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Research Article

Effect of Wind Speed and Capacitive Power on a Grid Connected 1MW Wind Energy Power Plant Using MATLAB/Simulink

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Abstract

This study presents the design and simulation of a 1 MW grid-connected phasor-type wind turbine system using MATLAB/Simulink. The turbine is modelled with a line-to-line voltage of 400 V and operates at a frequency of 50 Hz, aligning with standards in India. Advanced features include high-temperature superconducting generators to reduce size and weight while maintaining efficiency with minimal losses. The aerodynamic design is optimized using blade element momentum (BEM) theory to enhance performance across various wind speeds. The simulation incorporates a step device for wind speed control and a rate limiter to regulate speed variations. Power flow is measured from the wind turbine to the grid, with a capacitor bank providing necessary reactive power. The results demonstrate that the system successfully delivers 1 MVA of power to the grid, confirming the effectiveness of the design and simulation parameters.

The analysis indicates that as wind speed drops below nominal levels, the pitch angle increases, and reactive power becomes negative, around -0.22. Real power decreases with wind speed, from 1 PU at 12 m/s to 0.495 PU at 10 m/s. At 14 m/s, real power exceeds from 1 PU. With a 400 kVAR capacitor bank, some reactive power is supplied by the grid; whereas at 1 VAR, the grid provides all required reactive power. For a wind speed of 12 m/s, the turbine's power measurement is about 163.2 kVA, while the grid measures 179.5 kVA which is reflecting minor reactive power losses. Ultimately, the wind turbine delivers approximately 0.96 MW of real power to the grid.

Keyword: ***wind turbine, reactive power loss, MATLAB, Blade element moment, real power etc.***

1. Introduction

Now a days the electricity call for is increasing swiftly in India. The power call for is increasing every day and the conventional resources of power are getting exhausted. traditional power sources also are inflicting many fitness troubles. Given our urgent strength desires, we have to attention on opportunity assets of electricity which are renewable and whose use reasons minimal or no harm to the environment. Renewable power is supply that reduces emissions of greenhouse gases and other hazardous gases such as sulphur dioxide and nitrogen oxides. persisted consciousness and elevated use of renewable energy can limit the dependence of the us of a's improvement on imported fossil fuels and lead India toward self-reliance and electricity independence. therefore, it's far necessary to fully enlarge and make use of renewable sources of energy like sun, wind, hydropower, biomass strength from waste and so forth [1].

The need of energy has a massive contribution inside the economy of United States. As in early a while energy production takes region by means of burning of fossil fuels that are not extended as the call for of strength rising day by day and the traditional resources of electricity production are coming to cease, so to be able to attain net 0 emission by using 2050 and to reach toward smooth and green power production we need to transport towards non-conventional electricity sources that are lasting for years. As wind and solar are playing an essential role in the era of energy. amongst of these, wind is a traditional source of electricity, used to offer high potential electricity at low energy rates. To obtain our smooth and green energy purpose the power technology from wind energy resources are very low-budget [2]. Indian government has taken initiatives with several key aspects for promoting the non-conventional energy resources that includes wind energy also.

In 2023 the worldwide wind power enterprise made tremendous steps with the addition of 88.15 GW of latest potential bringing the full installed wind power capability to an excellent 988 GW this marked a strong nine percent growth over the previous yrs underscoring the sectors consistent enlargement most of the people of this growth became driven through key markets which includes China, US, Brazil, Germany and India those 5 international locations on my own have been liable for 73 percent of the newly mounted capacity worldwide displaying a mild growth of their collective share in comparison to 2022 but this growth comes with nuanced challenges considerably china and the USA regardless of being leaders in the wind energy quarter faced hurdles that caused a four percent decline of their blended marketplace share this decline marks the 33 consecutive year of market proportion discount for those two giants highlighting the evolving dynamics inside the international wind energy panorama as those international locations navigate coverage monetary and infrastructural demanding situations their enjoy could function a bellwether for the future trajectory of wind energy worldwide [3].

With 45 GW to be installed by the beginning of 2024, India is getting ranks fourth in the world in terms of renewable wind energy and is the second largest wind market in the Asia Pacific region. The country plans to expand its capacity to 140 GW by 2030. In 2023, India achieved its highest annual addition of onshore wind capacity since 2017, reaching 2.8 GW. There is a significant pipeline of over 13 GW of wind projects in the country. Additionally, a new offshore wind strategy includes a 4 GW lease in Tamil Nadu, supported by updated guidelines and funding. Public Sector Undertakings (PSUs) are spearheading new auctions and forming partnerships to advance the sector [4].

The landscape of wind strength in India provides a compelling juxtaposition of extremely good ability coupled with continual obstacles that obstruct development. As of the data recorded in March 2020, the country boasted an established wind electricity potential amounting to 37.69 Gigawatts (GW), a determine that unluckily represents a trifling 12.47% of the comprehensive expected capability, which stands at a magnificent 302 GW, thereby illuminating a big disparity within the effective utilization of this renewable electricity resource. This discrepancy highlights the urgent need for strategic projects and progressive regulations aimed toward harnessing the abundant wind strength ability that stays untapped in the USA, thereby facilitating a transition toward a extra sustainable electricity framework [5]. The governmental authorities have hooked up a strategic objective to enhance the existing capacity of strength production to a full-size range of a hundred and forty to 150 GW by the year 2030; but, this ambitious increase trajectory has encountered substantial deceleration as a result of a myriad of challenges, which encompass, however are not restrained to, complications associated with the procurement of land for development functions, the necessity for sturdy monetary incentives to stimulate investment, and the pervasive presence of antiquated infrastructure this is sick-equipped to guide such expansive energy technology projects [8]. in spite of the truth that India holds the commendable role of being ranked fourth inside the international in phrases of the entire capability of wind energy installations, it's far vital to note that the real usage of this ability is alarmingly inadequate, thereby underscoring an urgent need for the method and implementation of better policies and the development of strong infrastructure that could correctly facilitate and expedite the advancement of this important quarter [6,8]. In summary, even though it is obvious that India has made massive progress and advancements within the realm of wind energy improvement, the belief of its fantastically ambitious objectives and dreams will necessitate the surmounting of vast limitations in addition to the augmentation and enhancement of funding on this crucial sector of renewable electricity [7].

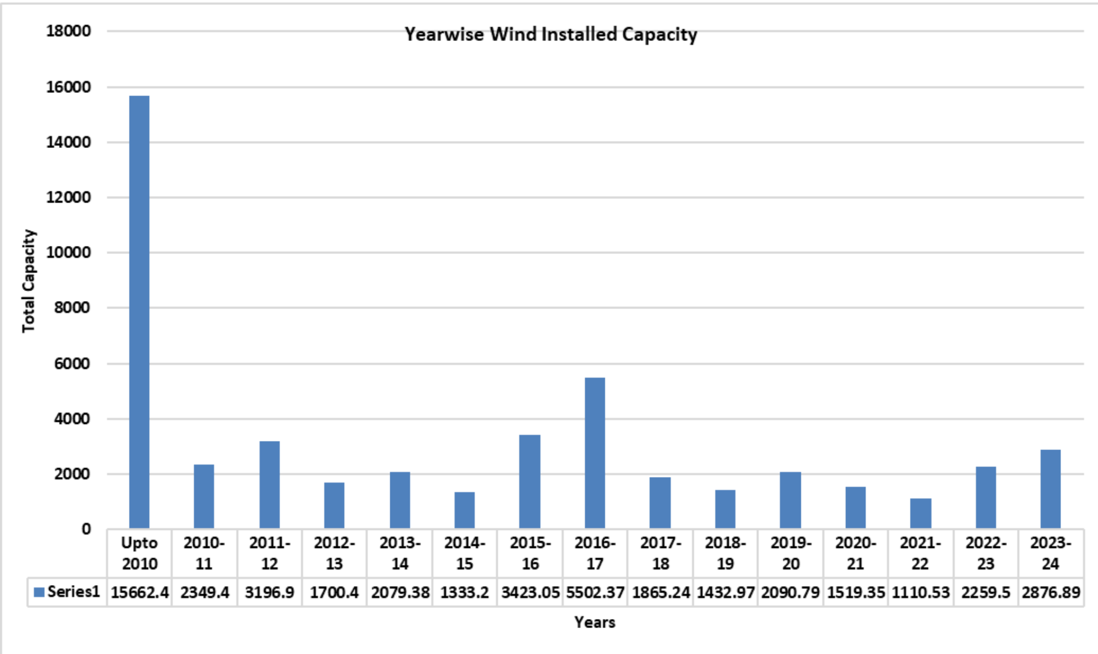


Figure 1: Year-wise wind installed capacity [9,10]

India has taken revolution for production of green hydrogen as per the MNRE (Ministry of New and Renewable Energy)

Significant progress has been made in wind energy research, with a strong emphasis on refining energy extraction techniques and addressing the issues caused by inconsistent wind patterns. Recent breakthroughs in turbine technology, including innovative designs and advanced computational simulations, have been instrumental in these efforts. These advancements are crucial for improving the efficiency and reliability of wind turbines, enabling them to generate more power even under variable wind conditions. As a result, wind energy is becoming an increasingly dependable and effective component of the global renewable energy portfolio [9].

The comprehensive analysis of systems designed for the harvesting of wind energy underscores the critical necessity of a profound comprehension of the intricate dynamics associated with wind speed, alongside the strategic application of hybrid forecasting methodologies, which collectively serve to enhance the predictability of wind resources and foster a greater appreciation for their potential contributions to energy generation. In addition to these technological considerations, it is paramount to acknowledge that the successful execution and deployment of wind energy systems are heavily contingent upon the harmonious integration of various non-technological elements, which notably include the establishment of regulatory standards and the effective incorporation of these systems into existing power grids. Thus, it is clear that a multifaceted approach, which intertwines both technological innovations and regulatory frameworks, is indispensable for the advancement and optimization of wind energy harvesting initiatives in the contemporary energy landscape [10]. The ongoing and dynamic evolution from what were once fairly simple and unassuming wind turbines to the increasingly advanced and intricately designed multi-megawatt systems that are capable of generating substantial amounts of energy undeniably acts as a significant and persuasive testament to the burgeoning confidence and reliance placed upon wind energy as a credible and sustainable source of power, which in turn underscores its extraordinary ability to contribute meaningfully towards addressing the incessantly rising global energy requirements, especially when considered against the backdrop of the daunting and formidable obstacles that are presented by the pressing issue of climate change [9].

Table 1: Review of research

Author	Year	Country	Model	Output
Gulshan Bankar [11]	2022	India	Hybrid power system	The hybrid power system blends wind, diesel, and solar energy with battery storage, providing a reliable and efficient power source, especially for remote locations. This sustainable energy solution is key to advancing both industrial and agricultural growth.
Dong-Cheol Shin and Dong-Myung Lee [12]	2020	Korea	wind power generation system model	The study presents a wind power generation model using MATLAB/Simulink for operating modular multilevel converters (MMC) in a hardware-in-the-loop simulation (HILS). It connects wind power to the grid via HVDC and validates the model's real-time performance.
Anthony McFarlane [13]	2022	South Africa		The grid code specifies that voltage must stay within +/-1 pu, frequency within +/-5%, and harmonic distortions should not exceed 0.1% for voltage (THDv) and 5% for current (THDi). The power factor must range between 0.9 and 0.95. Furthermore, renewable distributed generators (RDGs) are required to remain operational during faults and help restore voltage levels.
J. Hussain *et al.* [14]	2019	Pakistan		This paper explores a method to improve power quality in grid-connected wind power plants by integrating a DSTATCOM with a battery energy storage system (BESS). The technique primarily addresses the reactive power demands of the load and the induction generator.
Guruswamy Revana *et al.* [15]	2020	India	mathematical model	This paper models and verifies a wind turbine system for clean energy generation, utilizing a DFIG with a wound rotor and an IGBT-based PWM converter. The simulation results confirm the model's effectiveness, aiding in improved system design.
S. D. M, S.Saranya [16]	2023	China	model analysis techniques	This paper examines oscillations in PMSG wind farms by modeling and simulating in MATLAB/Simulink. The study identifies two main oscillation modes: subsynchronous, driven by DC voltage control, and low-frequency, affected by grid strength and PLL dynamics.
G. Revana *et al.* [17]	2022	China	system transient stability	This paper examines the stability of grid-connected constant speed wind turbines (CSWT) and doubly-fed induction generators (DFIG) using dynamic models and the IEEE 3-machine 9-bus system, focusing on their impact on transient stability at different wind power penetration levels.
L. Zhu *et al.* [18]	2021	China	MATLAB	This article reviews the development and challenges of wind power grid integration. It models grid-connected variable speed wind turbines in MATLAB to analyze their output under normal and faulty conditions.
P. Li, Z. Lin *et al.* [19]	2024	Indonesia	Matlab Simulink	This study uses Matlab Simulink to model a wind power plant for coastal regions, focusing on a case study in Cilacap, Indonesia. It involves problem identification and data collection on local wind conditions and turbine components.
Y. Mao, X. Wang *et el.* [20]	2023	South Africa	RSCAD	This paper examines how standardized codes can enhance the design and integration of wind power plants. It reviews existing literature on wind turbine generators and simulates a large-scale wind power facility.
F. R. Saputri and N. Pranata [21]	2016	Barcelona	EMT and Phasor model	This paper offers simulation guidelines for Voltage-Source Converters (VSCs) in AC grids. It compares EMT and Phasor models for converter-integrated generation, assessing their effectiveness in both small and benchmark systems and addressing challenges with phasor models in transient analysis
V. A. Lacerda, E. P. Araujo *et al.* [22]	2018	India	Fuzzy Controllers	This paper examines using fuzzy controllers to enhance power quality in grid-connected wind turbines, improving harmonic current management and extending the life of power electronics compared to traditional PI controllers.

The main objective is to present the systematic approach to designing a wind turbine system that is both efficient and adaptable to varying wind conditions. It emphasizes the importance of advanced generator technology, like high-temperature superconducting generators, and aerodynamic optimization techniques, like the Blade Element Momentum (BEM) theory, in achieving high efficiency and effective power conversion. Additionally, the passage explains the simulation setup, including the use of a capacitor bank for reactive power compensation, and the method to measure power flow between the wind turbine and the grid.

Ultimately, this discussion aims to demonstrate the effective design and simulation of a wind turbine system capable of delivering 1 MW of power while maintaining stability and efficiency in a grid-connected environment.

2. Material and Methods

2.1 Wind mill construction detail

The complex process of building a wind turbine involves many important stages and many important factors that together contribute to the overall performance of the system. To begin this multifaceted endeavor, the foundation must be carefully designed, taking into account the specific soil and various environmental factors that will in turn affect the integrity of the structure; this includes the use of the concept of precast concrete elements, which help to create a solid and stable foundation that can withstand the powerful forces generated by strong winds [24]. Once a secure foundation is established, the towers, usually made of steel or concrete, are assembled in different sizes and then equipped with cranes for different heights, usually ranging from 80 to 160 meters [24,25].

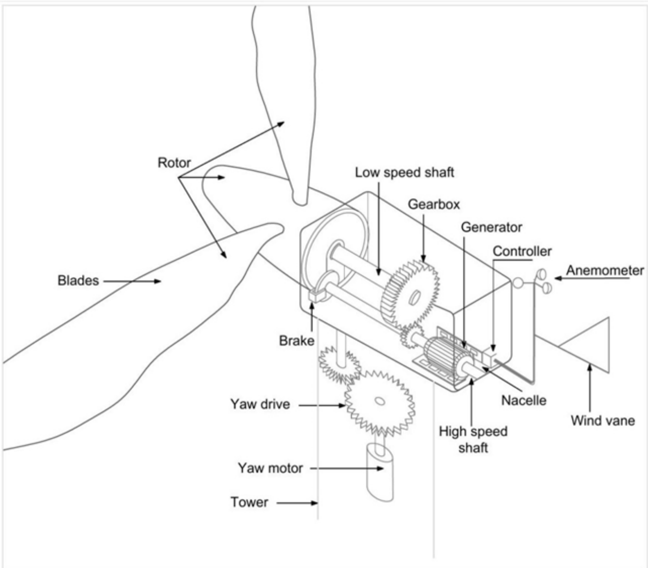


Figure 2: Construction of HAWT [27]

Once the tower is complete, the nacelle, the main component containing the main machinery such as gearboxes and generators, is carefully assembled at the top of the tower [24]. In addition, the rotor blades, carefully designed from the finest composite materials, are fixed to the central hub before being lifted into place, marking a unique, delicate and important stage in the entire construction process [26]. At the same time, the integration of the electrical system, which includes the cables running from the cabin to the ground and connecting it to the grid, has been carried out [24]. Inspection process is to ensure that the operation of the wind turbine is carried out through regular inspection and maintenance necessary to ensure the good operation of the turbine people [25].

2.2 Classification of Wind Turbine

Basically, wind turbines are of two types:

I. Horizontal Axis
II. Vertical Axis

Numerous sizes of wind turbines exist, of which the blade length is an important variable that affects electricity production from the turbine. Small wind turbines, rated at around 10 kW are capable of providing power to a single residence, and the largest wind turbines that are in operation currently, have added capacity of about 15000 kW and are still being manufactured in larger sizes. Turbines are often arranged in arrays to create wind power production plants, or wind farms, and supply electricity to the larger electric power grid [28].

2.2.1 Horizontal Axis

Blades of horizontal-axis turbines are much like airplane propellers and are established on a tower [eia]. A horizontal axis wind turbine is a kind of wind turbine wherein the primary rotor shaft is ready horizontally and the blades rotate round a vertical axis.

They are the most common sort of wind turbine and usually have three blades. as the wind blows, the blades spin around a horizontal axis, similar to the motion of a conventional windmill. The largest horizontal-axis mills can reach heights equal to six hundred metres homes and function blades extending over 33 metres in period. increased height and longer blades make contributions to higher power era. Horizontal-axis generators dominate the cutting-edge wind turbine market, with almost all operational mills following this layout [29].

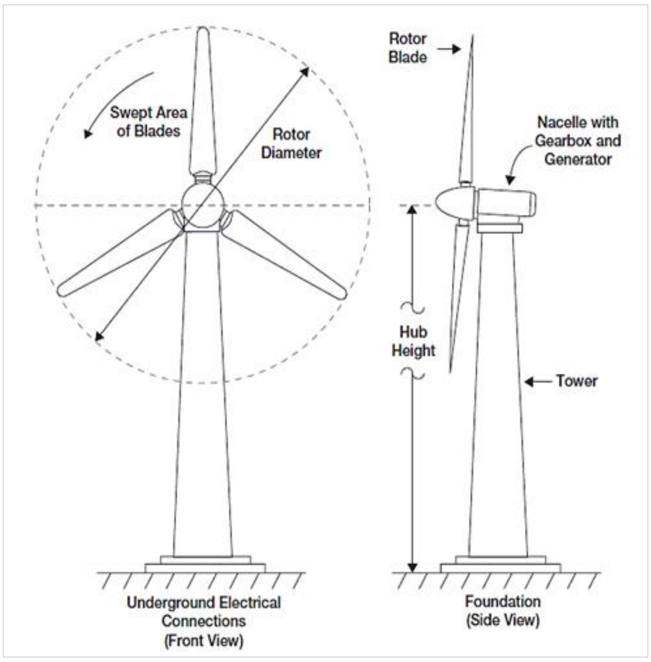


Figure 3: Horizontal axis wind turbine [30]

2.2.1.1 Forms of Horizontal Axis Wind turbine

➢ **Pitched Controlled Wind Turbines:**

Pitch controlled wind mills exchange the orientation of the rotor blades alongside its longitudinal axis to manipulate the output power. Those mills have controllers to check the output electricity numerous instances according to 2nd, and whilst the output electricity reaches a maximum threshold, an order is sent the blade hydraulic pitch mechanism of the turbine to pitch the rotor barely out of wind to sluggish down the turbine. Conversely, while the wind slows down, then the blades are grew to become (or additionally known as pitched) decrease again into the wind. in some unspecified time in the future of operation, the blades are pitched some stages with every exchange in wind to maintain the rotor blades on the top-rated attitude to most power seize.

➢ **Stalled Controlled Wind Turbines**

The rotor blades of a stall-controlled wind turbine are bolted onto the hub at a set attitude.

The blades are aerodynamically designed to sluggish down the blades when winds are too strong. The stall phenomenon resulting from turbulence on rotor blade prevents the lifting pressure to behave at the rotor. The rotor blades are twisted slightly along the longitudinal axis so that the rotor blade stalls progressively instead of suddenly when the wind reaches the generators' important fee.

- **Active Stall Controlled Wind Turbines**

Energetic stall turbine are very similar to the pitch managed turbine due to the fact they carry out the equal way at low wind speeds. However, as soon as tool has reached it's rate energy, energetic stall mills will flip its blades inside the opposite path from what a pitch-controlled machine might by way of doing this, the blades induce stall on its rotor blades and therefore waste the greater energy within the wind to save you the generator from being overloaded. This mechanism is generally both found out through hydraulic structures or electric powered stepper cars [31].

2.2.2 Vertical Axis

Vertical axis turbines have blades that rotate around a vertical axis, blades of which are attached to the upper and lower of a vertical rotor, resembling an eggbeater is a type of very common vertical axis wind turbine. Vertical axis wind turbines have their heights equivalent to 33 metres and width of 16 metres. They can capture wind from any direction without needing to face into the wind like horizontal-axis turbines. This design makes them suitable for areas with variable or turbulent wind patterns [32].

2.3 Wind power design and development

According to Chauhan et al the size of wind turbine in 2004 was 0.77 Mega Watt which further increased in 2009 having the size of 1 Mega Watt [31]. Designing and development involves several critical components and methodologies of 1 Mega Watt wind power system. A significant advancement is the use of high- temperature superconducting generators, which can reduce the generator's size and weight while maintaining efficiency, with losses not exceeding 1.6 percent of nominal output power [33]. The rotor speed of 600 rev/min is showing the potential for compact and efficient energy conversion. Additionally, the aerodynamic design of horizontal axis wind turbines (HAWT) is crucial. Utilizing blade element momentum (BEM) theory, researchers have optimized turbine performance, achieving effective power coefficients under specific operational conditions [34-36]. The integration of innovative designs, such as those tailored for low wind speeds, further enhances the viability of wind power in diverse environments [37]. Overall, the combination of advanced generator technology and aerodynamic optimization is essential for the successful implementation of 1MW wind power systems.

To design a grid connected wind turbine (phasor type) an induction generator is used which is about 1MVA (1 MW). We are to design the generator's parameters as line-to-line voltage of 400 V and make it's frequency of about 50 Hz because the frequency in India is about 50 Hz and the same is 60 Hz for the other countries. The nominal power of the turbine will be 1e6 VA. We will input the desired wind speed according to our requirement. Based on the above parameters the wind when we see the characteristics diagram at different wind speed at pitch angle beta equal to 0 degree then it is vary in between 1 PU to 0.1 for the wind speed of about 12 m/s to 6 m/s. When wind speed is about 12 m/s then wind turbine output power and turbine speed is 1 PU.

In case of wind speed is less than 12 m/s i.e. 10.8 m/s then the turbine speed is 1 PU and the turbine power output is less than 1 PU that is approximately 0.75 PU. If the wind speed further reduces the turbine power is also reduced accordingly.

If the rotational speed and maximum power at base wind speed changes the turbine power characteristics also changes with it[38].

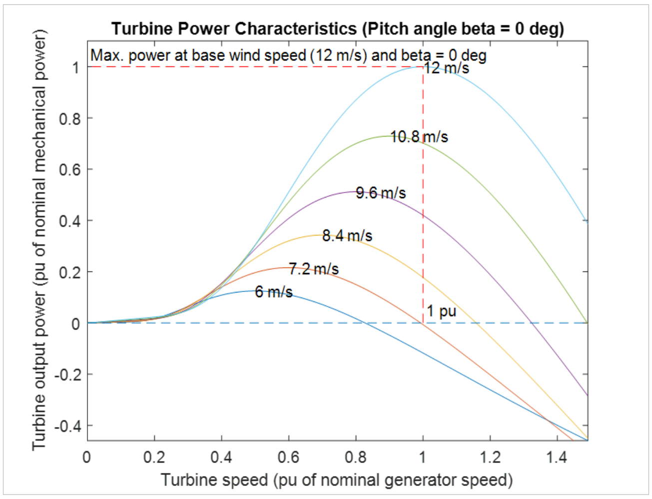


Figure 4: Wind turbine power characteristics

Further we use a step device which controls the quality of wind being supplied to the wind turbine with initial value 8 and final value as 12. Now for controlling the wind speed a rate limiter is used which is connected with step with slew range from +1 to -1. Make it's sample time modes continuous. The other end of this rate limiter is connected with the input port of wind turbine generator. Trip signal is maintained to 1 with a constant. Take output from a wind turbine go for bus selector. Select then inputs for it as real power P (pu), reactive power Q(pu), rotor speed wr(pu), electrical torque Te(pu), pitch angle in degree. Further we connect this bus selector with a scope for each and every signal which provide the output result of the turbine. In this real power port is connected with rate limiter. To take output we connect A, B and C port of wind turbine with three phase programmable Voltage source with changing it's parameters by taking it's it amplitude 25e3, phase zero and frequency is about 50 Hz. This three phase programmable voltage source is connected with neutral to ground. For measuring the power flow in grid side we take three phase V-I measurement source in which parameters of voltage measurement is phase to ground. Insert signal label as V_{abc}, and in the current measurement similarly we use signal label as I_{abc}, and output signals as in terms of complex.

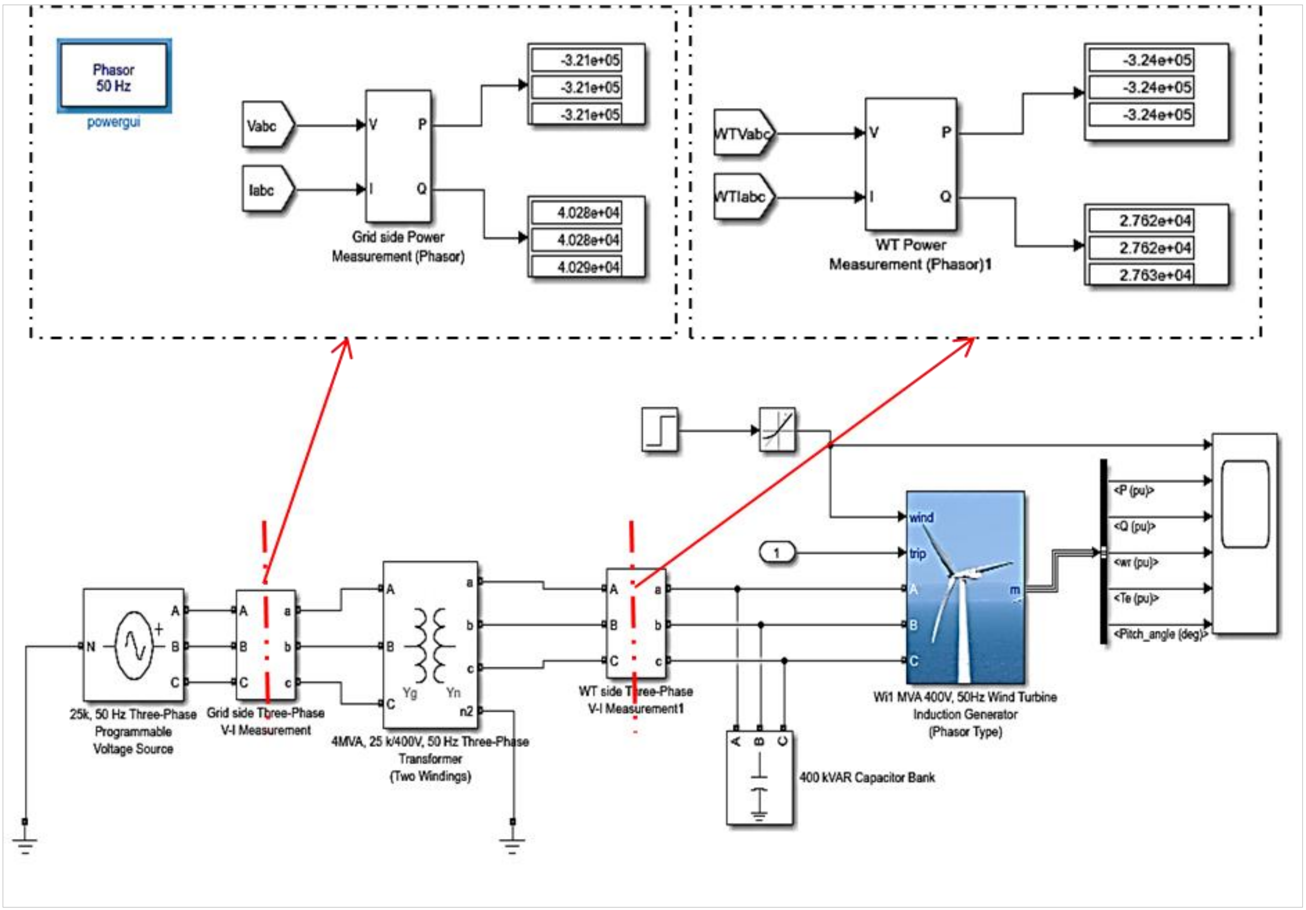


Figure 5: Grid connected wind turbine

Take a three phase two windings transformer of 4MVA of nominal power, phase to phase winding 1 and winding 2 parameters changing with 25 kV and 400 V. Configuration of these windings are Y_g, Y_n having type of three single- phase transformer. Set the magnetic resistance as infinite. Use ground to connect transformer's neutral to ground. Now we take a WT side three-phase V-I measurement and connect it with transformer's output. Now this is a wind turbine induction generator-based system it will take some amount of reactive power so it is necessary to connect a capacitor bank of 400 kVAR, with the help of which a required amount of reactive power can be injected to this wind turbine. This capacitor bank and V-I measurement block is connected with wind generator.

Finally we have to conclude power flow from wind turbine generator to grid side. For which take power measurement block (Power- phasor) named as grid side power measurement. Similarly, we take wind turbine power measurement to give input from voltage and current measurement of grid side for which we use from block with parameters of it's are V_{abc}. Similarly, for current we use I_{abc}. We can connect display to Grid side power measurement and WT power measurement to measure the power. For wind turbine measurement block take signal label as WTV_{abc} for voltage and WTI_{abc} for current at WT side three phase V-I measurement. Put powergui and make it as phasor type frequency having 50Hz. Do setting for model configuration parameters start time of which is 0 sec. and end time is 10 sec. See solver details select solver type. After making these all configuration we run the simulation the total of the output value is 1 MVA; negative value indicating that power is measuring at WT side.

2.4 Mathematical calculation

The calculations show that the total active power generated by the wind turbine is approximately 1 MW. The active power is calculated as follows:

Total Active Power

$$P_{total} = \sum_{i=1}^{n} P_i$$

- P_{total}: Total active power (W or MW)
- P_i: Active power contribution of the i^{th} source or load (W or MW)
- n: Number of sources or loads

The total active power P is calculated by summing the individual components of active power, as follows:

$$P = (3.24\times10^5) + (3.24\times10^5)+(3.24\times10^5)$$
$$P = (3.24\times10^5) + (3.24\times10^5) + (3.24\times10^5)$$
$$P = 9.72\times10^5 \text{ W}$$

Converting this into a more convenient unit:

$$P \approx 1.00\times10^6 \text{ W}=1 \text{ MW}$$

The slight discrepancy is due to minor losses, confirming the output as 1 MW. The negative sign indicates the direction of power flow from the wind turbine to the grid.

Total Reactive Power

$$Q_{total} = \sum_{i=1}^{n} Q_i$$

- Q_{total}: Total reactive power (VAR or MVAR)
- Q_i: Reactive power contribution of the i^{th} source or load (VAR or MVAR)
- n: Number of sources or loads

The total reactive power Q is calculated by summing the individual components of reactive power, as follows:

$$Q = (2.76\times10^4)+(2.76\times10^4)+(2.76\times10^4)$$
$$Q = 8.29\times10^4 \text{ VAR}$$

This reactive power is the amount drawn from the grid by the wind turbine. Additionally, the system supplies 400 kVAR via a capacitor bank, resulting in:

Total Reactive Power (Q) absorbed by the WT

The total reactive power (Q) absorbed by the wind turbine can be calculated by summing the individual components of reactive power. Based on the expression received by simulation studies:

$$Q = 8.29\times104 \text{ VAR} + 4.00\times105 \text{ VAR}$$
$$Q = 4.83\times105 \text{ VAR}$$

Converting this into MVAR:

$$Q \approx 0.483\text{MVAR}$$

Thus, while generating 1 MW of active power, the wind turbine also absorbs approximately 0.483 MVAR of reactive power.

3. Result and Discussions

The work provides simulation data of a 1 MVA phasor-type wind turbine system using MATLAB/Simulink. The simulation process involved constructing an elaborate model of the phasor-type wind turbine system with a specified turbine design including a 400 V (line-to-line) voltage and a frequency of 50 Hz. The system also incorporated additional features including a high temperature superconducting generators, and incorporated a 400 kVAR capacitor bank for managing reactive power. The simulations evaluated the performance of the turbine using various wind speeds, finding that the turbine model behaved as intended, producing 1 PU of power at 12 m/s wind speed and limited variation of the generated power at lower wind speeds. Further, estimates the capacity to compensate for reactive power were achieved, where the models experienced accurate accounting for the flow of power from turbine to the grid and met expectations with regard to the produced power from the turbine and load conditions. Overall, the simulated, expected and validated results achieved are supportive of the accuracy of the model and performance of the phasor-type wind turbine system. The accuracy a confirm that the wind turbine model provides a reasonable representation of operational conditions of the real wind turbine model are considered satisfactory results in the design specifications.

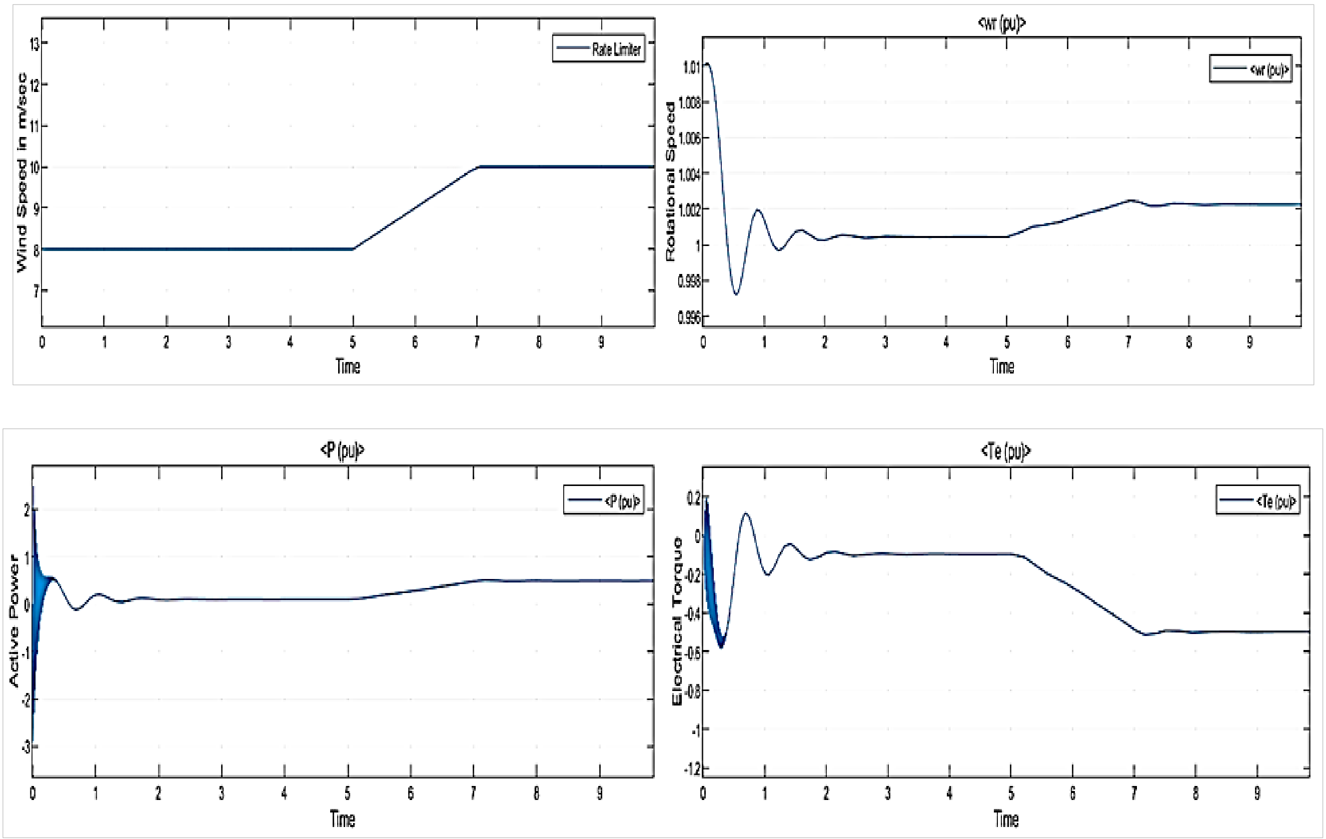
3.1 Effect of variable wind speed

Simulation studies provide a detailed analysis of the wind turbine's behaviour under varying wind speeds to evaluate its performance across multiple parameters. These parameters include active power (P), reactive power (Q), rotor speed, pitch angle, and torque. The objective is to assess how effectively the turbine adapts to changes in wind conditions and ensure its optimal operation while maintaining grid stability.

3.1.1 WTP parameters for 10m/s

In figure 6 graph shows that when we take wind speed as 10 m/sec here the analysis showing that wind power changing from 8 to 10 PU look at pitch angle it is making zero value because for 10 m/sec our power output is less then nominal power i.e. 1 PU. So, for 10 m/sec real power is maintaining approximately 0.495 PU.

The reactive power (Q) started at high then slightly come down at approximately 0.8 MVAR when the wind speed reaches 10 m/sec. This indicates that the wind turbine is consuming more reactive power as the wind speed decreases.



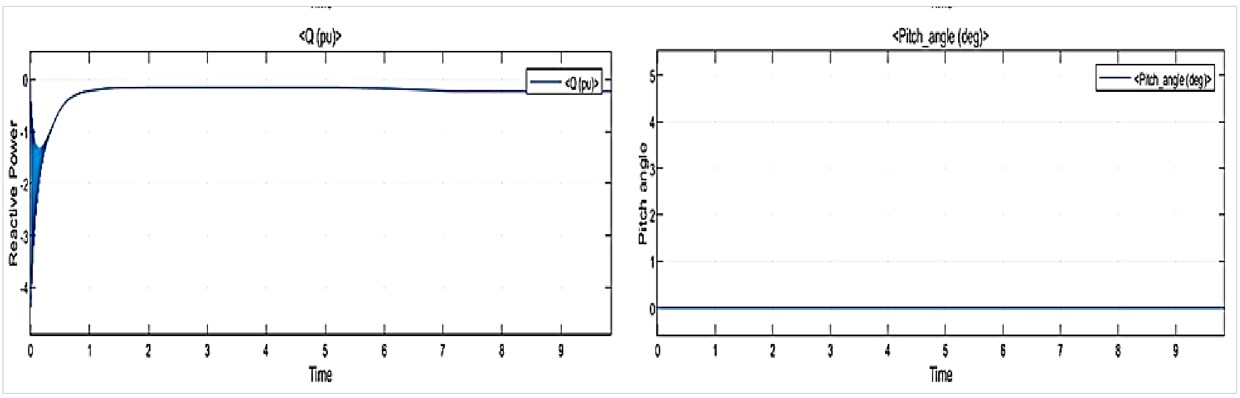


Figure 6: Graphs at wind speed of 10 m/sec.

3.1.2 WTP parameters for 12 m/s

Similarly in figure 7, graph 1 represents the relationship between wind speed and time, showcasing the performance of wind power generation. The graph indicates that the wind speed remains constant at 8 m/sec for the first 5 seconds, resulting in a steady output. After 5 seconds, the wind speed begins to increase. When the wind speed reaches 12 m/sec, the real power output of the wind turbine rises to 1 per unit (PU), equivalent to 1 MW. This illustrates that as wind speed increases, the power generated by the wind turbine also increases, with 1 MW achieved at 12 m/sec.

The reactive power (Q) initially starts high but stabilizes at approximately 0.48 MVAR when the wind speed reaches 12 m/sec. This indicates that the wi, nd turbine is consuming less reactive power as the wind speed increases. Additionally, the rotor speed is slightly greater than 1 PU, specifically around 1.004 PU. This is expected since the system operates as an induction generator, where the rotor speed slightly exceeds the synchronous speed during power generation.

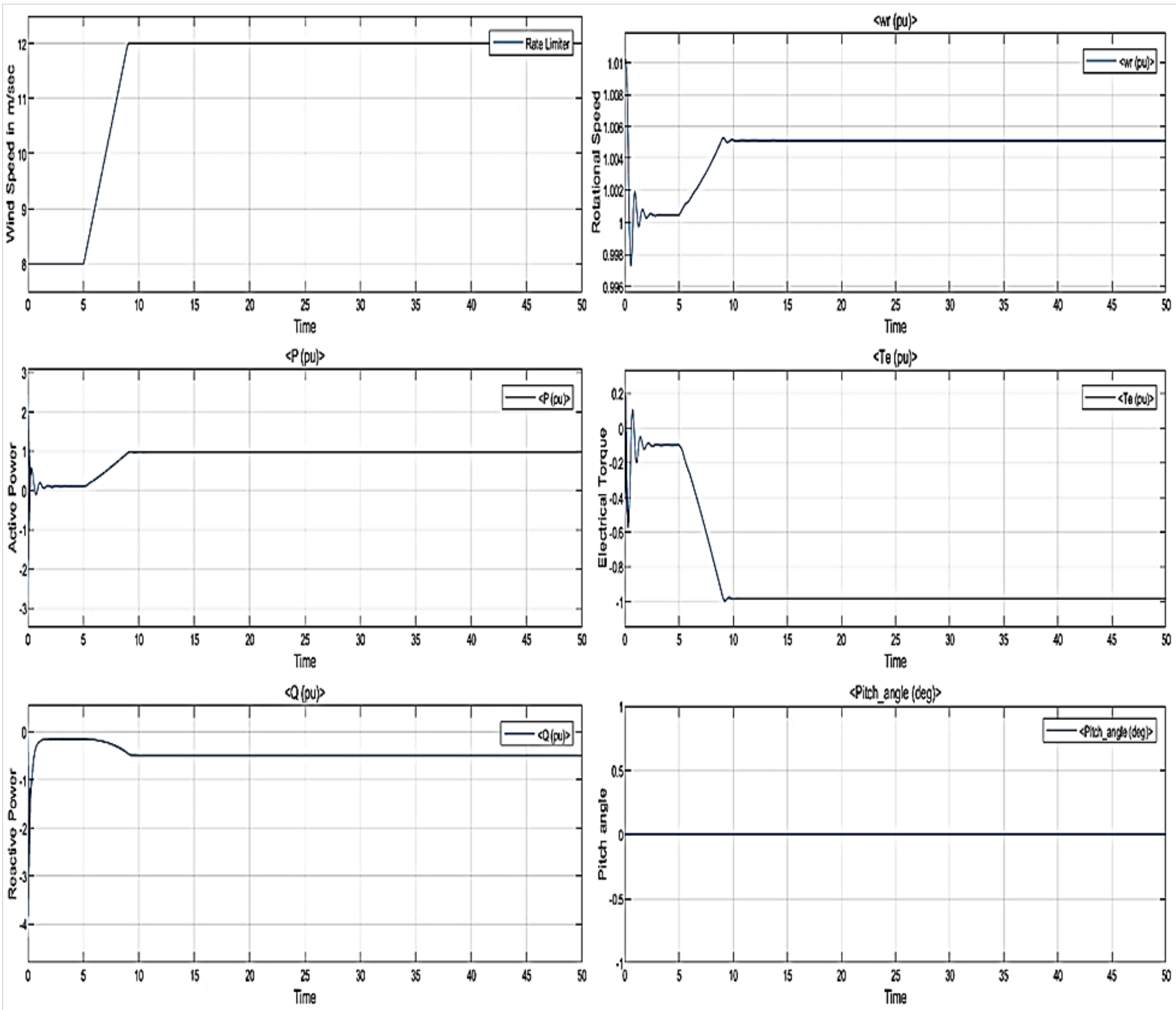


Figure 7: Graphs at wind speed of 12 m/sec

The torque produced by the wind turbine is 1 PU, but it is negative, indicating that the turbine is generating power. The pitch angle remains at 0 degrees since the power output does not exceed 1 PU when the wind speed is below 12 m/sec. In scenarios where the wind speed exceeds 12 m/sec, the pitch angle would need to adjust to control the output power, but in this case, with no change in nominal power, the pitch angle stays at 0 degrees. As the wind speed increases, the pitch angle will increase accordingly to prevent the turbine from exceeding its rated power output. Conversely, as the wind speed decreases, the pitch angle will decrease to maintain optimal power generation. This dynamic adjustment of the pitch angle ensures efficient operation across varying wind speeds while protecting the turbine from potential overloading.

3.1.3 WTP parameters for 14m/s

Practically if we see the variation in the graph as per below figure 8 we can say that if wind speed is changed with 14 m/sec the wind power change with 8 to 14 PU not with 8 to 12 PU. The real power is slightly greater then 1 PU it is not as changed by the wind speed that is 12 m/sec. When wind speed is 14 m/sec however the pitch angle increases from 0 to 5 degree to maintain or to reduce power within 1 PU and it is also controlling the reactive power. So, pitch angle is zero as long as there is no power violation takes place but soon after greater then nominal power pitch angle in force to control the power or to control the blade such that nominal power is maintained here.

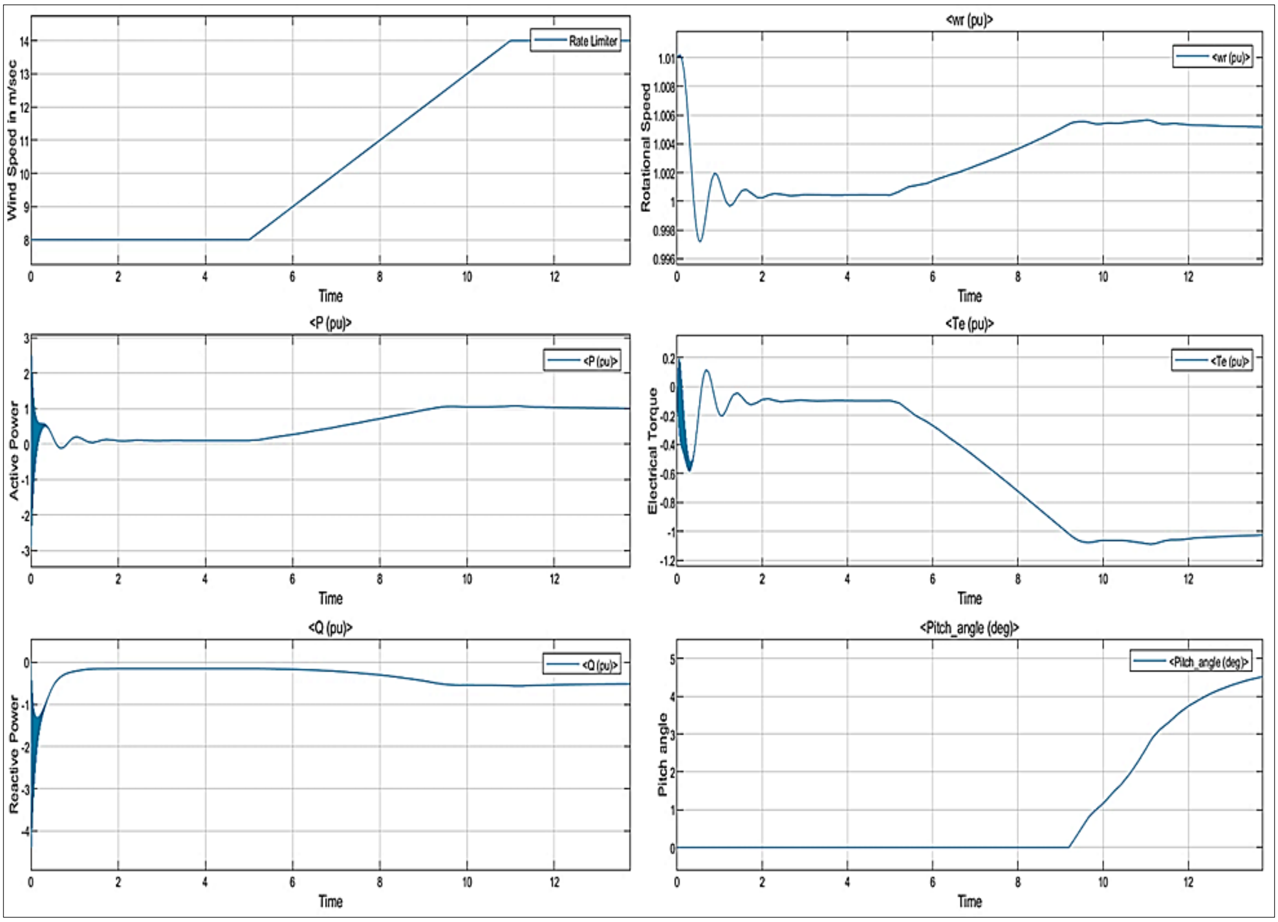


Figure 8: Graphs at wind speed of 14 m/sec.

3.2 Effect of variable capacitive power

If a capacitor bank is used to provide reactive power compensation for a wind turbine system, the **change in capacitive reactive power** depends on the capacitor bank's capacity, the applied voltage, and the frequency.

The reactive power (Q_c) provided by a capacitor bank is given by:

$$Q_c = V^2 \cdot \omega \cdot C$$

or equivalently:

$$Q_c = V^2 \cdot 2\pi f \cdot C$$

where:

Qc: Reactive power provided by the capacitor bank (VAR or kVAR)

V: Line voltage (RMS) across the capacitor (V)

$\omega = 2\pi f$: Angular frequency (rad/s)

f: System frequency (Hz, e.g., 50 or 60 Hz)

C: Capacitance of the capacitor bank (F)

For a capacitor bank rated at 400 kVAR:

$$Q_{c1} = 400 \text{ kVAR}$$

If the system voltage or configuration changes, C can be calculated or adjusted to meet the target Q_c.

If we want to calculate the capacitance required to achieve a specific Q_c:

$$C = \frac{Q_c}{2\pi f . V^2}$$

For example:

At 400 kVAR, V=11 kV (line voltage), and f=50 Hz

$$C = \frac{400000}{2\pi 50.(11000)^2} = 0.0000105 \text{ Fs}$$

At 1 VAR, the calculation will yield a much smaller C at the same condition.

$$C = \frac{1}{2\pi 50.(11000)^2} = 2.6296 \times 10^{-11} \text{ F}$$

$$\approx 3 \times 10^{-11} \text{ F}$$

3.2.1 Wind Power at 1 VAR capacitive power

In a wind turbine system, a **capacitor bank** is commonly installed to provide reactive power support, which is crucial for maintaining grid stability and ensuring efficient operation. Reactive power, while not directly contributing to active power output (useful work), plays a key role in regulating voltage and supporting the magnetic fields required for inductive loads.

If we analyze the performance of a capacitor bank with two distinct reactive power ratings - **400 kVAR** and **1 VAR** - it helps us understand how varying the size of the capacitor bank impacts the system's overall behavior.

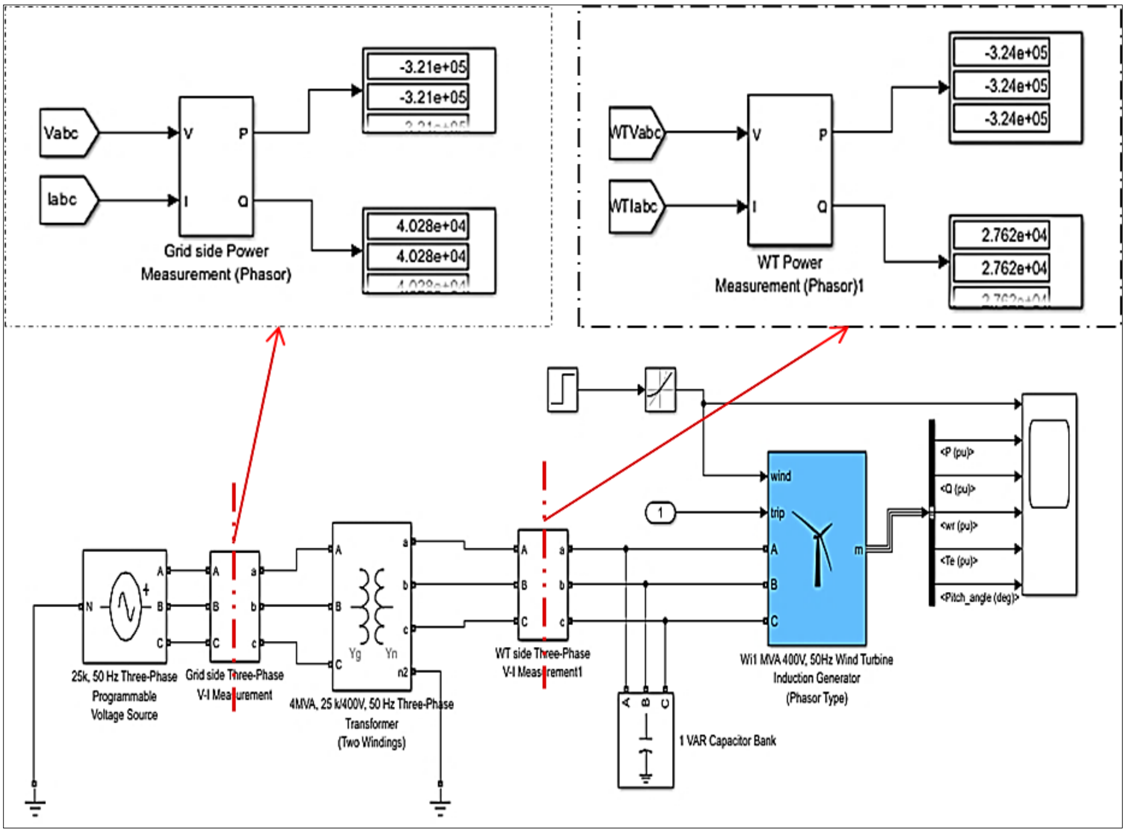


Figure 9: Simulation of Grid connected wind turbine for 1 VAR reactive power of capacitor bank

3.2.2 WTP parameters for constant capacitive power and variable wind speed

In the below figure 10 and figure 11 at **10 m/s** wind speed, the real power output is approximately **0.495 PU**, which is below the nominal power of **1 PU**. As the wind speed increases, the real power output rises, reaching **1 PU (1 MW)** at **12 m/s**, indicating a direct relationship between wind speed and power output. When the wind speed reaches **14 m/s**, the power output slightly exceeds **1 PU**, requiring adjustments to the turbine's pitch angle to maintain optimal power generation and prevent overloading. This dynamic adjustment ensures the system operates efficiently across varying wind speeds while controlling reactive power consumption.

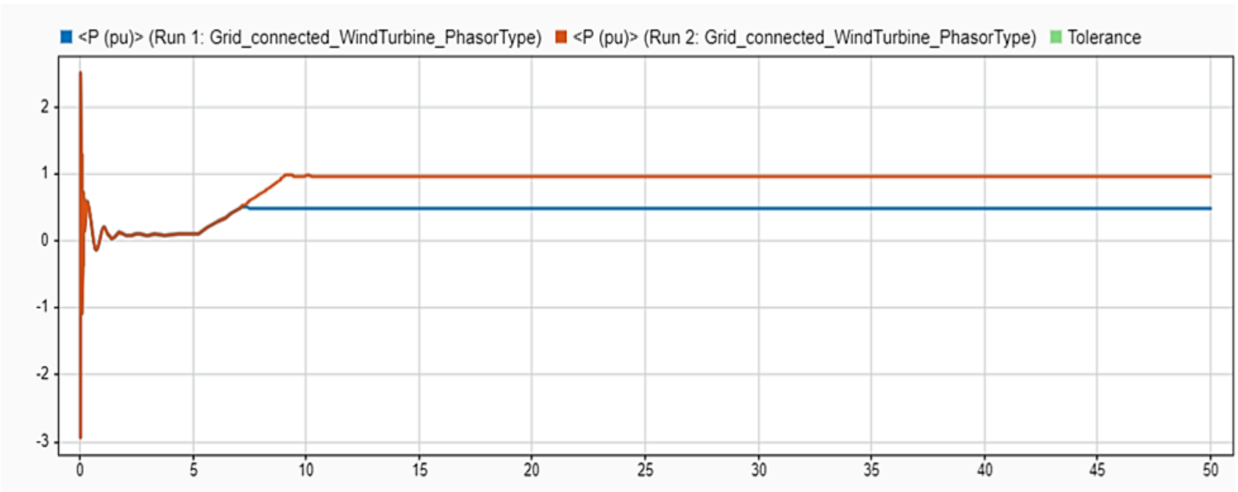


Figure 10: Real power variation at 10 m/sec and 12 m/sec for a constant capacitive power 400kVAR.

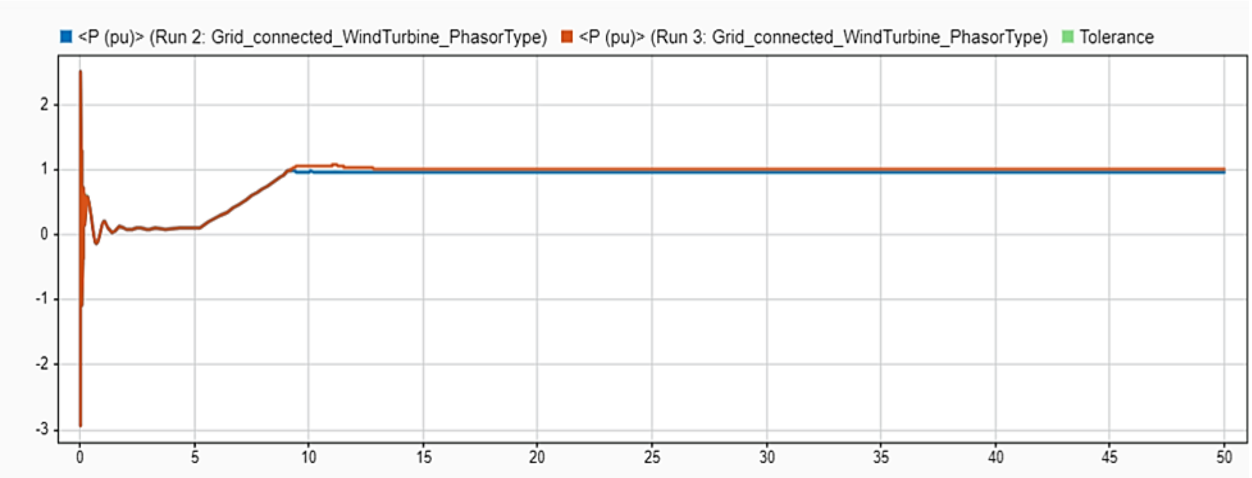


Figure 11: Real power variation at 12 m/sec and 14 m/sec for a constant capacitive power 400kVAR.

The pitch angle remains zero as long as the wind speed does not push the power output beyond nominal limits. However, when power output exceeds 1 PU, the pitch angle increases to control power generation and maintain efficiency. This ensures that the wind turbine operates optimally across varying wind speeds, protecting it from potential overload situations.

Thus, while the real power increases with wind speed, the pitch angle adjusts dynamically to prevent excessive power generation and ensure efficient, safe turbine operation.

3.2.3 WTP parameters for variable capacitive power and constant wind speed

The comparison between a 400 kVAR and a 1 kVAR capacitor bank as per below figure 12, highlights the importance of choosing an appropriately sized capacitor bank based on the wind turbine system's scale and reactive power needs. The **400 kVAR capacitor bank** is ideal for large wind turbine systems with high reactive power demand, offering substantial compensation to maintain grid voltage stability and improve the system's power factor, thereby reducing energy losses and utility penalties. However, it requires more space and higher investment due to its larger capacity. In contrast, the **1 kVAR capacitor bank** provides minimal reactive power support, suitable for small-scale or localized systems where fine-tuning is needed. While compact and cost-effective, its limited impact on voltage stabilization and power factor correction makes it unsuitable for high-demand applications.

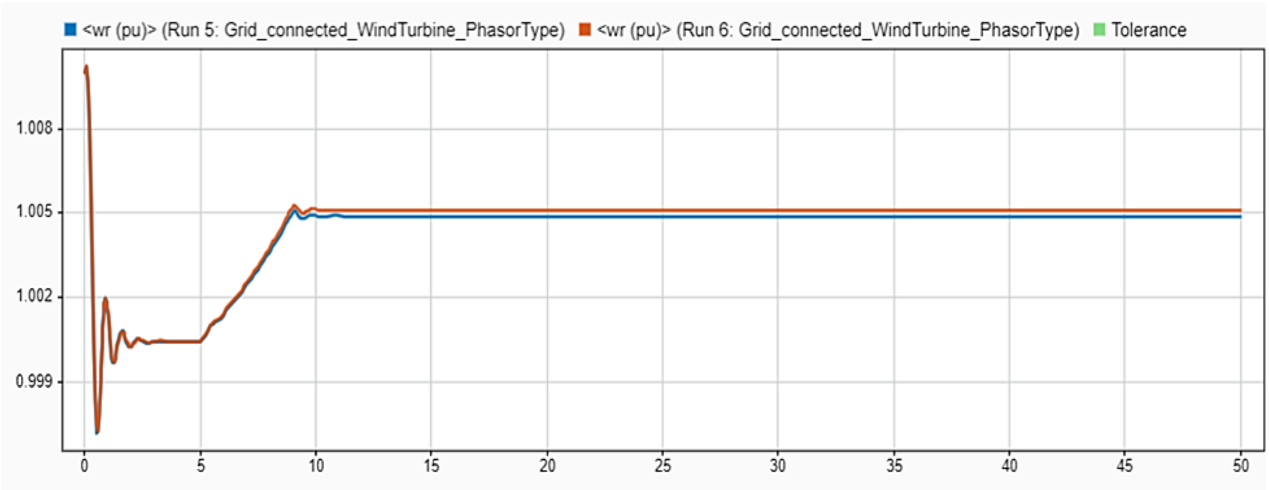


Figure 12: Rotational speed of wind turbine (Wind speed 12 m/s) for 400 kVAR and 1 VAR reactive power of capacitor bank

4. Conclusions

The conclusion from the previous chapter results is that when the wind turbine operates below nominal power, the pitch angle increases. Additionally, the reactive power becomes negative, indicating a value of approximately -0.22, which suggests that the turbine is absorbing reactive power from the grid rather than supplying it.

When the wind speed is lower than the base speed, the real power generated by the wind turbine decreases proportionally. For instance, at a wind speed of 12 meters per second (m/s), the real power output should be maintained at a nominal value of 1 per unit (PU). However, if the wind speed drops to 10 m/s, the real power output falls to approximately 0.495 PU, indicating a significant reduction in power generation. On the other hand, if the wind speed increases to 14 m/s, the real power output slightly surpasses the nominal value of 1 PU, reflecting the turbine's ability to generate more power when the wind speed exceeds the base level. This relationship between wind speed and real power output highlights the importance of operating wind turbines within their optimal wind speed range to maintain efficient power generation.

The capacitor bank in the system is rated at 400 kVAR. When the reactive power of the capacitor bank is reduced from 400 kVAR to just 1 VAR, the wind turbine becomes dependent on the grid to supply all the reactive power it requires. This is because the capacitor bank no longer provides sufficient reactive power, forcing the grid to compensate for the deficit. Conversely, when the capacitor bank is supplying 400 kVAR, it meets a significant portion of the wind turbine's reactive power needs, reducing the amount of reactive power that must be drawn from the grid. Essentially, the higher the reactive power supplied by the capacitor bank, the less the grid needs to contribute, optimizing the system's efficiency and reducing strain on the grid.

Based on the calculations for a wind speed of around 12 m/sec, the wind turbine (WT) power measurement is approximately 163,200 watts. Meanwhile, the power measured on the grid side is about 179,500 watts. The close proximity of these values suggests that the difference, which is mainly around 16,300 watts, can be attributed to reactive power losses occurring within the transformer.

Furthermore, the real power output from the wind turbine is close to 1 MW. Of this, about 960,000 watts (0.96 MW) is successfully transferred to the grid, indicating that the wind turbine is effectively supplying most of its generated power to the grid, with minimal losses.

Declarations

Conflicts of Interest

The authors declare that they have no conflict of interest.

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Authors' contributions or CRediT Roles

Kumkum Malakar: Conceptualization, Writing-original draft, Shiv Lal: Review and Editing

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Nomenclature

BEM	Blade element momentum
BEM	Blade Element Momentum
BESS	Battery energy storage system
C	Capacitance
CSWT	Constant speed wind turbines
DC	Direct currect
DFIG	Doubly-fed induction generators
DSTATCOM	Distribution STATic synchronous COMpensator
EMT	Electromagnetic Transient
f	System frequency
GW	Gigawatt
HAWT	Horizontal axis wind turbines
HILS	Hardware-in-the-loop simulation
IGBT	Insulated Gate Bipolar Transistor
kVA	Kilo volt-ampere
kVAR	Kilo-Volt-Amperes Reactive
kW	Kilo Watt
MATLAB	Matrix Laboratory
MMC	Modular multilevel converters
MVA	Mega Volt-Ampere
MW	Mega Watt
N	Number of sources or loads
Pi	Active power contribution of the ith source
PLL	Phase-Locked Loop
PMSG	Permanent Magnet Synchronous Generator
Ptotal	Total active power
PU	Per un it
PWM	Pulse Width Modulation
Qc	Reactive power provided by the capacitor bank
Qi	Reactive power contribution of the ith source
Qtotal	Total reactive power
RSCAD	Real-Time Simulator Computer Aided Design
THDV	Total Harmonic Distortion of Voltage
US	United Satates
V	Voltage
VSCs	Voltage-Source Converters
WT	Wind turbine
ω	Angular frequency

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