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Research Article

Simulation Studies of Grid- Connected 1 KW Wind Energy Power Plant using MATLAB for Renewable Energy Building in RTU Kota, India

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Abstract

The renewable energy sources like wind energy takes an important role to achieve sustainable goal. The wind energy is freely available pollution-free source by which electricity can be produced by the help of wind turbine. Small wind is available in Kota of speed 3m/s to 5 m/s for whole year. So small windmill which can be operated on the small and medium wind can be installed in Kota along with the Chambal River in plain areas and nearby hills.

This study focuses on the design and simulation of a 1 kW grid-connected wind energy power plant for a Department of Renewable Energy building in Kota, India. The project aims to harness wind energy as a sustainable source of power to meet the energy demands of the building. By integrating a small-scale wind turbine with the existing grid infrastructure, this system ensures both renewable energy generation and reliability through grid support. The wind energy potential of the Kota region is analyzed, and the system is designed based on local wind speed patterns. The design includes key components such as the wind turbine, power electronics for grid interfacing, and battery storage for energy stability. Simulations are conducted using MATLAB/Simulink to evaluate the system's performance in terms of energy output, efficiency, and grid compatibility. The study demonstrates the feasibility of implementing small-scale wind energy systems in urban institutional buildings and highlights the potential of renewable energy integration in India's energy mix.

Keywords: ***Wind energy, MATLAB, grid-connected system design, Simulink, Feasibility etc.***

1. Introduction

Wind energy is increasingly vital in today's world as it addresses several critical needs, including environmental sustainability, energy security, and economic growth. As a clean and renewable source of power [Fuskele *et al*. 2021, 2022; Malakar and Lal 2025], wind energy significantly reduces greenhouse gas emissions, helping to combat climate change and minimize air and water pollution. It also plays a crucial role in diversifying energy sources, reducing dependence on imported fossil fuels, and enhancing energy security by decentralizing power generation. Economically, the wind energy sector creates jobs in manufacturing, installation, and maintenance, stimulating local economies, especially in rural areas where wind farms are often located [Singh *et al* 2023; Hussain *et al* 2024]. Technological advancements have made wind energy more cost-competitive with traditional fossil fuels, contributing to long-term affordability. As countries around the world pursue renewable energy targets to transition to low-carbon economies, wind energy has become essential for meeting these goals. Additionally, wind farms can coexist with agricultural and other land uses, providing dual-use opportunities that benefit landowners. Altogether, wind energy is a key component of a sustainable and secure energy future [Singh *et al*. 2023].

The scope of wind energy is broad and multifaceted, encompassing a range of applications, innovations, and global initiatives aimed at harnessing wind as a clean and sustainable energy source. Wind energy is generated by converting the kinetic energy of wind into electricity using turbines, and it has the potential to supply a significant portion of the world's electricity demand. The versatility of wind power is evident in both onshore and offshore wind farms, with offshore installations gaining traction due to stronger and more consistent wind patterns found at sea, which allow for higher energy yields.

Kara *et al* [2024] evaluated the performance for sustainability using fuzzy based SF-DIBR II-AROMAN model which was robust and consistent overall. A case study is carried out to illustrate its feasibility of WEPPs in Çanakkale, Turkey, whose capacities range from 25 - 150MW. Kanberger *et al* [2024] evaluating an empirical examination of private backing for local power plant growth. An examination of Germany's nuclear, coal and wind energy sectors which support for the regional installation of wind turbines is strongly correlated with being close to wind turbines; however, there is no discernible association between proximity and coal & nuclear power facilities.

Sahin *et al* studied the combined LSTM and Copula-based trees to evaluate wind power potential. By recognizing and resolving the non-independence of variables, novel frameworks such as the Copula-LSTM based decision tree approach can greatly enhance the precision and dependability of the evaluation & analysis of wind power plant potential in various real-world cases.

Xiong *et al* presented the co-optimization of energy trading, pricing, and scheduling decisions for IWC-VPP using DRO. Information encryption for multiple IWC-VPPs is presented using a completely decentralized system based on ADMM. By employing the multipliers in alternating direction management method (ADMM), show that for typical ADMM, the variable penalty factor method improves computing efficiency by as much as 46.51%. Wang *et al* assessed the use of an electric heat pump and thermal energy storage for heat-power decoupling is investigated. A study is conducted on the choice of peak shaving devices for wind power accommodations. Based on EnergyPRO, a simulation model is created for wind power accommodation that takes into accounts the energy balances and limitations of every production unit.

Jaman *et al* [2024] assessed a hybrid power system based on biogas and municipal solid waste has been designed. The integration of a hybrid hydrogen and battery storage system into a renewable energy system is being researched. NSGA-II in a MATLAB environment, where the main objectives are cost-effectiveness, minimizing health risks, and guaranteeing a steady supply of electricity. Novel HRES are then optimized for size and performance.

Sheikh *et al* [2023] assessed renewable energy, especially wind power which is causing dynamic changes in power systems. We underline that in order to integrate more renewable energy sources, power systems must adjust operationally. This offers critical insights for the development of sustainable power systems. the problem of frequency stability in power systems where wind turbine penetration is considerable. An extensive examination of the IEEE 39-bus test system is carried out in order to look at the suggested approaches. Using wind turbines for frequency management makes the power system operate in a more secure manner.

Yi *et al* [2022] *et al* assessed a SOC-based dynamic control approach is suggested. Frequency regulation services have the potential to significantly increase system income. The most economical approach that nevertheless preserves dependability is the dynamic control strategy. The dynamic control approach is expanded by 5.63%, 327.69%, and 4.75%, in that order. Mu *et al* [2022] assessed in contrast to the system-level approach, a unit-level cooperative operation framework for wind farms and CHP plants is suggested, which is more suitable for their cooperation. When compared to the revenue from independent operations, the revenue from combined operations is higher.

Munoz *et al* [2023] assessed models of optimization for wind-battery VPP re-dispatch and generation scheduling. The suggested models are feasible and useful for day-to-day use since they work well for short-term scheduling and VPP re-dispatch with little computational overhead. Postnikov [2022] assessed a hybrid energy source that uses wind farms and combined heat and power facilities, created a process for evaluating the heating system's dependability from a given source. After analysis, certain qualitative correlations defining universal characteristics for related things have been discovered.

Wu *et al* [2021] assessed and examined the Wave-Wind-Solar-Compressed Air Energy Storage Power Plant's risk status. Evaluate project risk using a focused, scientific fuzzy synthetic framework. Wave-Wind-Solar-Compressed Air Energy Storage currently has an unfavorable risk level. The risks associated with the WW-S-CAES project's construction and operation are complicated, long-term, and variable for project management. To assess the risk associated with the WW-S-CAES project in the context of low-carbon development, this article first identifies 14 important management, economic, and environmental criteria. Offshore WW-S-CAES has a risk rating that is more akin to moderate high, with management risk and economy risk holding the key roles.

Carta *et al* [2021] assessed and recommended approach is made for the ideal sizing of desalination facilities driven by wind. Using bulk energy storage is not used in this method; instead, a water storage reservoir is used. The system components are chosen using genetic algorithms in this manner. The inter-annual wind energy is estimated by the application of machine learning. I order to ensure continuous operation; the case study's ideal solution is compared to those that are derived using a backup battery design.

Campos *et al* [2020] assessed In the Brazilian Northeast, solar and wind resources complement each other temporally in a relevant way. A 40% wind and 60% solar energy mix requires the least amount of storage capacity to meet Brazilian NE load; the role of storage in lowering the need for transmission infrastructure for renewable energy is assessed. The daily Pearson's Correlation Coefficient for solar and wind resources in the region is −0.51. Kiryanova *et al* [2022] assessed, using high-capacity energy storage devices, such hydrogen storage, to incorporate it into the current power infrastructure. Large businesses' electricity market rates also fluctuate throughout the day at the same period. To run simulations and determine the economic efficiency of a wind turbine with and without a hydrogen storage device, software and a simulation model have been put into place.

Table 1: Country Wise Literature Review

Author	Country	Model	Output
Yongli *et al* [2018]	China	capacity optimization model	Applying Monte Carlo simulation to determine the optimal energy storage system (ESS) capacity configuration that satisfies both construction and operational requirements, as well as analyzing methods and outcomes of the actual operation of energy storage capacity planning

Gonzalez *et al* [2020]	Island	Predictive control model	The BESS demonstrated its capacity to effectively control the hybrid power plant's power output & adhere to production schedule within the specified limitations.
Sahin *et al* [2024]	Netherlands	Fuzzy regression model	According to the findings, 35317.2 km2 are ideal for solar power plants, 34844.5 km2 are acceptable for wind turbines, but only 34875.8 km2 are eligible for the setup of solar-wind power plants combined.
Souza *et al* [2024]	Brazil	Capacity factor model	The outcomes showed that it was feasible to produce green hydrogen using the leftover energy from the modest wind and hydroelectric generation facilities. SHPs had an average capacity of 5.95 MNm3 per day, while wind farms had an averaged potential of 7.66 MNm3/day.
Yorke *et al* [2023]	Ghana	levelized cost of energy (LCOE)	The findings indicated that the research site is appropriate for wind turbines with a power output between 1 and 1.5 MW.
Mendoza [2024]	Peru's countryside	System Advisor Model (SAM)	According to the results, the cheapest Levelized Cost of Energy was found at elevations from 3000 - 4200 m above sea level, with a range of from 35 to 39 $/MWh. On the other hand, the most expensive, which varies between 50 - 79 $/MWh,
Garcia *et al* [2024]	Spanish	LCOE	This approach could cut the levelized cost of energy (LCOE) for newly installed wind farms in the European Union by over 50%
Lohr *et al* [2024]	Germany	The linear optimization	According to our findings, there is a moderate influence of various distribution systems on the overall layout of the energy system.
Abarghooee *et al* [2024]	Britain	generic dynamic model	The BESS system with reserve & inertial frequency support features has been shown to improve stability of frequencies parameters such as frequency nadir, RoCoF ,& steady-state frequency derivation.
Islam *et al* [2024]	Bangladesh	Daily load demand, Anuual Peak Demand, LCOE	The PV system features an 89% performance ratio, a levelized energy cost of $0.017, and a payback period of 6.6 years.
Betancor *et al* [2024]	Canary Islands	LCOE	Reveal offshore wind energy cutoff rates above 35% and LCOE increases of up to seventeen percent. The first of the results emphasizes the necessity for government action to counterbalance the rise in the LCOE.
Weiss *et al* [2024]	Finland	Mixed integer (LP/MIP) optimization model	el P2X-plant optimization model is applied to a The P2X-plant optimization model is implemented for a Hydrogen Direct Reduction Iron (HDRI) plant with an annual production of 1.5 million tons.
Fang *et al* [2024]	China	cooperative game model	Regional market regulators or governments can set the mandatory settlement electricity price to match or be lower than the market value, based on anticipated market prices. This approach aims to incentivize wind and solar power plants to engage in market transactions, ultimately facilitating a shift towards a fully market-based transaction system.
Sarmast *et al* [2024]	Canadian	A hybrid wind-diesel adiabatic compressed air energy storage (H-WD-A-CAES)	There was a notable decrease in diesel fuel usage, with a 55% drop in diesel consumption when a single wind turbine was paired with a CAES system and an even larger reduction of 63.4% when two wind turbines were combined with a CAES system.
Lindvall *et al* [2024]	Sweden	regression models	The potential for financial benefits is the most promising factor in shaping the attitudes of people living near wind power installations.

As of 2023, global installed solar PV capacity exceeded 1,000 GW (1 TW), marking a significant milestone in the renewable energy sector. Countries like: China, the United States and Europe are leading in installations, with China alone accounting for around 40% of the world's PV capacity. The International Energy Agency (IEA) projected that solar PV could become the dominant source of electricity by 2050, contributing over 30% of global electricity generation. Continued investments in technology, policy support, and infrastructure are crucial to realizing this potential.

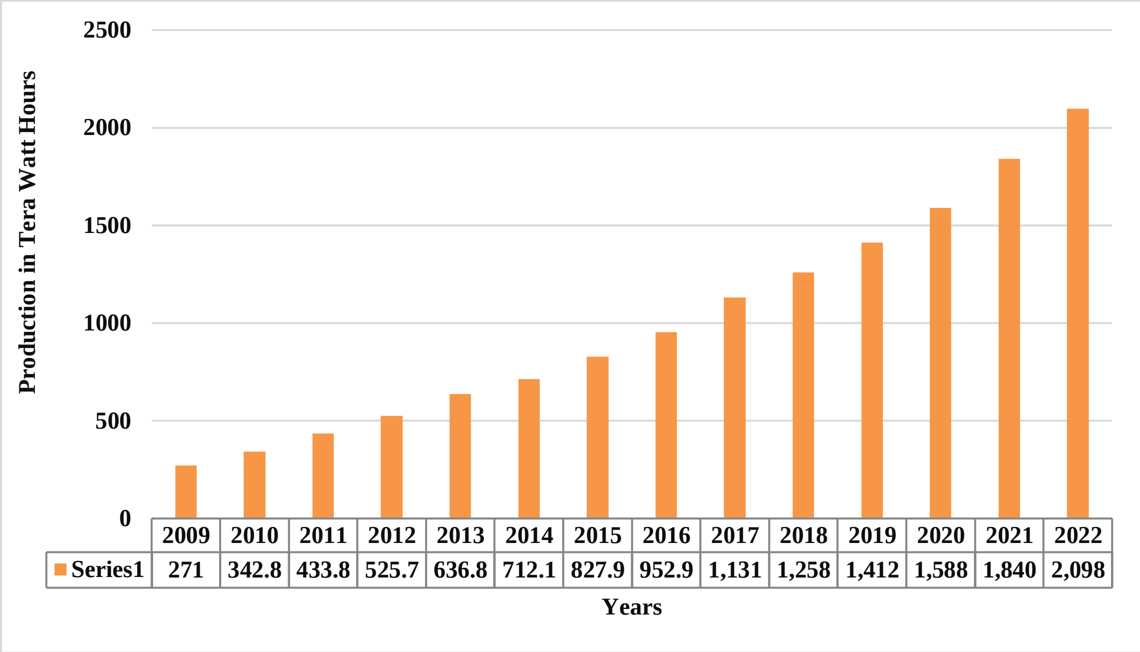

Figure 1: Wind energy production worldwide from 2009-202(in terawatt hours)

India has achieved significant growth in its solar PV capacity. As of mid-2024, India has surpassed 70 GW of installed solar capacity. This includes both large-scale solar parks and distributed solar installations, such as rooftop solar. India set an ambitious target of achieving 100 GW of solar capacity by 2022 as part of its National Solar Mission. Although this target was not fully met, the country remains committed to increasing its solar capacity and aims to achieve 280 GW of solar energy by 2030 under its updated renewable energy roadmap, under its updated renewable energy roadmap.

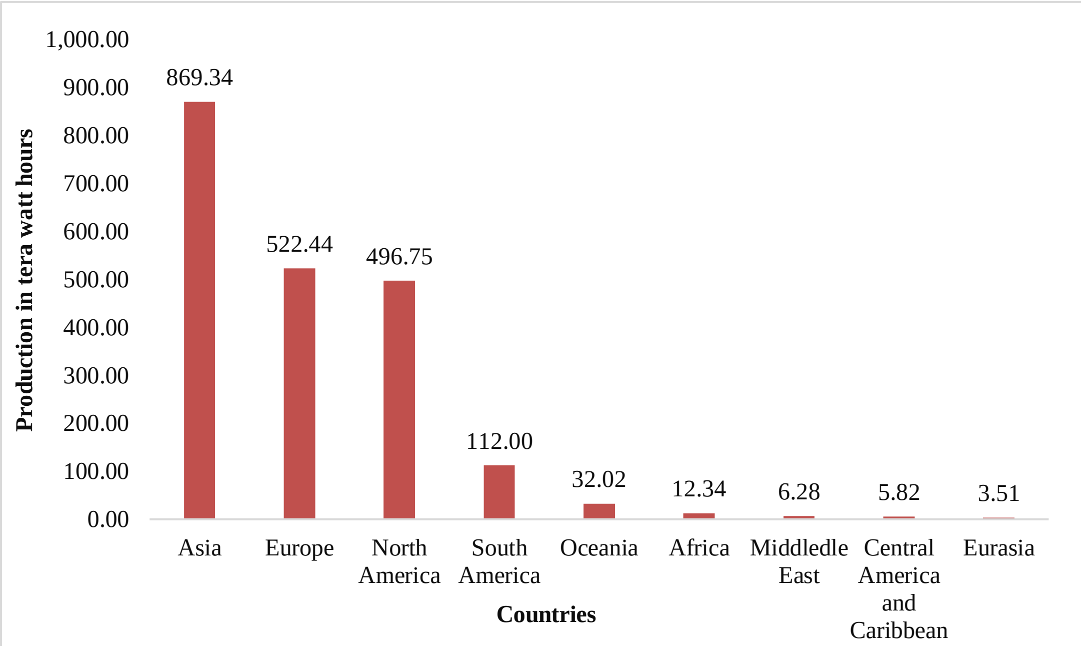

Figure 2: Energy Production area-wise

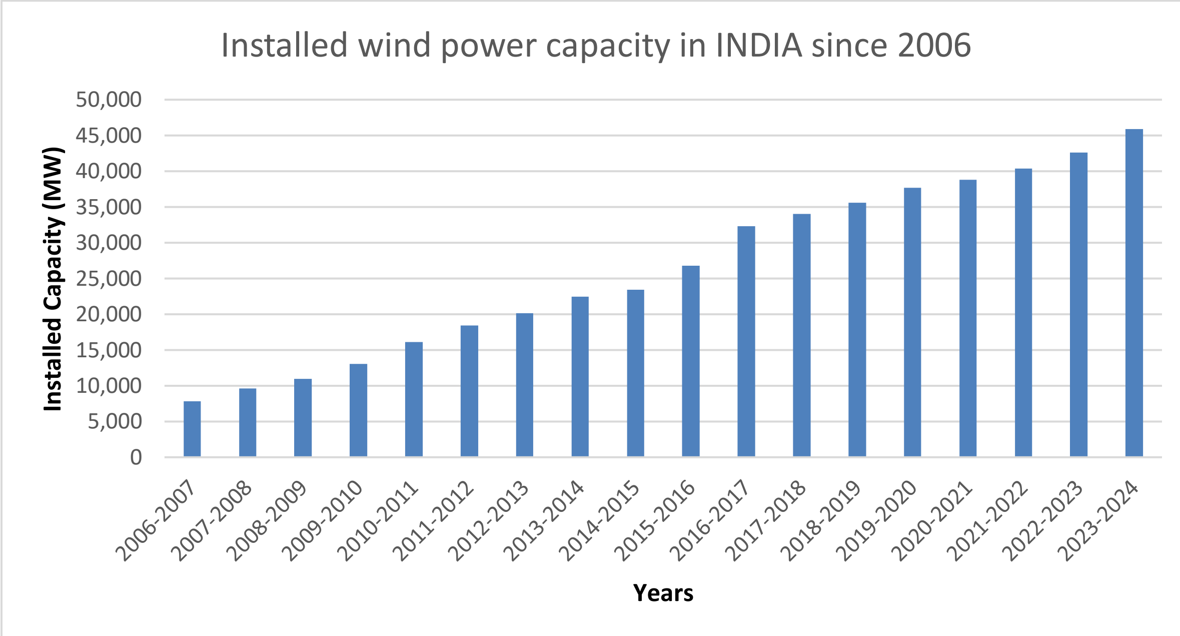

Figure 3: Installed wind energy Capacity in India

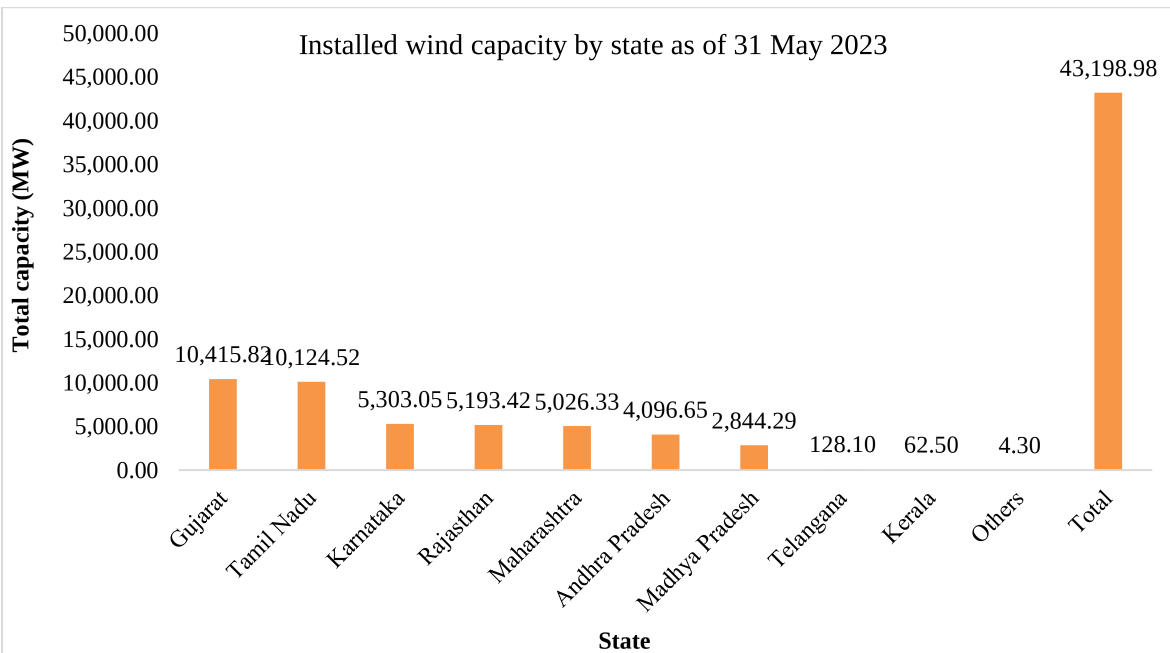

Figure 4: State - Wise Wind Capacity in India of 2023

India has significant wind energy potential, making it one of the largest wind power markets in the world. As of 2023, India had installed over 42 GW of wind energy capacity, primarily concentrated in the southern, western, and northwestern states. Tamil Nadu, Gujarat, Maharashtra, Karnataka, and Rajasthan are the leading states in wind power generation due to their favorable wind conditions and large-scale wind farms. India's wind energy sector benefit comes from the country's extensive coastline and diverse topography, which provide a variety of locations suitable for wind farms. The Indian government has set ambitious targets to further expand wind energy capacity, aiming to reach 60 GW by 2022 as part of its broader renewable energy goals. However, challenges such as grid integration, land acquisition, and variability in wind patterns still need to be addressed. Despite these obstacles, wind energy remains a key component of India's strategy to reduce its carbon footprint and achieve energy security [Kumar, 2024 and 2025]. As per Ministry of New and Renewable Energy the India have 695.5GW at 120m agl and 1163GW at 150m agl. Rajasthan is one of the key states of wind energy which have the potential of 127.75GW and 284.2GW respectively to AGL's [Malakar and Lal 2025].

Designing and simulating a 1 kW grid-connected wind energy power plant for a Renewable Energy Centre (REC) building in Kota, India, requires several steps, including site analysis, turbine selection, system design, simulation and feasibility analysis. Here's a detailed breakdown of the key considerations: For a 1 kW system, you would typically use a small wind turbine with a rotor diameter of about 1.5 to 3 meters, depending on the turbine model. Horizontal-axis wind turbines (HAWT) are more common for small-scale applications, but vertical-axis wind turbines (VAWT) could be considered if space is limited, or if the wind direction is highly variable. Choose a turbine with a rated wind speed that matches the average wind speed at your site. The turbine should reach its rated power output at this wind speed. Ensure that the selected turbine is compatible with the grid-tied inverter you plan to use.

A grid-tied wind power system will require an inverter to convert the turbine's AC output (usually variable frequency and voltage) to grid-compatible AC (50 Hz, 230V in India). The system will also need a bidirectional meter to measure both the power consumed from the grid and the power fed into it. Although not essential for a grid-tied system, battery storage can be added to store excess energy for use during grid outages. However, this adds to the system cost and complexity. This includes wiring, disconnects, protection devices, and mounting structures. For rooftop installations, ensure that the mounting system can handle wind loads according to local building codes. Use software like, MATLAB/SIMULINK to simulate the wind energy system. These tools allow you to model the wind turbine's performance based on wind resource data, system components, and load requirements.

2. Material and methods

2.1 Site selection

A microgrid lab is situated in the Research hub laboratory in the building of renewable department, Rajasthan technical university Kota, India which is shown in figure 5. with latitude and longitude as 25.142962 N, 75.805551E.

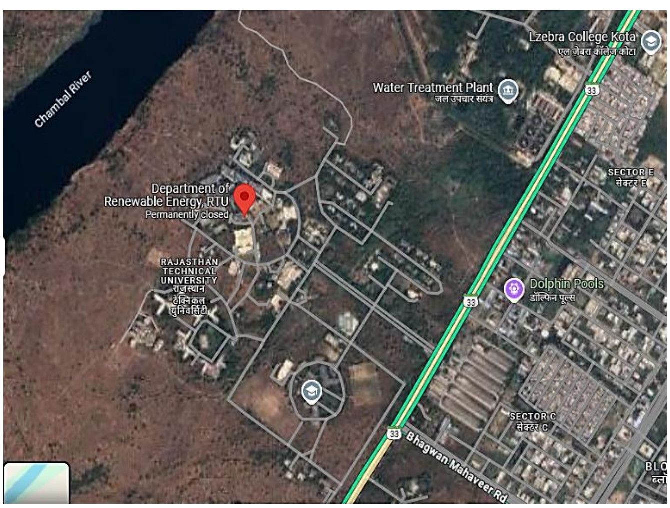

Figure 5: Google satellite map of Department of Renewable Energy, RTU Kota

Grid-connected solar and wind microgrid system with or without grid-connected hybrid systems are using in this research pper. The total requirement of the system is 1.3kW (Included the system components, fans, coolers, tube-lights and computers), therefore 1kW wind and 1kW solar PV are used for the study purpose. The 1kW wind power plant is studied in this study for various configurations and output parameters in the next section.

2.1 Basic Components of Wind Energy Conversion System

Aero turbines are used to convert energy from moving air to rotary mechanical energy. For their proper operation they require pitch and Yaw control. To transmit the rotary mechanical energy to an electrical energy, a mechanical interface consisting of a step-up gear and a suitable coupling is required. The generator output so connected to the load or power grid as the application warrants.

Yaw control functions when the location of site has prevailing winds in direction most of the time, the turbine design can be greatly simplified. The rotor can be fixed in such an orientation such that the swept area is always perpendicular to the predominant wind direction. Such a machine is said to be yaw fixed. However, most of the turbines are Yaw active. When a wind changes its direction, motor rotates the turbine slowly to align along vertical axis so that blades face the wind and rotor sweep the maximum area of wind stream.

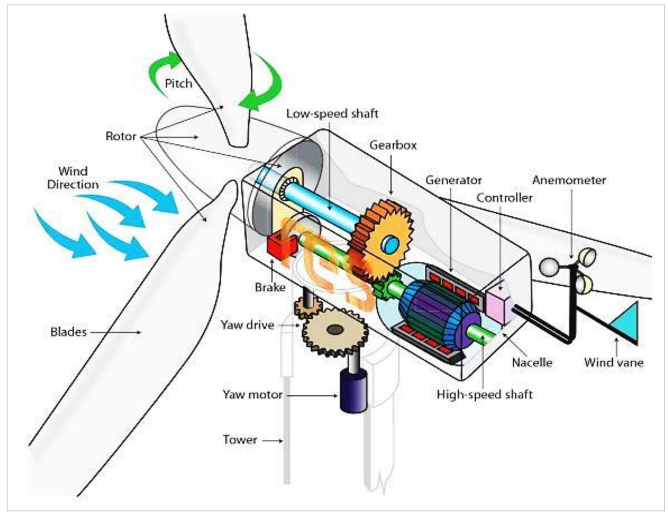

Figure 6: Wind electrical generating power plant

In the small turbine, yaw action is controlled by a trail vane whereas in large machines a servomechanism operated by a wind direction sensor controls the yaw motor the keeps the turbine is properly oriented. The purpose of controller is to sense wind speed. Wind direction, shaft speed and torque at the point so that it can control the output power and match the electrical output with wind energy input so that it can protect the system from extreme condition like cyclone and electrical faults due to strong winds. The wind-electrical generating power plant with its components is shown in figure 6, where the first main component is rotor. Basically there are two types of rotor which are as followed: (a) Horizontal axis rotor (b) Vertical axis rotor. The second core component is wind mill head and the wind mill head performs the following functions: it supports the rotor housing and the rotor bearing; it also accommodates any control mechanism incorporated like pitch control mechanism, and yaw control mechanism to orient the rotor toward wind, the latter is mounted on the top of the supporting structure on suitable bearings. The other key components are Transmission system (Gear system), generator and control systems which are described as follows: Transmission system: By varying the of the rotor blades about 40-50 revolution per minute, the rate of rotation of large wind turbine generator can be controlled. For the optimum generator output it is required to have much greater rates of rotation.

The generator is the heart of the wind turbine. It typically operates on the principle of electromagnetic induction. As the rotor turns, it spins a rotor inside the generator, which is surrounded by magnets. This movement creates a changing magnetic field, inducing an electrical current in the coils of wire within the generator. Mainly two types of Generators are used in Wind Turbines: (i) Synchronous Generators: Permanent Magnet Synchronous Generators (PMSG): Use permanent magnets to create the magnetic field. They are efficient, especially at lower speeds, and are commonly used in direct-drive turbines. Electrically Excited Synchronous Generators (EESG): Use an external power source to create the magnetic field. These are less common due to the need for additional power to excite the generator. (ii) Asynchronous Generators (Induction Generators): Doubly-Fed Induction Generators (DFIG): The most commonly used in large-scale wind turbines. They allow variable speed operation and can adjust to changes in wind speed, improving efficiency. Squirrel Cage Induction Generators (SCIG): Simple and robust but typically used in fixed-speed wind turbines.

Control system performs the following functions. Yaw Control aligns the turbine with the wind direction and rotates the nacelle to face the wind using motors. Pitch Control adjusts blade angle for optimal power output and rotates blades to control speed and energy capture. Brake Control stops or slows the turbine in emergencies and uses mechanical and aerodynamic brakes. Power Electronics/Grid Control manages electrical output to match grid requirements and Converts and regulates power using inverters. SCADA System supports remote monitoring and control of turbine operations and collects data and allows for real-time adjustments. Protection and Safety Systems safeguards the turbine from extreme conditions and includes over speed protection, vibration monitoring, and automatic shut downs.

2.2 Mathematical modeling

Conversion of kinetic energy of the wind energy in to mechanical energy can be utilised to run a windmill which is turn. Rotate the generator to produce electricity when the wind blows against these blades. They rotate about their axis and this rotational motion is extracted performing work. The wind energy conversion device is mainly called the rotor.

There are three parameters that are responsible for the best output from wind energy conversion system, these are wind speed; cross section of the windswept by the rotor; and overall conversion efficiency of the rotor, transmission system generator or pump.

Theoretically it is possible to get 100 percent efficiency by halting and preventing the passage of air through the rotor. However, no device can extract all of wind energy and only able to decelerate the air column to one third of its free velocity. Hence a 100 percent efficient wind generator is able to convert maximum up to 60 percent of available energy in wind into mechanical energy. In addition this, losses incurred in the generator or pump decreases the overall efficiency of power generation to 35 percent.

A windmill works on the principle of converting kinetic energy of the wind to mechanical energy. Now, power is equal to energy per unit time and energy that is available in the wind as in Eq (1), (2) and (3).

Kinetic energy in the particle = power = $\frac{K.E.}{time} = \frac{1/2(mass)*(velocity^2)}{time}$ (1)

We know that

$\frac{mass}{time}$ = density * area* velocity (2)

Putting the value

Power = $^1/_2$(density)*area*($velocity^3$) = $\frac{\rho A V^3}{2}$ (3)

Where $\rho = air\ density$; A = area swept by wind mill rotor; V = wind speed in m/sec

This equation tells that the power available is proportional to air density (1.225 kg/m^3 at the sea level). Due to pressure and temperature change, it may vary 10-15 % during a year. Water content present in the air does not affect power in the wind. Equation also tells us that the wind turbine is proportional to the intercept area. Thus an aero turbine with a large swept area has larger power than a smaller area machine. Since area is normally circular of diameter D as in Eq (4)

Then A = $(\pi/4)$ D^2

Available wind power P = $(\pi/8)\rho D^2 V^3$ (4)

This equation tells us that the maximum power available depends on square of the rotor diameter. Thus doubling the die of rotor will result in a fourfold increase in the available wind power.

The Weibull decided the maximum efficiency of turbine that is approximately 59%. The Weibull density probability function shows the time at which wind has a certain speed (x)

The formula is practically similar to the three parameters Weibull, except that μ isn't included in Eq (5):

$$f(x) = \frac{\gamma}{\alpha}\left(\frac{(x)}{\alpha}\right)^{\gamma-1} exp\left(-\left(\frac{(x)}{\alpha}\right)^{\gamma}\right), x \geq 0 \quad (5)$$

The failure rate is determined by the value of the shape parameter γ.

- If γ < 1, then the failure rate decreases with time
- If γ = 1, then the failure rate is constant
- If γ > 1, the failure rate increases with time

Here, α is scaling factor which is varying 1 and 2 and γ is Weibull shape factor which is selected by 0.5,1, and 2 as shown in figure 7. It is observed that the peak frequency moves toward left for increasing the value of α and γ.

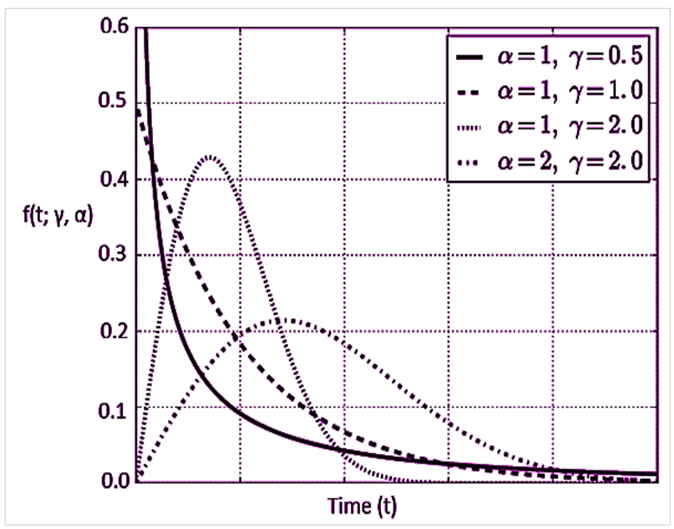

Figure 7: Weibull Curve where frequency is the function

3. Result and Discussions

3.1 Model development in MATLAB/SIMULINK

The wind turbine is responsible for converting the kinetic energy in the wind into mechanical energy. In Simulink, the wind turbine block calculates the mechanical power output based on wind speed, rotor characteristics (such as blade pitch angle), and turbine parameters like the power coefficient (Cp). The wind turbine is designed for 1kW as shown in figure 8, which having rotor diameter approximately 3m, power coefficient (function of the tip-speed ratio and pitch angle) 0.35-0.45 for small turbine and wind speed varying between 3m/s to 17m/s. The other details are summarised in table as follows:

Table 2: Details of 1kW wind power plant key parameters.

Gearbox (Optional)	The gearbox adjusts the rotational speed of the wind turbine rotor to match the optimal operating speed for the generator. However, in direct-drive systems, this component may be omitted. **Gear Ratio**: Defines the ratio between the rotor speed and the generator speed.
Permanent Magnet Synchronous Generator (PMSG)	The PMSG converts the mechanical energy from the wind turbine into electrical energy. This type of generator is often used in small wind turbines due to its efficiency and ability to operate without a gearbox in some designs. **Rated Power**: 1 kW **Rated Speed**: Depends on turbine design (e.g., 100-300 RPM). **Number of Poles**: Affects the generator's frequency and is important for synchronization with the grid. **Back EMF Constant**: Determines the voltage generated per unit speed.
AC-DC Converter (Rectifier)	The AC-DC converter converts the variable frequency AC power generated by the PMSG to DC power. This step is necessary to regulate the output before it can be converted back to AC for grid connection. **Type**: Usually, a three-phase rectifier is used. **DC Link Voltage**: The regulated DC voltage at the output of the rectifier.
DC-AC Inverter	The DC-AC inverter converts the DC power from the rectifier back to AC, synchronized with the grid frequency and voltage (typically 50 Hz, 230V in India). The inverter plays a crucial role in ensuring the power fed to the grid is of high quality. **Switching Frequency**: Determines the control of power electronics switches (e.g., IGBT or MOSFET). **Control Strategy**: Common control strategies include pulse-width modulation (PWM) or space vector modulation (SVM) for efficient conversion and grid synchronization. **Output AC Voltage**: 230V (single-phase or three-phase depending on grid requirements).
Interface	The grid interface ensures that the power from the wind turbine is properly synchronized and integrated with the local grid. This includes a bidirectional meter and protections to manage the flow of electricity between the turbine and the grid. **Grid Frequency**: 50 Hz (for India). **Voltage Level**: 230V AC (single-phase for residential systems). **Grid Synchronization**: Ensures that the inverter output matches the grid phase, voltage, and frequency before connecting.

The simulation demonstrates a clear relationship between wind speed and the rotational speed of the wind turbine. As the wind speed increases, the rotational speed of the turbine also increases, leading to higher mechanical power generation. The active power output graph shows that the turbine effectively converts mechanical energy from the wind into electrical energy. The reactive power graph highlights the dynamic nature of the wind power system's interaction with the grid. Reactive power is crucial for maintaining voltage stability and power factor correction. The torque graph illustrates the mechanical torque produced by the turbine, which directly influences the generator's performance. The simulation results demonstrate that the 1 kW wind power plant operates efficiently under varying wind conditions, converting wind energy into electrical power while maintaining stable interaction with the grid. To further enhance the system's performance, it is recommended to explore advanced control strategies for reactive power management and torque regulation.

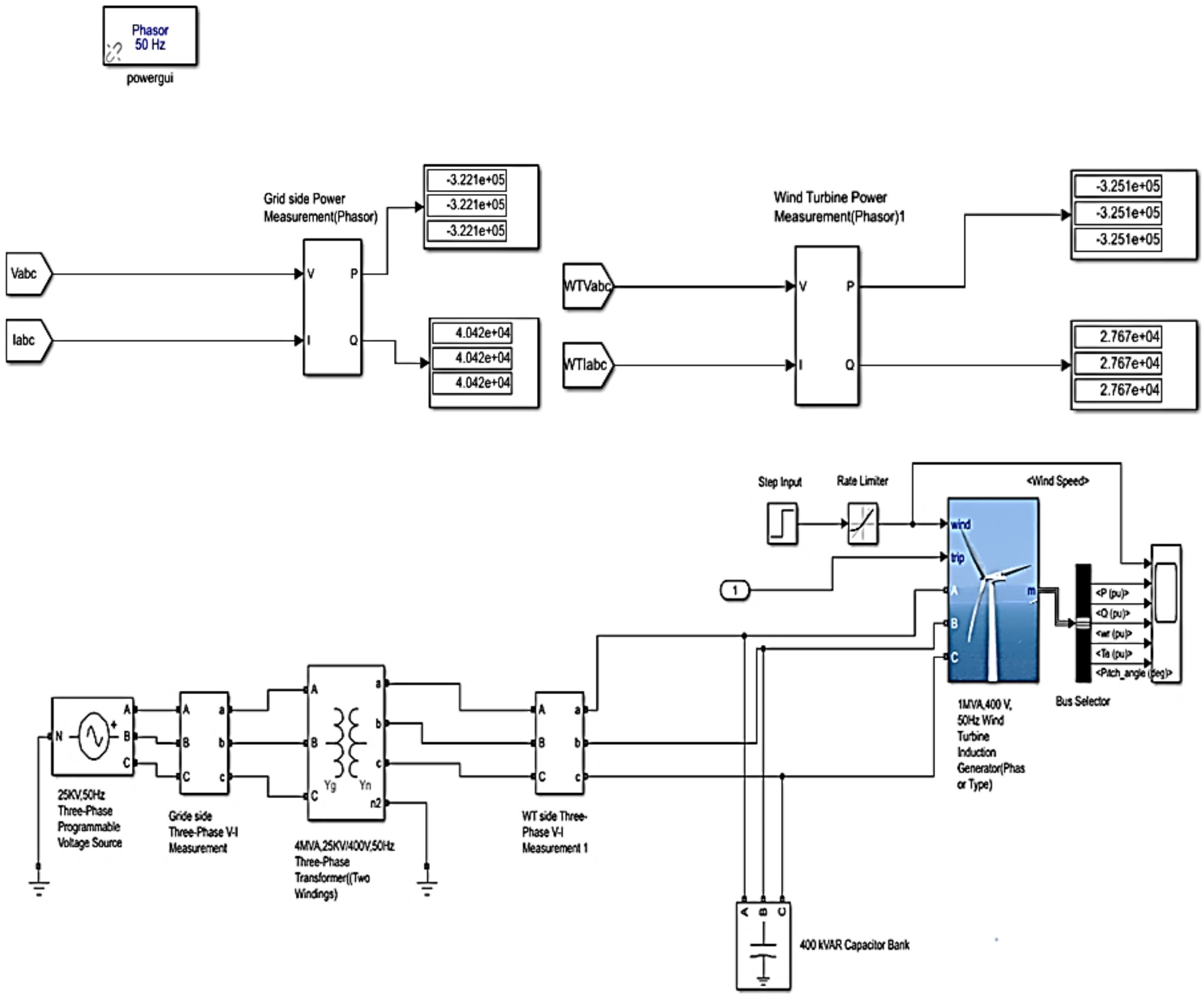

Figure 8: MATLAB/SIMULINK model

3.2 Simulation studies of designed wind power plant

In figure 9, the variation of wind speed is increasing from T=5 sec to the highest wind speed that is 12 m/ sec. The Cut in Speed is the minimum wind speed at which the turbine begins to produce power. Below this speed, the wind is not strong enough to overcome internal mechanical resistance and generator losses, so the turbine remains idle. The cut-in speed is typically around 3 to 4 m/s. As the wind speed increases above the cut-in speed, the turbine starts generating power. In this range, the power output increases rapidly with wind speed, generally following a cubic relationship due to the kinetic energy in the wind being proportional to the cube of the wind speed**.** Rated speed is the wind speed at which the turbine produces its maximum rated power output. Beyond this speed, the turbine is designed to limit power production to avoid overloading. The rated wind speed is typically between 11 to 15 m/s for most turbines.

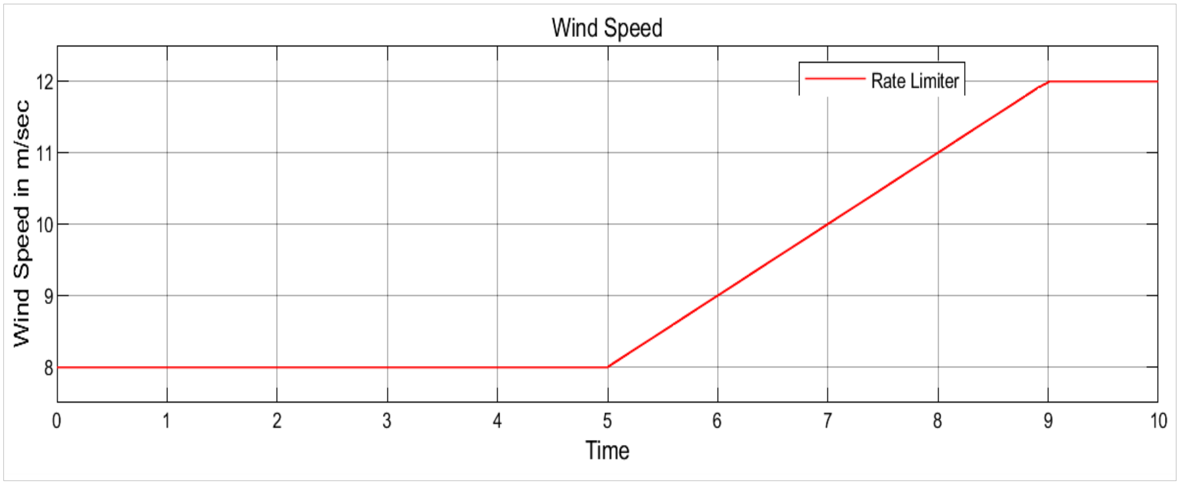

Figure 9: wind speed curve

Wind speeds exceed the rated speed, and the turbine's control systems (such as pitch control and torque regulation) act to maintain constant power output at the rated level. The turbine adjusts its operations to prevent excessive forces on the blades and mechanical components.

Cut –out speed is the maximum wind speed at which the turbine can safely operate. At or above the cut-out speed, which is usually around 20 to 25 m/s, the turbine automatically shuts down to prevent structural damage and ensure safety. The blades are pitched to minimize aerodynamic forces, and the rotor is broken.

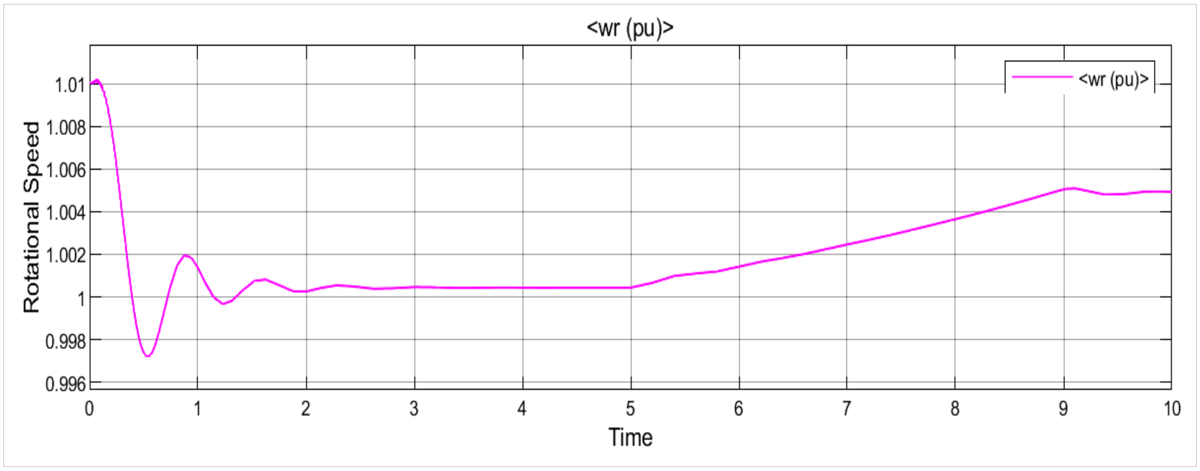

Figure 10: Rotational speed curve

In figure 10, at low wind speeds (below the cut-in speed), the turbine rotor begins to spin, but the rotational speed is low and not sufficient to generate power. The turbine is just overcoming friction and other resistances. As wind speed increases from the cut-in speed to the rated speed, the rotational speed increases nearly proportionally with wind speed. This region shows a linear relationship, where the rotor accelerates to maximize energy capture. Once the wind speed reaches the rated speed, the turbine reaches its maximum design rotational speed. The speed is maintained at this level even if wind speed continues to increase. This is achieved through active control systems, such as blade pitch adjustments, to prevent the turbine from over speeding. f wind speeds exceed the cut-out speed (typically to protect the turbine from damage), the turbine shuts down, and the rotor stops spinning.

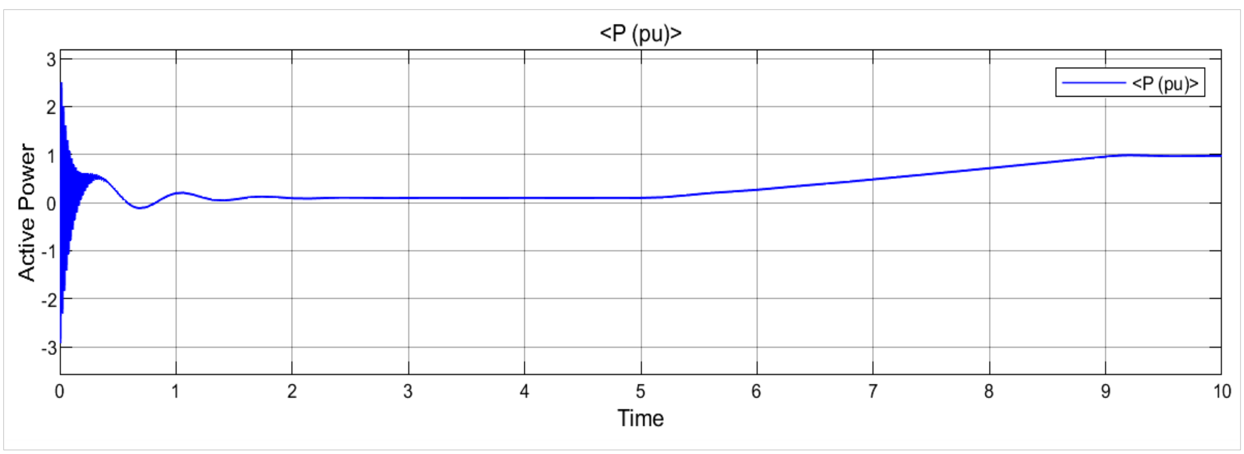

Figure 11: Active power curve

Figure 11 represents the active power curve and it is observed that at very low wind speeds, the wind turbine remains inactive and does not generate power. The cut-in speed is the threshold wind speed at which the turbine begins to produce power. Below this speed, the wind lacks sufficient force to overcome internal friction and inertia.

As the wind speed increases beyond the cut-in speed, the turbine's power output increases rapidly. In this region, the power output generally follows a cubic relationship with wind speed because the kinetic energy available from the wind is proportional to the cube of the wind speed. The turbine operates in this region by adjusting the rotor speed to optimize the angle of attack of the blades, maximizing energy capture.

At a certain wind speed, known as the rated speed, the turbine reaches its maximum designed power output, called the rated power (1 kW in this case). From this point onward, the turbine's control system (such as pitch control or generator control) regulates the power output to maintain it at the rated level despite increasing wind speeds. This ensures the turbine does not exceed its design limits.

If wind speeds continue to increase and reach the cut-out speed, the turbine will shut down to avoid damage from excessively high forces. The turbine's braking system activates, stopping the rotor and preventing power generation. This region is a protective measure against potential mechanical failure or structural damage.

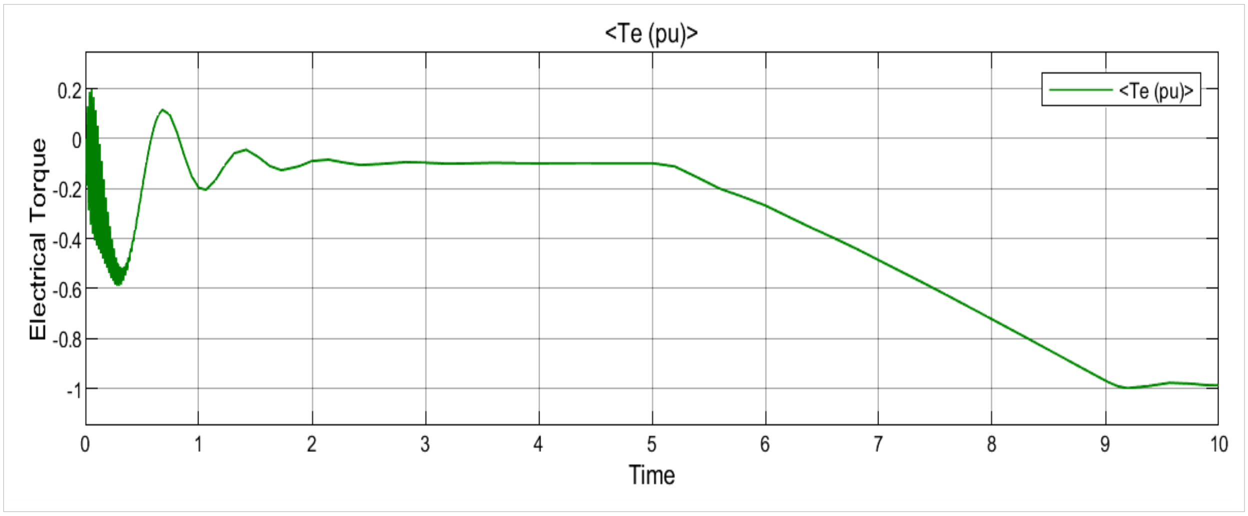

Figure 12: Torque curve

Figure 12 expressed at very low wind speeds, below the cut-in speed; the turbine does not generate torque because the wind's kinetic energy is insufficient to overcome internal friction and rotor inertia. The output torque is effectively zero in this region.

As wind speed increases past the cut-in speed, the turbine begins to generate torque. In this region, the output torque increases rapidly, approximately following a quadratic relationship with wind speed. This is because torque is proportional to the wind's kinetic energy, which itself depends on the square of the wind speed. The rotor blades capture more wind energy as wind speed increases, leading to higher torque output.

When the wind speed reaches the rated speed, the turbine generates its maximum rated torque. Beyond this point, the turbine's control system regulates the torque to prevent mechanical stress and maintain optimal operation. The torque is maintained at a constant level despite further increases in wind speed. This regulation is typically achieved through pitch control (adjusting the blade angle) or generator control (adjusting the electrical load).

As wind speeds continue to increase towards the cut-out speed, the control system ensures that the torque remains at the rated level to avoid overloading the turbine components. If the wind speed exceeds the cut-out speed, the turbine shuts down to prevent mechanical damage. During shutdown, torque generation ceases, dropping the output torque to zero.

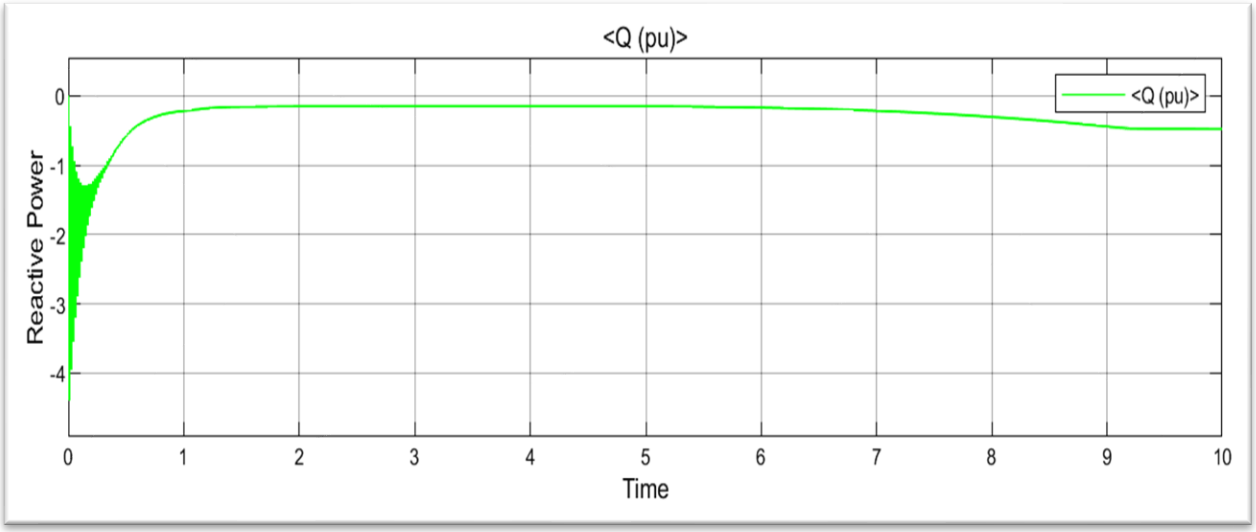

Figure 13: Reactive Power Curve

In figure 13: At very low wind speeds, the turbine is not generating active power, and consequently, reactive power output is also minimal or zero since the turbine's generator and converter are not active. As wind speed increases and the turbine starts generating active power, reactive power can also increase. The amount of reactive power output depends on the generator's operating conditions and the grid requirements. Reactive power does not directly follow the wind speed curve and is instead managed according to grid requirements. Control systems allow for reactive power adjustment independently from active power, providing grid voltage support.

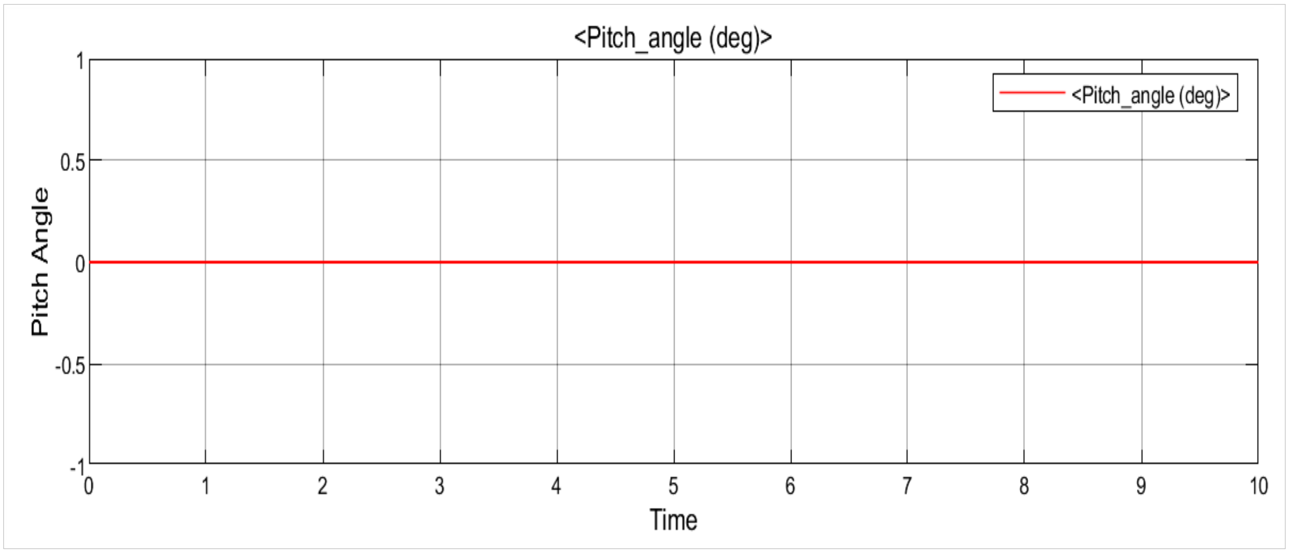

Figure 14: pitch angle curve

In Figure 14: At low wind speeds, the pitch angle is typically set to capture maximum wind energy, meaning the blades are positioned at a minimal pitch angle (close to flat) to optimize lift and start rotation. As wind speed increases, the blades remain at a low pitch angle to continue maximizing energy capture. This phase aims to extract the maximum possible power from the wind while the turbine is below its rated power output. When wind speeds approach the rated speed, the turbine reaches its maximum power output. To maintain this output and prevent over-speeding, the pitch angle begins to increase (blades turn slightly out of the wind). In high winds, the pitch angle increases significantly to reduce the aerodynamic load on the blades and prevent damage. The blades are pitched further out of the wind to reduce the rotor speed and control power output.

The study concludes that a 1 kW grid-connected wind energy system is viable for residential use, especially in areas with consistent wind patterns. The simulations demonstrate that, with appropriate design considerations, such systems can effectively contribute to household energy needs, potentially reducing reliance on conventional power sources. The simulations confirm that a 1 kW grid-connected wind power plant is suitable for small-scale, especially residential, applications where wind resources are available. The output power increases significantly with both wind speed and rotor blade radius. This highlights the importance of site selection and turbine sizing in practical deployments. There were noticeable deviations between the simulation results and theoretical power values (based on Betz's limit), but the error margin was generally acceptable. This suggests the MATLAB model is reasonably accurate for preliminary analysis. Discrepancies in modeling results are occurred mainly due to simplifications in the modeling process, such as ignoring losses in the generator, power electronics, and transmission, as well as assuming ideal environmental conditions. The study confirms that such systems, when well-designed and located, can contribute meaningfully to energy needs and help reduce reliance on conventional grid electricity.

4. Conclusions

The simulation results confirm that the 1 kW wind power plant is capable of delivering reliable power output, with the system responding effectively to varying wind conditions. The observed trends in wind speed, rotational speed, active and reactive power, and torque are consistent with the expected behavior of a small-scale wind energy conversion system, validating the overall design and control strategies employed in the simulation.

- The simulation demonstrates a clear relationship between wind speed and the rotational speed of the wind turbine. As the wind speed increases, the rotational speed of the turbine also increases, leading to higher mechanical power generation. The observed fluctuations in wind speed are reflected in the variations in rotational speed, highlighting the importance of effective control strategies.
- The active power output graph shows that the turbine effectively converts mechanical energy from the wind into electrical energy. The power output follows the wind speed trends, with higher wind speeds resulting in greater active power generation. The maximum power output aligns with the rated capacity of the system (1 kW), confirming that the turbine operates efficiently within its design parameters. However, at lower wind speeds, the active power generation decreases, indicating the system's sensitivity to wind resource availability.
- The reactive power graph highlights the dynamic nature of the wind power system's interaction with the grid. Reactive power is crucial for maintaining voltage stability and power factor correction. The simulation results suggest that the reactive power fluctuates in response to changes in wind speed and turbine operation. Effective control of reactive power is essential to ensure grid compliance and maintain power quality, especially during periods of rapid wind speed changes.
- The torque graph illustrates the mechanical torque produced by the turbine, which directly influences the generator's performance. The torque increases with wind speed, providing the necessary mechanical input to the generator. The smooth torque response indicates that the turbine and generator coupling is functioning effectively, with minimal mechanical stress or oscillations. This is crucial for the

longevity and reliability of the turbine's mechanical components.

- The simulation results demonstrate that the 1 kW wind power plant operates efficiently under varying wind conditions, converting wind energy into electrical power while maintaining stable interaction with the grid. The system's active power generation aligns with the expected performance, and the control strategies employed appear to manage both the mechanical and electrical dynamics effectively. However, the performance during low wind conditions suggests that further optimization, such as energy storage integration or hybrid systems, could enhance overall energy yield and system reliability.

For further enhancement of the system's performance, it is recommended to explore advanced control strategies for reactive power management and torque regulation. Additionally, considering the integration of energy storage could help mitigate the variability in power generation due to fluctuating wind speeds, ensuring a more stable power supply to the grid.

Nomenclature

A	Area	LSTM	Long short-term memory
AC	Alternating Current	MATLAB	Matrix laboratory
ADMM	Alternative direction management method	MOSFET	Metal oxide semiconductor
BESS	Battery energy storage system	MWh	Megawatt hour
CHP	Combined heat and power	NSGA-II	Non dominated sorting genetic algorithm
Cp	power coefficient	PMSG	Permanent Magnet Synchronous Generators
D	Circular diameter	PV	Photovoltaic
DC	Direct Current	PWM	pulse-width modulation
DFIG	Doubly-Fed Induction Generators	RES	Renewable Energy System
DRO	Distributional Robust Optimization	RPM	Revolution per minute
EESG	Electrically Excited Synchronous Generators	SAM	System Advisor Model
EMF	Electromagnetic field	SCADA	Supervisory control and data acquisition
GW	Giga Watt	SCIG	Squirrel Cage Induction Generators
HAWT	Horizontal-axis wind turbines	SOC	State of charge
HRES	Hybrid renewable energy system	SVM	space vector modulation
H-WD-A-CAES	hybrid wind-diesel adiabatic compressed air energy storage	V	Velocity
IEA	International Energy Agency	VAWT	vertical-axis wind turbines
IGBT	Insulated gate bipolar transistor	VPP	Virtual power plant
IWC	Integrated wind concentrated	WEPP	Wind energy power plant
K.E.	Kinetic Energy7	WW-S-CAES	Wave-Wind-Solar-Compressed Air Energy Storage
LCOE	levelized cost of energy	P (rho)	Density

Declarations

Conflicts of Interest

The authors declare that they have no conflict of interest.

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Authors' contributions or CRediT Roles

Himanshi Kumari: Conceptualization, Writing-original draft, Shiv Lal: Review and Editing; Shibna Hussain: Simulation work; Santosh Kumar Sharma: Review and Editing

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