Smart Grid Integration of Hybrid Photovoltaic & Wind Power Systems

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Abstract

As the global population increases the demand for energies increases rapidly, the energies demand is not fulfilled by traditional energy resources and it produces lot of pollution, which is a global concern for environment, so to meet the demands of clean energy has accelerated the adaption of renewable energy sources, such photovoltaic (PV) solar power and wind energy. However, integrating these technologies to traditional electrical grid systems comes with lot of challenges.
This paper investigates the idea of hybrid Photovoltaic – wind power systems and its integration into electrical grid systems.
It covers the potential solutions for the challenges based on the recent technological advancements ensuring the efficient integration of renewable energy sources.
Furthermore, it explores the smart grid technologies, such as real time- time monitoring, load distribution, and advanced control systems, which can enhance the reliability, efficiency and flexibility of grid when incorporating with renewable energy sources.
This paper also includes the case studies and suggests area for future research to improve the performance of grid and the reliability of hybrid renewable energy systems.

1. Introduction

The integration of renewable energy has become essential in global efforts to address greenhouse gas emissions, tackle climate-related challenges, and reduce reliance on limited fossil fuel resources, which are being rapidly depleted due to ongoing consumption. Many nations are now turning to renewable energy sources to drive next-generation technology development[1].. The adoption of renewable sources—such as solar, biomass, hydro, and wind—varies significantly by country. However, integrating these energy sources into existing power grids introduces challenges, including outages, voltage instability, and energy losses. Among the renewable options, solar and wind energy stand out as the most promising, though both are inherently intermittent: solar energy is available only during daylight, while wind power depends on varying weather conditions[2]. While the basic grid infrastructure has seen minor updates to meet growing electricity demands, the overall utility system still operates in much the same way it did a century ago. Energy flows from central power plants to end-users via the utility grid, with reliability supported by maintaining spare capacity. Unfortunately, this approach is both environmentally taxing and inefficient, as well as a major contributor to pollution and greenhouse gas emissions[3][4].

Moreover, the structure of today's energy infrastructure makes it prone to cascading failures, where a disruption in one part of the network can lead to widespread outages. This system operates much as it did a century ago, with power generated at large, centralized plants and distributed through an extensive utility grid to homes and businesses. Reliability in this setup relies on maintaining significant reserve capacity, which not only incurs high costs but also places a heavy environmental burden. The reliance on traditional energy sources contributes significantly to pollution and greenhouse gas emissions, highlighting the need for more sustainable and efficient alternatives.[5].

2.Electricity Generation in India

In India, the most common approach to increasing electricity supply is to set up centralized power plants and transmit energy directly to where it's needed. Distributing power in rural areas generally involves three main cost components: generation, transmission, and distribution. For more remote areas, renewable options like wind and solar energy can be used to generate electricity.

India’s sources of electricity can be divided into two main categories: conventional and non-conventional. Conventional sources include thermal (like coal, lignite, natural gas, and oil), hydro, and nuclear power. On the other hand, non-conventional, or renewable sources, consist of solar, wind, and energy from agricultural or household waste. Table 1(a) and Fig. 1(a) illustrated the installed capacity of electricity generation in India from these different sources [7].

Table-1(a): Installed Electricity Generation Capacity in India (GW), 2008-09 to 2022-23

Year	Thermal	Hydro	Nuclear	RES**	Total
2008-09	93.73	36.88	4.12	13.24	147.97
2009-10	102.45	36.86	4.56	15.52	159.40
2010-11	112.82	37.57	4.78	18.45	173.63
2011-12	131.60	38.99	4.78	24.50	199.88
2012-13	151.53	39.49	4.78	27.54	223.34
2013-14	168.26	40.53	4.78	34.99	248.55
2014-15	188.90	41.27	5.78	38.96	274.90
2015-16	210.68	42.78	5.78	45.92	305.16
2016-17	218.33	44.48	6.78	57.24	326.83
2017-18	222.91	45.29	6.78	69.02	344.00
2018-19	226.28	45.40	6.78	77.64	356.10
2019-20	230.60	45.70	6.78	87.03	370.11
2020-21	234.73	46.21	6.78	94.43	382.15
2021-22	236.11	46.72	6.78	109.89	399.50
2022-23*	237.27	46.85	6.78	125.16	416.06

Source: CEA, Growth of Electricity Sector in India, various issues.
*** RES includes Small Hydro Project (≤ 25 MW)*

Fig.-1(a): Installed Electricity Generation Capacity in India (%), 2008-09 to 2022-23

3.Smart Grid Technology

Smart Grid is an advanced electrical grid that different from the conventional electrical grid. It is grid in which there is bidirectional transmission of power supply. It uses the digital communications and automation to enhanced the monitoring, control, and efficiency of electricity delivery. It is designed to handle the bidirectional flow of energy and information which allows the better integrations of variable renewable energy like solar and wind energy.

Some core components of smart grid and there benefits:

• Engages directly with users and responds to market demands.
• Flexible and able to adapt and expand according to different needs.
• Designed to make the most of available resources and equipment
• Focuses on prevention rather than just reacting to problems as they arise.
• Features self-healing capabilities with high levels of automation
• Combines monitoring, control, and protection in a unified system.
• Supports maintenance, energy management (EMS), distribution management (DMS), advanced metering infrastructure (AMI), and more.
• Includes plug-and-play options for network hardware and IT solutions.

The fast-growing deployment of renewable energy sources demands a unified and coordinated approach, from the initial planning phases right down to the specific electronic devices used in power generations, distribution, storage, and consumption [8],[9].

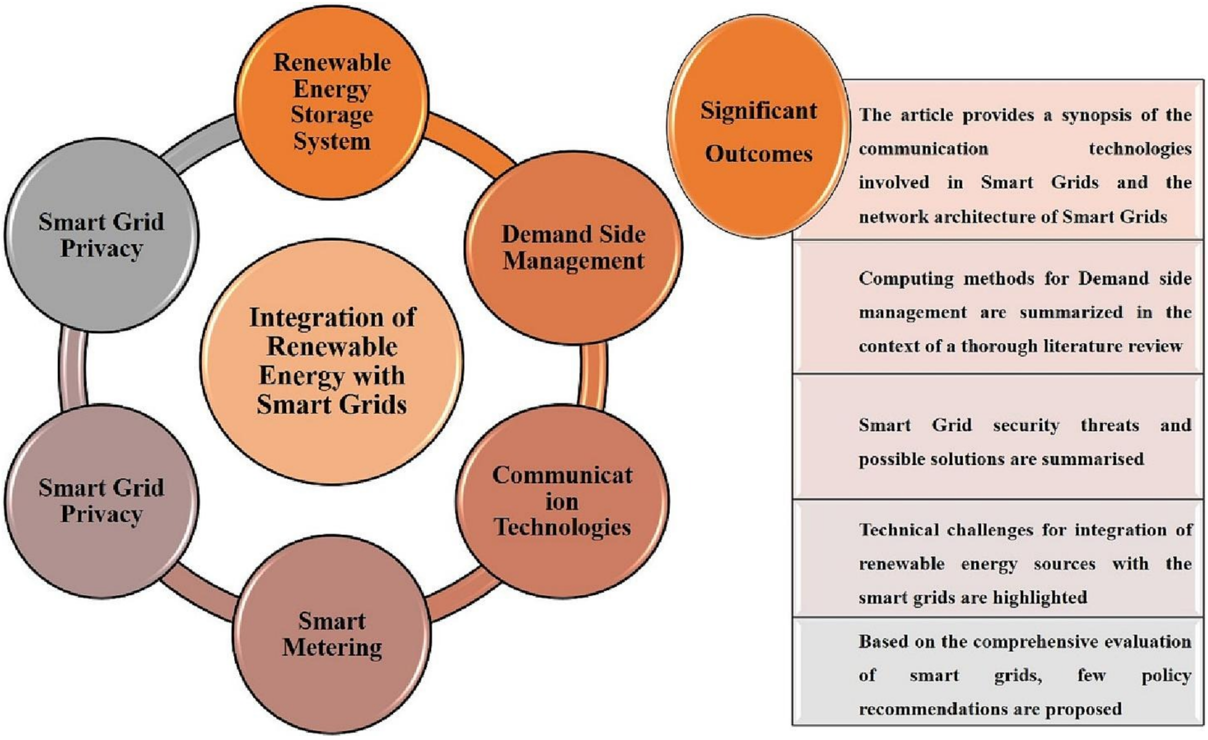
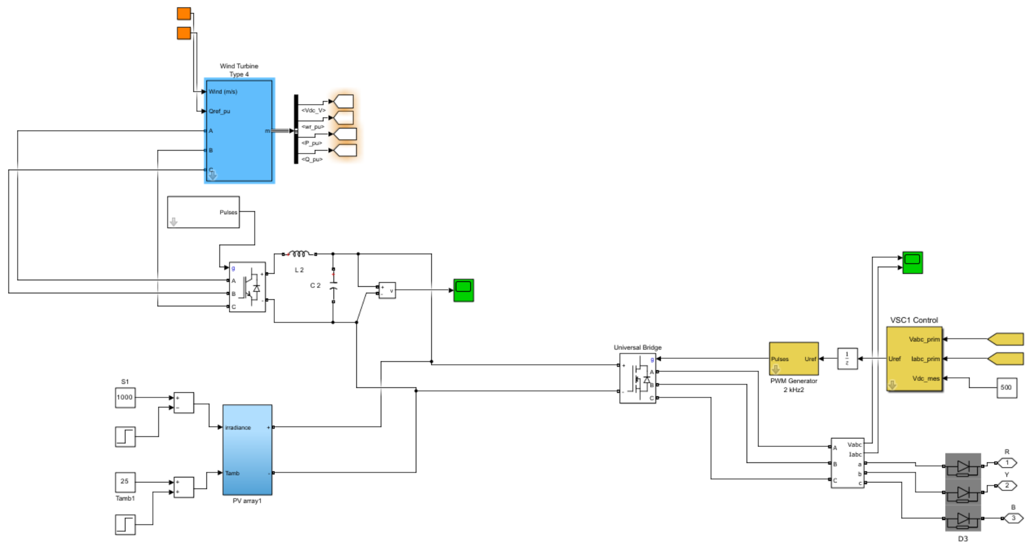


Fig. - 2 Smart grid Features

4.Hybrid Renewable Energy Systems

Hybrid power systems consist of various integrated components working together to generate power. The term "hybrid" reflects the system's ability not only to produce but also to store energy, often involving some form of energy storage. These systems are typically designed in conjunction with renewable energy sources, such as a combination of solar and wind power. Additionally, a blend of multiple sources can be utilized to meet specific energy demands. Hybrid systems enhance energy security and diversify the energy supply, leading to fewer power outages. They are also known for providing a dependable and long-lasting energy supplyhis version maintains the content's technical meaning but modifies the language



and structure [9].

Fig.3 Hybrid Photovoltaic and Wind Turbine Power System

4.1 Component of Hybrid Renewable Energy Systems

3.1(a) Wind Turbine: In this system, a wind farm with 1.5 kW turbines is modelled, where each turbine has a 1500 W capacity and is connected to a 25 kV distribution network. Power is then transmitted through a 30 km, 25 kV feeder line to a 120 kV grid. This example utilizes Type 4 wind turbines, equipped with a synchronous generator linked to a diode rectifier and a DC-DC IGBT-based PWM boost converter, along with a DC/AC IGBT-based PWM

converter. This advanced Type 4 setup enables the system to capture optimal energy from low wind speeds by adjusting turbine speed as needed. Additionally, the configuration helps reduce mechanical stress during sudden wind gusts, boosting the efficiency and lifespan of the system[10].
The input parameters for the wind turbine are wind speed is equal to 15m/s and Qref_pu is 0.

Wind Turbine Model Configuration Table

Parameter	**Value**
Number of Wind Turbines	1
Speed Regulator Gains [Kp Ki]	[5,1]
Grid-side Converter VAR Regulator Gain [Ki]	0.05
Grid-side Converter Voltage Regulator Gain [Ki]	2
Grid-side Converter Current Regulator Gains [Kp Ki]	[1, 50]
DC Bus Voltage Regulator Gains [Kp Ki]	[1.1, 27.5]
Boost Inductor Current Regulator Gains [Kp Ki]	[0.025, 100]

Power generated by Wind Turbine generator:

$$\text{Power} = \frac{1}{2}\, C_p \rho A V^3 \qquad (1)$$

Where,

C_p: The coefficient of performance in percentage.
V: The wind speed in meters per sec
ρ: The air density in kilograms per cubic meter
A: The rotor swept area in sqr meters.

Output Waveform generated by Wind turbine System

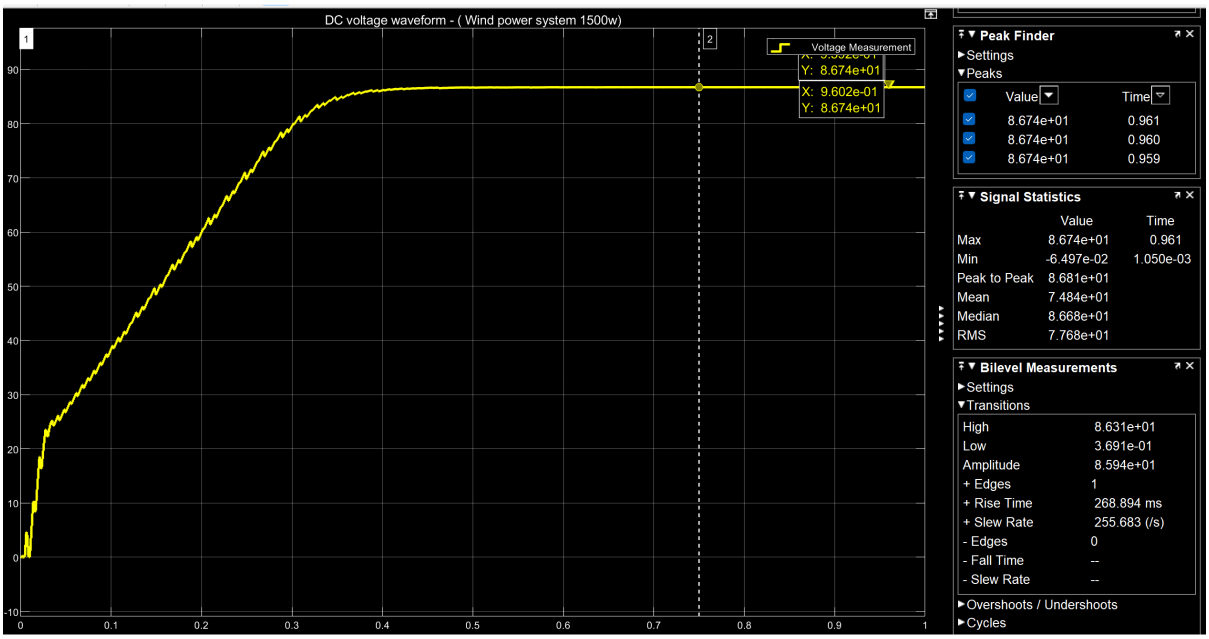


Figure 3.1(a) Output Waveform generated by Wind turbine System

3.1(b) Universal Bridge: The Universal Bridge block models a three-phase power converter in a bridge arrangement with up to six power switches. The type of switch and specific converter setup can be chosen within the block's settings. This block supports the simulation of converters that utilize either naturally commutated (line-commutated) devices, such as diodes and thyristors, or forced-commutated devices, including GTOs, IGBTs, and MOSFETs. It serves as the foundational block for constructing two-level voltage-sourced converters (VSCs). Device numbering varies based on whether naturally commutated or forced-commutated components are used; for naturally commutated three-phase converters (like those using diodes or thyristors), the numbering aligns with the natural commutation sequence[11].

3.1(c): Solar Photovoltaic Array: The PV Array block models an array of photovoltaic (PV) modules organized in strings, with each string comprising modules connected in series and multiple strings connected in parallel. This block offers flexibility, allowing the modeling of preset PV modules from the National Renewable Energy Laboratory (NREL) System Advisor Model (2018**)**, as well as custom PV modules defined by the user. The PV Array block operates on a five-parameter model, utilizing a light-generated current source (IL), diode, series resistance (Rs), and shunt resistance (Rsh) to simulate the I-V characteristics of the modules based on varying irradiance and temperature conditions[12].

The diode I-V characteristics for a single module are defined by the equations

$$I_d = I_0\left[\exp\left(\frac{V_d}{V_T}\right) - 1\right] \qquad (2)$$

$$V_T = \frac{kT}{q} \times nI \times Ncell$$

(3)
where

I_d	Diode current (A)
V_d	Diode voltage (V)
I_0	Diode saturation current (A)
nI	Diode ideality factor, a number close to 1.0
k	Boltzmann constant = 1.3806e-23 J.K-1
q	Electron charge = 1.6022e-19 C
T	Cell temperature (K)
$Ncell$	Number of cells connected in series in a module

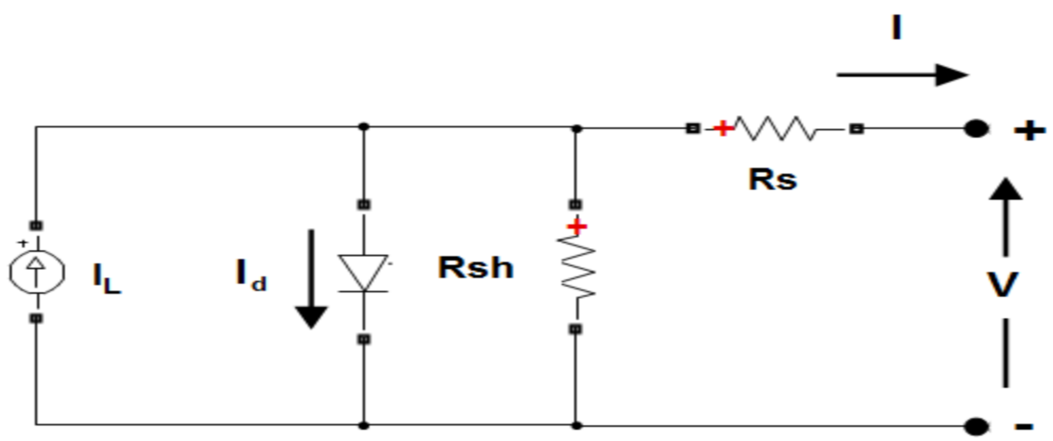


Fig.4- Circuit diagram of Photovoltaic Cell.

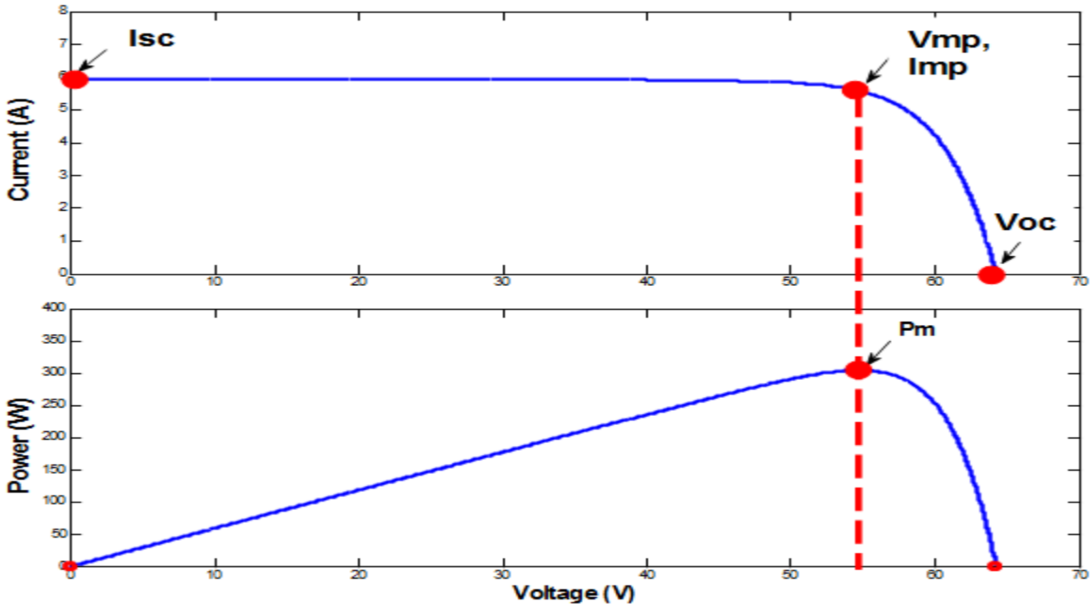


Fig.5 Output waveform diagram of photovoltaic system

3.2 Component of Hybrid Renewable Energy Systems

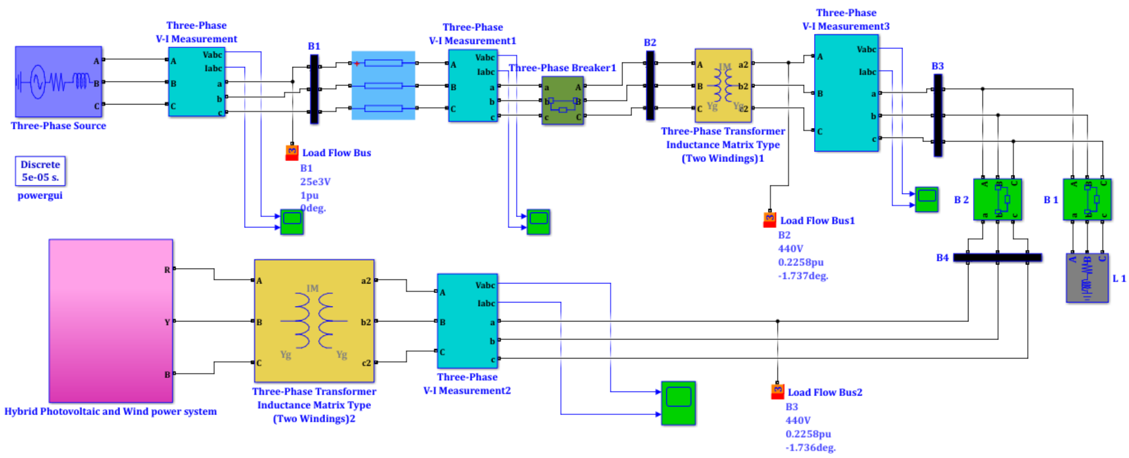


Fig.6 Grid integration of photovoltaic and Wind power system

3.2.1 The Three-Phase Transformer Inductance Matrix type (Two Windings) block models a three-phase transformer with a three-limb core, incorporating two windings per phase. Unlike the Three-Phase Transformer (Two Windings) block, which simulates the setup as three separate single-phase transformers, this model accounts for interactions between the windings of different phases, allowing for a more unified representation of the system.

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_6 \end{bmatrix} = \begin{bmatrix} R_1 & 0 & \dots & 0 \\ 0 & R_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & R_6 \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_6 \end{bmatrix} + \begin{bmatrix} L_{11} & L_{12} & \dots & L_{16} \\ L_{21} & L_{22} & \dots & L_{26} \\ \vdots & \vdots & \ddots & \vdots \\ L_{61} & L_{62} & \dots & L_{66} \end{bmatrix} \cdot \frac{d}{dt} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_6 \end{bmatrix}.$$

Transformer Model:
The Three-Phase Transformer Inductance Matrix Type (Two Windings) block operates based on a matrix relationship. In this model, R1 to R6 denote the resistances associated with each winding. The self-inductance values (Lii) and mutual inductance values (Lij) are computed using key parameters, including voltage ratios, inductive elements from the no-load excitation currents, and short-circuit reactances at the nominal operating frequency. With both positive-sequence and zero-sequence values provided, this configuration allows calculation of the six diagonal and fifteen off-diagonal elements in the symmetrical inductance matrix.

Key Parameters in the Transformer Block

Parameter	**Description**
Core Type	Specifies the type of core for the transformer. Options include three-limb or five-limb core, and it influences how the magnetic coupling is represented.
Winding 1 Connection	Specifies the connection type for winding 1 (primary winding). In this case, it is **Yg** (wye-grounded).
Winding 2 Connection	Specifies the connection type for winding 2 (secondary winding). Here, it is also **Yg** (wye-grounded).
Autotransformer Option	Allows the user to connect windings 1 and 2 in an autotransformer configuration (Y, Yn, or Yg). This option is unchecked, meaning the transformer operates as a standard two-winding transformer.
Measurements	Allows the user to choose the types of measurements (voltage, current, flux, etc.) to output for analysis. Here, it is set to **None**, so no additional measurements are taken.

4.Control System Used Smart Grid

4.1 **Maximum Power Point Tracking (MPPT):** An **MPPT controller** plays a critical role in photovoltaic (PV) systems by continuously adjusting the operating point of the PV array to align with its maximum power point (MPP), thereby maximizing power output. Given the non-linear voltage-current (V-I) characteristics of PV modules, which shift with changes in sunlight intensity (irradiance) and temperature, an MPPT controller is essential for adapting to these variations and extracting optimal power under all conditions. By tracking the MPP, the controller ensures that the PV system consistently operates at peak efficiency, even during fluctuating weather patterns. This technology not only improves energy yield but also contributes to the longevity of the PV system by reducing strain on the modules, thus enhancing the overall reliability and sustainability of solar power generation. [13][14].

The power output of a PV array is given by:

$$P = V \times I \quad (4)$$

where:
P : power output of the PV array.
V: operating voltage of the PV array.
I : operating current of the PV array.
Our goal is to find the optimal values of V and I to maximize the P using MPPT.

Maximum Power Point (MPP) Condition: At the maximum power point (MPP), the derivative of power with respect to voltage is zero:

$$\frac{dV}{dP} = 0 \quad (5)$$

Since P=V×I, applying the product rule of differentiation gives:

$$\frac{dV}{dP} = I + V\frac{dI}{dV} = 0 \quad (6)$$

which can be rearranged to:

$$\frac{dI}{dV} = -\frac{I}{V} \quad (7)$$

This equation represents the condition for maximum power, where the incremental conductance $\frac{dI}{dV}$ is equal to the negative of the instantaneous conductance $\frac{I}{V}$.

Perturb and Observe (P&O) Algorithm

The Perturb and Observe (P&O) algorithm adjusts the voltage and observes changes in power. The key logic is:

- If ΔP>0 (power increases with a voltage change), continue perturbing in the same direction.
- If ΔP<0 (power decreases with a voltage change), reverse the direction of perturbation.

Mathematically, this is represented as:

$$P(k) - P(k-1) > 0 \Rightarrow V(k+1) = V(k) + \Delta V \quad (8)$$

$$P(k) - P(k-1) < 0 \Rightarrow V(k+1) = V(k) - \Delta V \quad (9)$$

where:

- K is the current iteration,

- P(k) and P(k−1) are the power at the current and previous iterations,
- ΔV is a small perturbation applied to the voltage.

5.Performance analysis of Grid System

Start by analyzing how well the hybrid PV-wind system meets the energy demands. This includes looking at the total energy generated by the PV panels and wind turbines over different periods (daily, seasonal) and comparing it with peak and off-peak demand patterns. Discuss load matching capabilities, indicating if the energy generated aligns well with demand curves. Consider metrics like Capacity Factor (actual energy generated compared to potential maximum), Load Factor, and Power Curve Analysis for wind turbines.

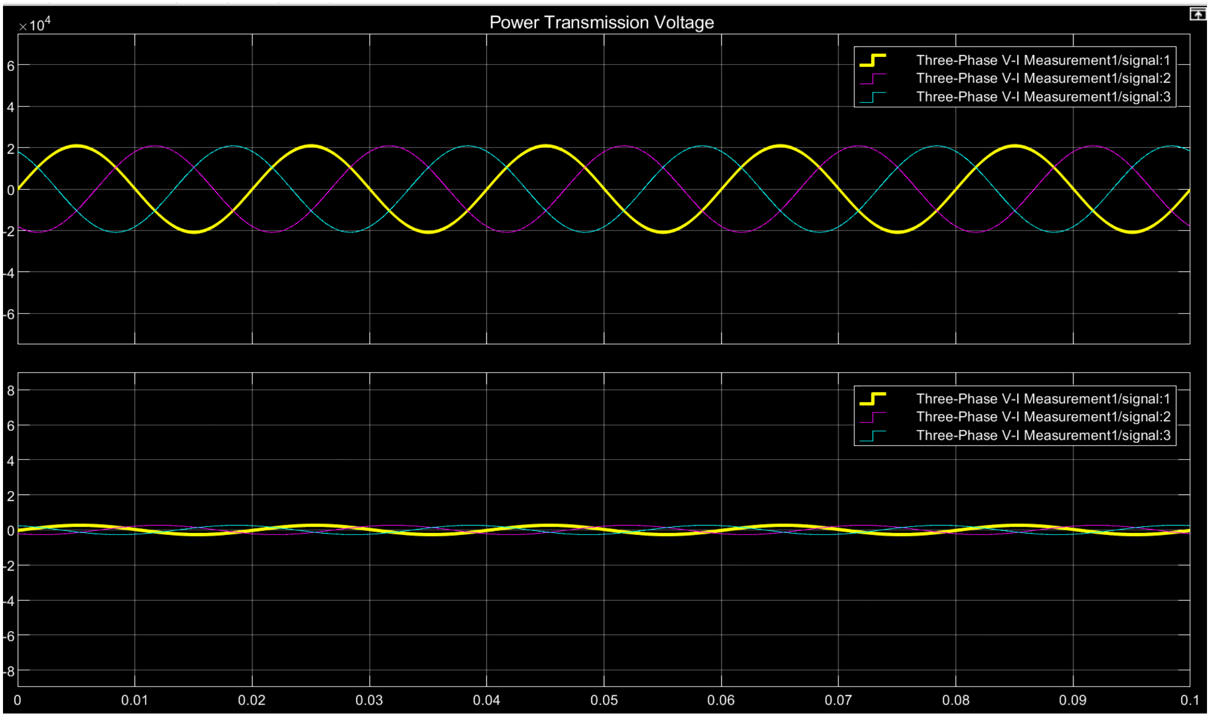


Fig.7 Performance analysis of Grid System

The main power-carrying voltage waveforms and any smaller residual signals, allowing engineers to assess the overall stability and quality of the power transmission. The top graph focuses on the primary power flow, while the bottom graph likely reveals minor fluctuations or noise, which could impact sensitive equipment and would be considered in maintaining system efficiency and reliability.

The efficiency of the system in converting solar and wind energy into usable electrical power. Include metrics like Inverter Efficiency for PV systems, Wind Turbine Conversion Efficiency, and Overall System Efficiency after integrating energy storage and distribution losses. Also, discuss potential energy losses in transmission and conversion and strategies to minimize these losses

6. Case Studies of Hybrid Photovoltaic-Wind Integration

6.1 The Horns Rev 2 Offshore Wind Farm and Solar Power Integration (Denmark)

Denmark has been a pioneer in renewable energy integration, with a significant focus on offshore wind power. The **Horns Rev 2 Offshore Wind Farm** is one of the largest offshore wind farms in the world. The Danish energy sector has made considerable progress in integrating **solar PV systems** with wind farms to create hybrid renewable systems that balance energy production.

The **smart grid** infrastructure in Denmark allows for seamless integration of solar and wind energy into the grid, using real-time monitoring and control to manage fluctuating power output. The integration of energy storage systems and demand response mechanisms ensures that power supply remains stable, even when wind and solar generation are low.

7.Conclusion

The integration of **hybrid photovoltaic-wind power systems** into **smart grids** represents a crucial step toward achieving a sustainable and reliable energy future. While there are challenges related to intermittency, grid compatibility, energy storage, and stability, the benefits of hybrid systems—such as reduced variability, higher capacity factors, and enhanced grid resilience—make them a promising solution. As advancements in control systems, energy storage, and grid technologies continue, hybrid systems will play an increasingly important role in modern energy networks. The future of renewable energy integration relies on innovation, collaboration, and the development of new technologies to ensure that energy from wind and solar is both abundant and reliable.

8.Appendix

Photovoltaic Cell and Power grid Specification: 3 kW; , Wind power : 1.5kW
PV Panel: V_{oc} =36.3V, I_{sc} =87.84A, V_m =29V,
I_m =7.35A, temperature coefficient of V_{oc} (% deg.C)=-0.36099, dc Capacitor= 3e-4F, Filter: 3e-2H, 0.03Ω and 60 μF; Wind power : 1.5kW.

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