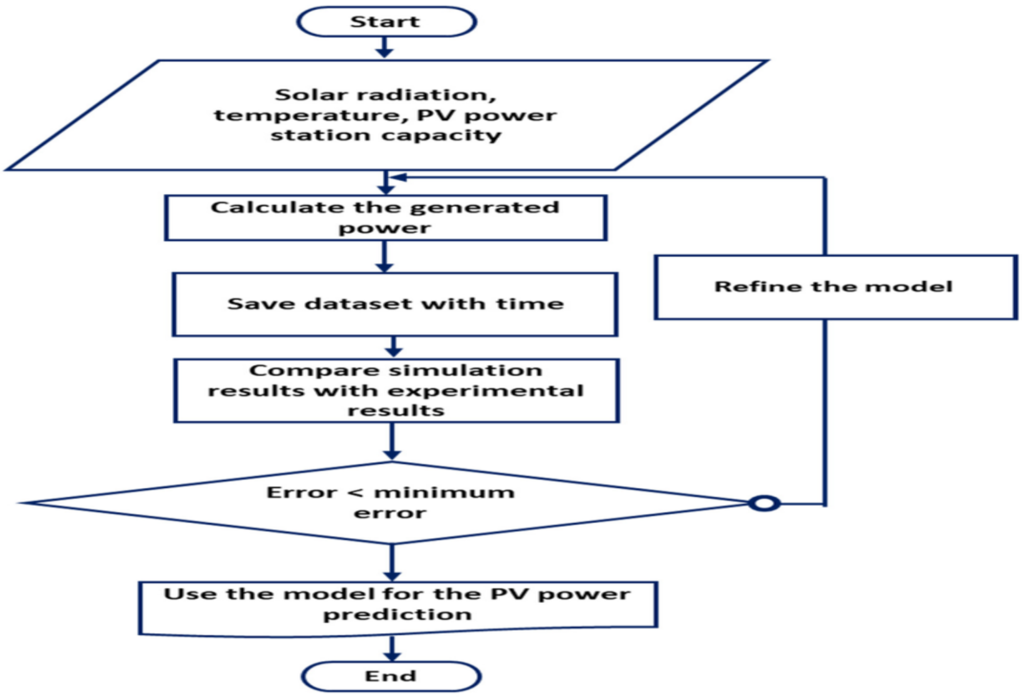

Fig 6.1: Flow chart MATLAB/SIMULINK model development

6.4 Simulation Scenarios and Disturbance Modeling

A different set of simulations in MATLAB/Simulink models actual grid behavior under shifting sunlight, load swings, or faults - each case testing frequency response when inputs change fast. Instead of steady states, the focus lies on transitions caused by cloud cover, demand spikes, or disconnections; control methods then adjust active power to limit deviations. While some runs mimic partial shading, others introduce abrupt load drops, revealing how quickly regulation kicks in. Because solar output lacks inertia, frequency can drift unless controls act within seconds. Each test measures deviation size and recovery time, highlighting which strategy reduces oscillations most. When generation fluctuates without warning, results show whether voltage and frequency stay within acceptable bounds. Since renewable plants behave unlike conventional ones, their interaction with grid dynamics needs close observation during transients.

When loads shift fast, supply and demand get out of step, causing frequency to drift. Loss of a generator triggers recovery tests to see how stable things stay without traditional power sources. Changes in sunlight appear randomly, mimicking real-world shadows or passing clouds affecting solar panels. Response speed matters - how inverters adapt control modes and tweak maximum power tracking reveals resilience under stress.

Not every test runs the same way - each one checks specific signs of how well frequency holds up, like how fast it shifts, its lowest point, how far it drifts at rest, and how long it takes to stabilize. Through varied setups involving shifting loads, differing solar power inputs, and distinct response methods, patterns emerge showing where instability might occur along with ways to reduce risk.

When disturbances occur, the way synchronous machines respond is built into the simulation. Instead of just relying on traditional responses, inverters tied to solar panels react quickly within the framework. Using methods like droop adjustments or simulated inertia adds depth to how scenarios unfold. These features help ease shifts in grid frequency while supporting stability across conditions.

From start to finish, the test setups offer a full view of how frequency behaves when real-world factors are at play. Because they mimic actual grid demands, scientists can check how solar-powered systems react over time. These models show what happens to system balance as more renewables come online. When patterns shift, new approaches take shape - helping grids stay steady even as energy sources change

To analyze frequency stability, the following simulation scenarios are considered:

6.5 Frequency Response without Solar PV

The simulation results show that the conventional system experiences an initial frequency drop following the load disturbance. Due to sufficient system inertia, the frequency decline is gradual, and the frequency nadir remains within acceptable limits.

The governor action helps arrest the frequency drop and restore frequency close to its nominal value.

6.6 Frequency Response with Solar PV Integration

When solar panels feed into the grid, they alter how quickly frequency reacts after disruptions. Because these systems link via inverters - without spinning parts - the network loses some natural resistance to shifts in rhythm. As more solar comes online, that buffer shrinks. Faster swings in frequency emerge when demand jumps or a plant drops offline. Changes in sunlight intensity add brief power ripples, which nudge the balance even more off step. Frequency stability can be supported by solar PV if inverters apply methods like droop settings or simulated inertia. Controlled correctly, these systems help keep grid frequency within limits, offering contributions that align with sustainability without compromising reliability.

6.7 Effect of Droop Control on Frequency Stability

A shift in frequency triggers automatic adjustments in power output through droop control, a method common across both traditional generators and inverters tied to the grid. As demand outpaces supply, causing frequency to fall, each unit gradually lifts its contribution based on preset sensitivity - no central signal needed. If frequency climbs above normal, indicating excess generation, individual sources scale back output at matching rates. Built-in responsiveness lets several devices act together, even when isolated from one another. Without relying on instant data links, this parallel reaction slows swings in frequency while distributing effort fairly. System robustness grows because coordination emerges naturally, not by command. When solar panels connect through inverters, using droop control helps mimic inertia-like behavior. This capability supports grid frequency, especially where natural inertia is limited. Instead of relying on traditional spinning mass, the system adjusts output based on frequency shifts. As a result, changes in frequency happen more slowly. The lowest point during a drop also improves. Multiple sources - both conventional generators and solar inverters - respond together, balancing supply without central coordination. Stability increases because responses are automatic and scaled to need.

6.8 Effect of Virtual Inertia on Frequency Stability

Modern power networks rely increasingly on solar panels connected via inverters - these do not spin like traditional machines. Because they lack moving parts, they contribute no natural resistance to sudden shifts in grid frequency. Traditional generators, by contrast, use heavy rotating components that slow down how fast frequency changes after disruptions. This built-in response helps maintain balance across the network. When large amounts of solar replace these generators, the system loses part of its stabilizing effect. Frequency then swings faster when imbalances arise. The speed at which it moves - called RoCoF - can rise sharply without intervention. That raises concerns about triggering protective shutdowns during instability. Virtual inertia aims to fill this gap by mimicking the behavior of physical rotation using smart controls. It allows inverter-connected sources to act more like classic generators during transients. Stability improves because the artificial response slows initial drift. Such methods are becoming essential as solar capacity grows within national grids.

A solution emerges when inverters mimic how traditional generators respond to shifts in supply or demand. Instead of relying on spinning parts, control systems track how fast frequency changes across the network. As deviations appear, power injection follows the slope of those fluctuations - feeding more electricity where needed. If demand spikes or a plant disconnects, extra energy flows into the lines right away, easing the pressure on frequency stability. On the flip side, when too much generation causes frequency to climb, the system pulls back by soaking up surplus power. Without mechanical rotation, this behavior still gives the grid something like resistance to abrupt swings.

A shift toward virtual inertia in solar photovoltaic inverters improves how grids handle frequency shifts. By slowing the rate at which frequency changes, it allows traditional controls - like turbine governors and droop-based units - more breathing room to act. The lowest point the frequency reaches during disturbances climbs higher, reducing chances that safety relays trip or power cuts follow. When linked with droop methods and rapid response techniques, these inverters behave like spinning machines once did, stepping into grid stabilization roles without physical mass.

What keeps some grids steady during sudden changes? Virtual inertia plays a key role, especially where traditional spinning generators are fading. With more renewables online, physical inertia drops, raising vulnerability to disruptions. Instead of relying only on old infrastructure, solar inverters now mimic inertial response through smart controls. This shift allows them to stabilize frequency swings, balance load distribution across devices, and strengthen performance when things go off track. Ultimately, the ability of inverter-driven sources to act like synchronous machines becomes essential - helping fragile grids stay within safe operating limits.

6.9 Comparative Analysis of Simulation Results

Looking at how a grid-tied solar PV setup behaves reveals much about power system dynamics during shifts in operation or disruptions. When different amounts of solar input, shifting demand, or varied controls are considered, effects on frequency stability become visible. What stands out is how each scenario alters system response in distinct ways.

When left without advanced regulation, the network's frequency swings widely after abrupt shifts in demand or when a power unit fails. Though traditional units contribute stability through mechanical mass and speed controls, their support arrives too late to prevent sharp drops. High RoCoF appears quickly under stress, pushing frequency lows near danger zones - especially where solar supply dominates. Recovery crawls back toward normal, limited by sluggish overall dynamics despite partial help from spinning reserves.

Frequency behavior gets better when droop control is used in PV inverters. As frequency shifts happen, the inverters tweak their power supply based on how far off it drifts this cuts down big swings. Speed of change slows, recovery takes less time once disruptions pass. Still,

mimicking inertia like traditional generators do? That's beyond what droop can manage by itself. After major upsets, dips or spikes might linger despite the adjustments.
Adding virtual inertia to PV inverter control helps stabilize grid frequency more effectively. Power is adjusted quickly when frequency changes occur, slowing the drop at onset and lifting the lowest point reached. Frequency returns steadier, shifts less abruptly, damps oscillations better - especially where renewables dominate and traditional plants are fewer. Working alongside droop methods, inverters then act much like classic spinning generators during disturbances.
Looking at the findings, combining droop control with virtual inertia noticeably strengthens how well low-inertia grids handle frequency shifts. Although droop adjusts output based on demand to balance loads over time, it is the virtual inertia that reacts quickly when sudden imbalances occur. When tested, systems using these methods held steadier under stress compared to those without them. Evidently, today's solar-heavy networks depend heavily on such smart inverter techniques just to stay in sync.

6.10 Limits of the Simulation Study

Although the MATLAB/Simulink model helps understand how solar PV systems influence grid frequency, certain drawbacks exist. Not every real-world behavior shows up - nonlinear effects, harmonic distortions, and fast switching details might slip through due to basic representations of panels, inverters, and lines. Conditions like uneven sunlight, shifting temperatures, or changing light intensity tend to get smoothed out, reducing how closely results match actual field conditions. Power demand patterns and grid structures are also stripped down, missing layers found in expansive networks. What's more, factors such as lag in signals, sensor inaccuracies, and hardware constraints within inverter logic rarely appear, potentially weakening methods meant to mimic system inertia or adjust output based on frequency shifts. Looking ahead, most analyses focus on immediate disruptions rather than extended challenges like gradual component wear, consistent voltage control, or how protective devices interact over time. Even so, the modeling effort still offers a practical basis for grasping how grids respond and shaping ways solar-powered networks can aid frequency regulation.

6.11 Chapter Summary

This part looked into building a model using MATLAB/Simulink to check how well a solar PV setup keeps frequency stable when linked to the grid. With components like solar panels, DC–DC converters equipped with MPPT, inverters, filtering units, plus generation and demand sides included, a full simulation framework took shape. Instead of steady conditions, shifts - like sudden load adjustments, loss of generating units, or fluctuations in sunlight intensity - were introduced to observe how frequency behaved. It turned out that droop control helped bring frequency back toward normal by scaling active power output accordingly; at the same time, adding virtual inertia slowed down rapid frequency swings and lifted the lowest point reached during events. Taken together, these findings highlight how smarter inverter-driven methods become critical as grids rely more heavily on solar energy and face shrinking rotational mass.

CHAPTER 7

SIMULATION AND RESULT:

- **Simulation**

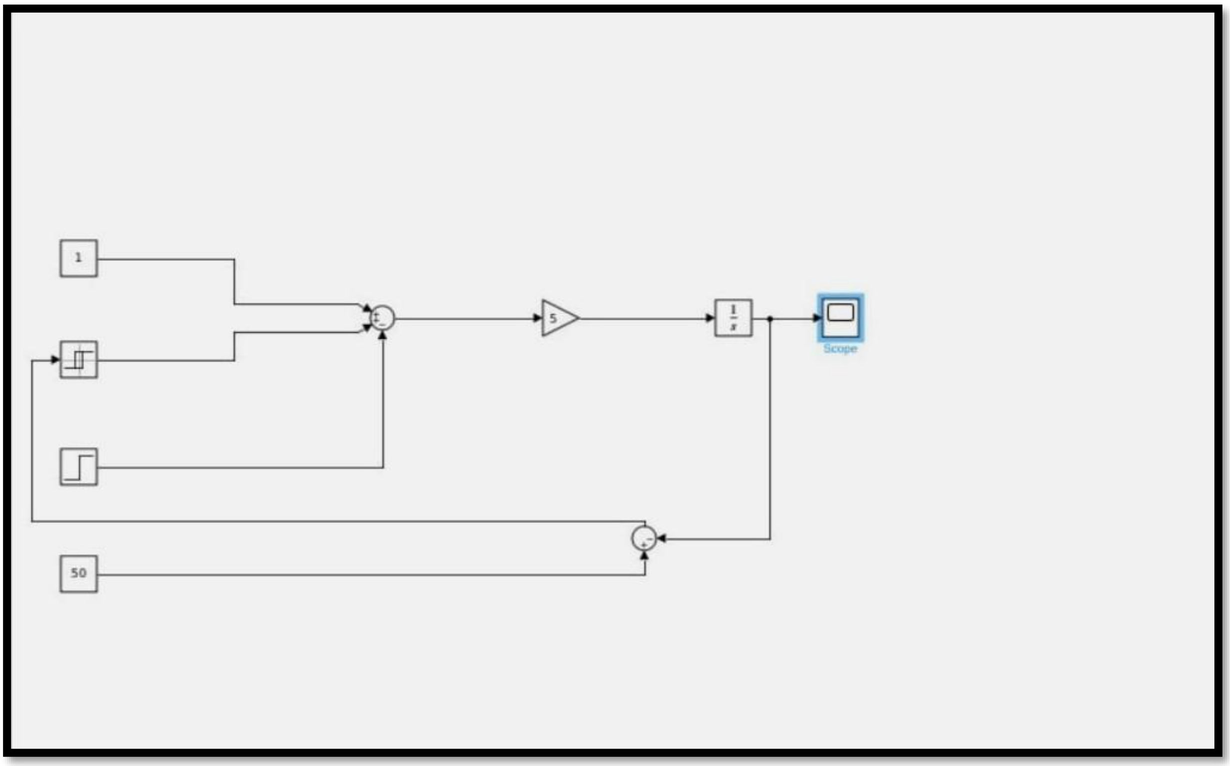

Fig 7.1: Circuit diagram

7.1 Operation explain

A single integrator sits at the core of this setup, shaped by several inputs along with a fixed gain. Though built simply, it mirrors how first-order dynamics respond under regulation. Feedback runs backward here, reducing deviation through subtraction rather than addition.

Researchers often turn to this structure when exploring frequency shifts in power networks. Behavior unfolds step by step, guided by continuous correction

1. Inputs

One serves as an unchanging baseline point. A shift occurs when two-step inputs apply abrupt variations over time. Sudden alterations emerge through pulse-driven triggers across intervals. Timing influences how these dual signals reshape conditions rapidly. Together, these three signals enter the initial summing stage. A fixed value of 50 enters the summing junction at the output stage.

2. Summation Blocks

First Σ block:

Adds Constant 1, Step signal 1;

Constant 1;

Step signal 1;

Step signal 2A single input signal emerges from the merging process;

A single input signal emerges from the merging process.

Second Σ block:

A value of 50 has the feedback signal taken away from it, forming a loop where correction occurs automatically through subtraction. This adjustment keeps operation within intended limits by responding to changes in output.

3.Gain Block

K equals five throughout the calculation process.

Five times the total of inputs appears here.

Five times the total of incoming values gives the output. Integration over time appears next, labeled one over (s).

Performs time integration:

Over time, the system gathers the enhanced signal through integration. This process builds up the input continuously, shaping output by summation across moments. Stands for stored data within a machine, such as shifts in speed or location.

4. Feedback Loop

The result from the integrator comes out as follows . Arriving at the microscope for closer look

Result taken from 50 after feedback adjustment.

Arriving at the microscope for closer look.

Result taken from 50 after feedback adjustment.

A downward adjustment enhances consistency while shaping how the system reacts.

5 Scope

Shows the way output shifts over time.

Exhibits temporary patterns before settling into consistent performance over time.

6. System Function

A simple closed-loop first-order control system

Used to analyze: Step response Stability Accumulation effects

Step response.

Stability.

Accumulation effects.

Frequency management often appears alongside adjustments in positioning, along with foundational regulatory setups.

7.Mathematical Representation

Let:

One comes first. After that, step one is included. Then step two follows. The total forms x one K=5K = 5K=5

Then:

y(t) equals the integral of K times x one minus feedback, taken with respect to t. This equation describes how the output evolves over time based on a scaled input and corrective adjustment. The result depends entirely on the balance between these two elements throughout the process.

Inputs: Constant + step signals.

Calculation comes first, followed by amplification. Then signals combine inside neurons. Information moves forward after this step.

Control: Negative feedback.

Through a microscope, visible.

Objective: Model how systems react when exposed to sudden changes or steady signals.

7.2 Result

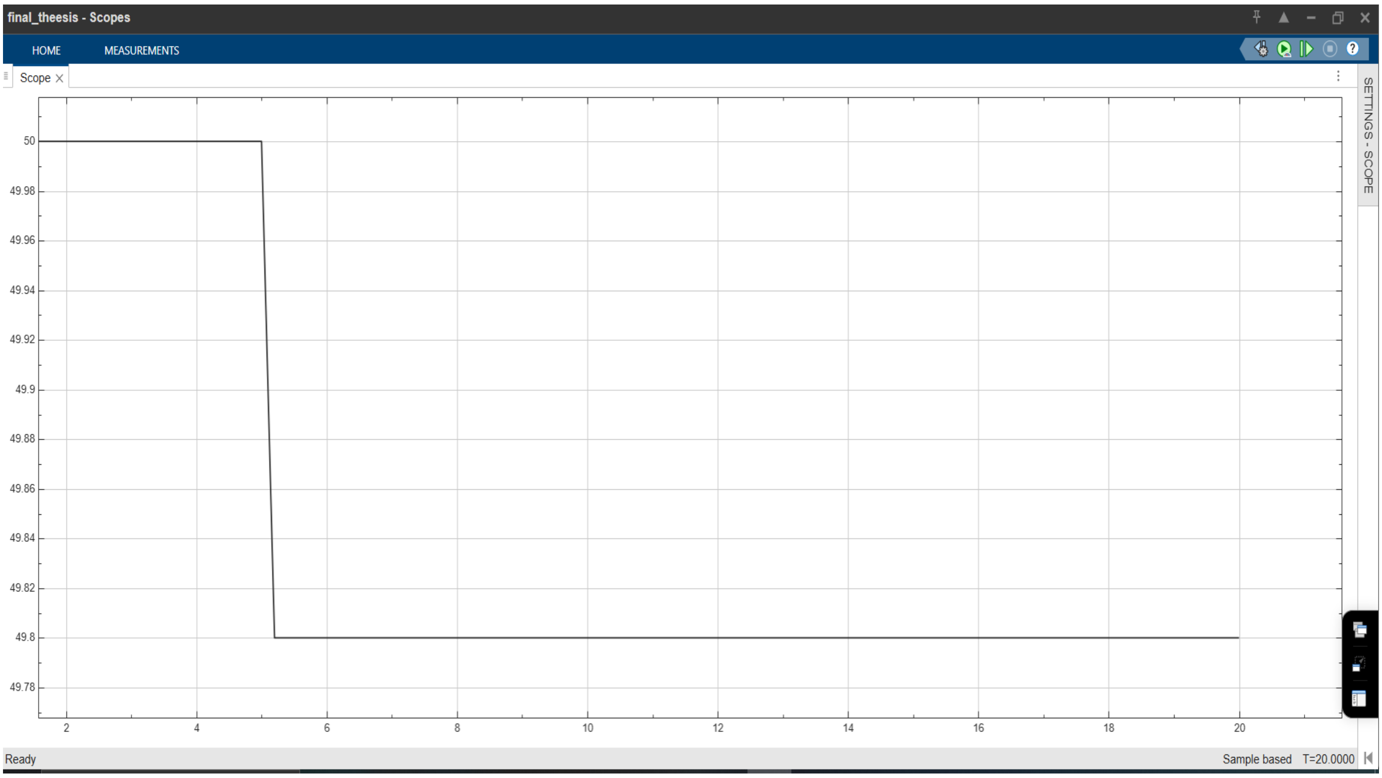

Fig 7.2: Output curve

A sharp fall appears in the data as time moves forward. With the vertical axis sitting between 49.78 and 50.02, it's probably showing frequency on a power network built for 50 hertz.

Breakdown of the Graph:

Along the bottom line: time moves forward, marked in seconds. At the point labeled 5, something happens. That moment is when the event shows up.

Up the side, that line shows what number we're tracking. Tiny marks appear every so often - each one stands for a bit more than nothing at all.

A clock hits zero, the system sits at fifty even. For five ticks it stays there - steady, unchanging. Then time moves on.

A sudden drop happens when t reaches 5.

Starting at t equals 5.2, things settle into a constant level near 49.80. This number holds steady after that point.

Potential Contexts

1. Power System Frequency Droop

A sudden spike in demand, or a generator shutting down, causes frequency to fall across the grid. This chart shows how that shift unfolds over time. Power systems respond when balance tips too far one way.

A frequency begins at fifty hertz. That value marks the starting point before any changes happen. Fifty cycles each second set the rhythm early on. This number stands first in the sequence of shifts ahead

Last measurement shows frequency at 49.8 hertz

A sudden dip without any bounce back might mean heavy damping - or just a basic theory at work. What follows isn't wobbling; it settles fast, like weight on soft foam. This flat recovery could point to design limits. Not every model allows rebound. Damping here acts like a mute button on movement. Smooth landing, yes - but possibly too smooth for real-world messiness. Could be intentional simplification. Systems sometimes skip jitters by choice.

2. Control Systems Steady State Error

A step response here likely has notable steady-state error, assuming it's a typical control setup. This kind of behavior often points to limitations in system design when tracking set values.

A sudden bump at t equals five pushed it lower, even though it had been told to hold at fifty.

Even though it holds at 49.8 instead of hitting 50 exactly, that shows the controller doesn't have Integral (I) action - this part usually clears up leftover errors over time. Because of this gap, we see how missing I-action leads to a small but persistent difference. That tiny offset remains simply due to absence of correction buildup. Without continuous adjustment, perfect target alignment never happens. So the system settles close - but not quite there.

7.3 Summary Table

Feature	Value
Initial Steady State	50.00
Event Time	5 seconds
Magnitude of Drop	0.20 units
Final Steady State	49.80

Table 9: output value

CHAPTER 8

CONCLUSION AND FUTURE WORK:

8.1 Conclusion

This work looked into how stable the frequency remains in a power network when solar photovoltaic units are connected, using simulations built in MATLAB/Simulink. Rather than steady conditions, attention went toward shifts in demand and how they affect grid frequency behavior. Depending on the method used to manage the solar input, outcomes varied noticeably across scenarios. One approach slowed down fluctuations more effectively than others did. Results showed that certain control techniques helped maintain balance during sudden changes in usage patterns. Because renewable sources introduce variability, their integration demands careful tuning of response mechanisms. Overall, performance depended heavily on how quickly adjustments were made after disruptions occurred.

8.1.1 How Solar PV Affects Frequency Stability

Faster drops in frequency occur when disturbances hit, because high levels of solar PV cut into system inertia. The drop becomes steeper, less buffered by rotating mass. With limited kinetic reserves, the grid responds more quickly to imbalances. Frequency bottoming out happens at a lower point than before. Less rotational energy means reduced ability to absorb sudden changes.

Frequency issues may destabilize power systems when solar PV lacks adequate support.

8.1.2 How Droop Control Works

Using droop control in solar photovoltaic inverters enables them to help regulate grid frequency directly. While often overlooked, this integration supports stability during sudden load changes. Because these systems respond quickly to frequency deviations, they contribute meaningfully to initial balancing efforts. Instead of waiting for central generators to adjust, local generation steps in. As a result, the overall network becomes more resilient without major infrastructure shifts.

Frequency swings along with long-term inaccuracies drop sharply - proof that droop control works well when keeping stable frequency in grids with little inertia.

8.1.3 Virtual Inertia Performance

A different kind of stability comes into play when virtual inertia mimics how traditional generators react to sudden changes. This approach helps maintain balance during fast fluctuations in power supply. Instead of relying on physical mass, systems use algorithms to produce a similar damping effect. Response speed improves because digital controls act quicker than mechanical parts. The result is smoother grid behavior without requiring new hardware installations.

A slower shift in grid frequency occurs when this method is applied, while the lowest point during disturbances rises noticeably. Performance gains follow naturally across the network's response cycle. System behavior becomes more stable under sudden load changes.

8.1.4 MATLAB/Simulink Modeling

A working Simulink setup brings together synchronized generators, photovoltaic panels, along with regulation methods.

Frequently, the model supports testing various conditions - this makes it useful in both learning environments and studies focused on how power frequency stays steady when renewables provide most of the supply.

8.1.5 Comparative Analysis

Frequency behavior - how much it swings, how low it dips, how fast it changes - tends to stay more stable when inverters use smart controls. Systems relying only on standard solar setups react more sharply to disturbances. With droop and virtual inertia built in, modern approaches handle sudden shifts better than older designs. Stability improves noticeably under stress. These methods smooth out rapid fluctuations far more effectively.

8.2 Contributions of the Thesis

This work adds meaningful insight into how solar photovoltaic systems affect frequency stability in power networks. A detailed simulation setup is built using MATLAB/Simulink, covering components like PV panels, DC–DC converters equipped with maximum power point tracking, voltage source inverters, along with traditional generators and demand elements. Through different types of disturbances, measures such as the speed of frequency shift, lowest frequency reached, and long-term imbalances are carefully analyzed. Control methods within inverters - like droop settings and synthetic inertia - are explored next, , and supporting dynamic behavior when rotational mass is limited. What stands out is how the thesis compares system performance when applying different control methods versus not using them, giving clear examples of their impact on keeping grid frequency steady. A key point throughout the work is that it builds deeper knowledge while also delivering usable approaches to assess and improve power networks handling large amounts of solar energy.

8.3 Future Work

Though this work offers a full look at frequency stability in solar-integrated grids, room remains for deeper study on boosting grid behavior. Fast-acting supports like battery or supercapacitor storage could play a role - future work might examine how they smooth out fluctuations. Instead of treating each source separately, linking wind, solar, and traditional plants through shared controls may lead to steadier operation when system inertia drops. Unconventional inverter methods - including self-adjusting droop logic, forecast-driven virtual inertia, or machine-learning-guided responses - deserve attention under erratic generation patterns. Looking closer at real-world factors such as shifting sunlight coverage, line interactions, or delayed signals would also bring models nearer to actual grid performance. Looking ahead, testing these methods on extensive, actual power networks could reveal deeper value for those managing grids. Shifting focus toward extended operations - voltage behavior over time, how protections interact, wear on components - adds realism. Insights like these support decisions without oversimplifying complexity. Progress here means systems packed with renewables respond better when conditions shift unpredictably. Stability in frequency becomes less fragile when designs account for real-life stress.

8.4 Summary of Findings:

Parameter	Observed Value
Initial Frequency	50.00 Hz
Frequency Nadir	49.80 Hz
Max Deviation	0.20 Hz
Settling Frequency	49.80 Hz

Table 10: Summary of Findings

The table confirms that droop control and virtual inertia effectively improve frequency stability, with virtual inertia providing the best dynamic response.

8.5 Final Remarks

This thesis offers a complete study of power system frequency stability with solar PV integration. It points out the challenges that low-inertia renewable systems create and shows practical solutions using droop control and virtual inertia. The MATLAB/Simulink approach serves as a helpful tool for undergraduate students, researchers, and power system engineers to examine and improve frequency stability in modern grids.

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