Performance Improvement of Grid-Connected Wind Energy System Using STATCOM with PID Control

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Abstract: *Wind energy has emerged as one of the most significant renewable energy resources because of the increasing depletion of conventional energy sources. However, maintaining stable voltage levels in wind energy conversion systems remains a major technical challenge due to variations in wind speed and fluctuating power generation. To address this issue, several compensation and control techniques have been developed for improving grid stability and power quality. This work focuses on enhancing the stability of a grid-connected wind farm through effective voltage regulation and reactive power compensation using a Static Synchronous Compensator (STATCOM). A PID-based voltage control loop is implemented to regulate the operation of the STATCOM, while Pulse Width Modulation (PWM) is employed as the switching control technique. A comparative analysis is carried out under varying wind speed conditions to evaluate the performance of different stabilization approaches, including the use of capacitor banks, standalone STATCOM, and STATCOM integrated with a PID controller. The obtained results indicate that the PID-controlled STATCOM provides superior voltage stability, improved reactive power support, and better overall dynamic performance of the wind farm system.*

Keywords: WPPS Wind Power Plants , STATCOM, Static Synchronous Compensator , SCIG Squirrel Cage Induction Generator etc

I. INTRODUCTION

This paper presents an investigation of a 6-pulse STATCOM control scheme for improving the performance and stability of a grid-connected wind energy generation system. The proposed approach provides fast dynamic response and effective voltage support under varying operating conditions. To achieve smooth voltage regulation and enhanced system performance, a PID controller is incorporated into the STATCOM control loop. Pulse Width Modulation (PWM) technique is utilized for switching control of the converter.

The performance of the wind farm system is analyzed in PSCAD by considering different compensation methods, including the use of capacitor banks, standalone STATCOM, and STATCOM integrated with a PID controller. The comparative simulation results demonstrate that the STATCOM with PID controller offers superior voltage regulation, faster response, and improved reactive power compensation compared to other approaches.

In modern interconnected power systems, increasing transmission line loading and changing load characteristics often lead to electromechanical oscillations, voltage instability, and power quality issues. Traditionally, Power System Stabilizers (PSS) have been employed to suppress such oscillations. However, under varying operating conditions, PSS parameters require continuous retuning for effective performance. In this context, Flexible AC Transmission System (FACTS) devices, particularly STATCOM, have emerged as efficient solutions for voltage control and power flow management. When combined with supplementary damping control techniques such as PID controllers, FACTS devices significantly enhance system stability and reduce oscillatory behavior in grid-connected wind energy systems.

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II. LITERATURE REVIEW

Shiba R. Paital et al. (2016) optimized PID controller parameters of STATCOM using Particle Swarm Optimization (PSO) and Bacterial Foraging Optimization techniques. The proposed optimization methods improved voltage regulation and enhanced stability performance in interconnected power systems.

Z. Ghadimi et al. (2022) developed a supplementary damping controller for STATCOM integrated with a wind farm system. The controller effectively reduced low-frequency oscillations and improved damping characteristics under varying operating conditions.

Habib Bali et al. (2025) investigated the use of STATCOM for stabilizing disturbed microgrids integrated with wind energy systems. Their study demonstrated improved voltage regulation and system stability during load fluctuations and wind speed variations.

Kishankumar P. Patel et al. (2025) proposed an optimal placement methodology for DSTATCOM and TCSC devices in renewable energy integrated power systems. The PID-controlled DSTATCOM significantly reduced power losses and enhanced voltage stability.

N. G. El Sayed et al. (2025) analyzed PID and fuzzy logic based STATCOM controllers for improving low-voltage ride-through capability in hybrid PV-wind systems. The optimized control approach provided better dynamic response and reduced voltage oscillations during faults.

S. Bhukya et al. (2025) introduced a fuzzy logic based E-STATCOM controller for grid-connected wind cogeneration systems. The proposed controller enhanced transient stability, reactive power compensation, and overall power quality.

I. Griche et al. (2025) proposed a fractional order PI-controlled STATCOM for wind farm integrated power systems. Simulation results showed improved damping capability and faster transient response under disturbed operating conditions.

Andrew Mole et al. (2025) developed a reinforcement learning-based collaborative control strategy for wind farms. The proposed intelligent control technique improved system stability and optimized power generation efficiency.

Sebastiano Randino et al. (2025) presented a nonlinear adaptive control framework for wind turbine systems operating under turbulent wind conditions. The study demonstrated enhanced power stability and improved turbine dynamic performance.

Mohamed I. Mossad (2026) published a review on the application of STATCOM devices in wind energy systems. The paper discussed advanced control strategies such as PI, PID, adaptive, and intelligent controllers for improving grid stability and reactive power support in modern wind farms.

III. METHODOLOGY

The basic configuration for Variable speed wind turbine generator is shown in Fig 3.3

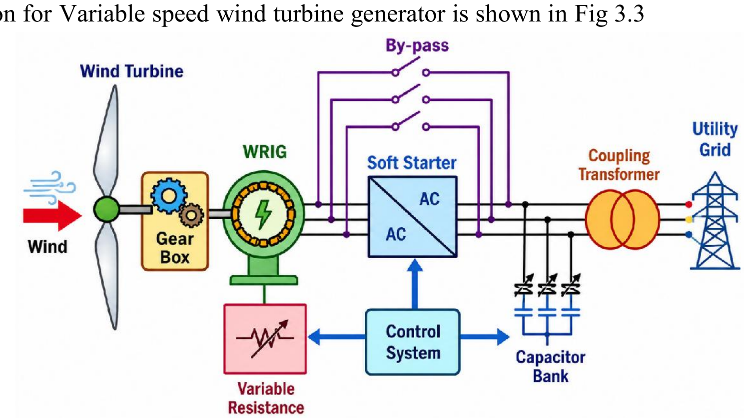

Fig. 3.3 The basic configuration for Variable speed wind turbine generator

In this configuration, the generator is directly connected to the utility grid, while the rotor winding is connected to a variable rotor resistance. A power electronic converter is employed to control the rotor resistance dynamically. By varying the rotor resistance, the rotor flux and electromagnetic characteristics of the machine are adjusted, enabling variable speed operation and maximum power extraction from the wind energy system. Typically, the rotor resistance is varied within a range of 0–10% of its rated value. However, a portion of the generated energy is dissipated as heat across the external rotor resistance. A soft starter is incorporated in the system to minimize starting current and reduce the reactive power compensation requirement during generator operation. In the proposed system, both variable rotor resistance control and blade pitch angle control are utilized to maintain stable operation and optimize power generation under varying wind conditions. One of the major advantages of this system is the reduction of mechanical stress on the drive train and transmission components, thereby minimizing power fluctuations caused by sudden wind speed variations. Additionally, the system improves operational flexibility and enhances energy capture efficiency. However, the system also has certain limitations, such as a restricted speed control range and additional power losses due to the external rotor resistance, which may reduce overall system efficiency and require larger resistance ratings for higher operating capacities.

3.12 MATHEMATICAL MODELING OF AERODYNAMIC SYSTEM

Under this section, the relationship between thrust force and that of rotor torque has been established.

$$F_T = F_{ST} C_T(\lambda, \beta)$$

$$T_A = F_{ST} R C_Q(\lambda, \beta)$$

Here Ct and Cq represent the thrust and torque coefficients, respectively, depending upon tip speed ratio and pitch angle. Therefore, the force and torque equation can be remodified as,

$$F_T = \frac{1}{2}\rho\pi R^2 v^2 C_T(\lambda, \beta)$$

$$T_A = \frac{1}{2}\rho\pi R^3 v^2 C_Q(\lambda, \beta)$$

From the above two equation(s), it can be seen that non-linearity in the system is due to wind speed and pitch angle. Therefore, while simulating the system, these parameters were evaluated analytically, and necessary mapping has been carried out for its insertion in the Simulink.

IV. FACILITIS REQUIRED FOR PROPOSED WORK

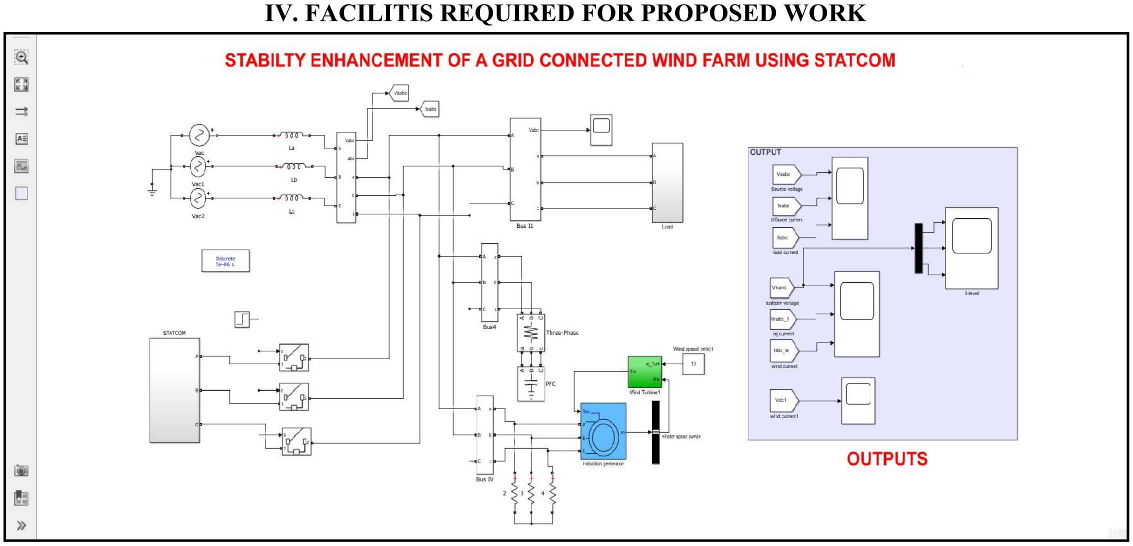

Fig. 4.1 Simulink model for Stabilty Enhancement of A Grid Connected Wind Farm Using STATCOM

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Wind turbine is used to convert the wind's kinetic energy into electrical energy. Modeling wind turbine is the main factor for analyzing stability concept. As wind is a renewable energy source, many countries are using this source as an alternative to the fossil fuels. Due to the simplicity and robustness, an induction generator is used which is connected to the electrical grid. At the terminal bus of the wind farm STATCOM and Capacitor bank are STATCOM or Static Synchronous Compensator is a device of Flexible AC Transmission System (FACTS). For the improvement of the transient stability and power flow of electrical systems STATCOM is generally used. In case of the improvement of power factor and voltage regulation it is also used. In STATCOM the DC capacitor creates the voltage source converter. In the var control mode operation of the STATCOM the output reactive power is constant and independent of other system parameters [16].

V. PROPOSED EXPERIMENTAL RESULTS

In this portion, the simulation results of a wind farm along with induction generator is exposed using MATLAB. The wind farm is connected with STATCOM and capacitor bank to compensate the reactive power. Simulation results have been compared along with necessary graphs.

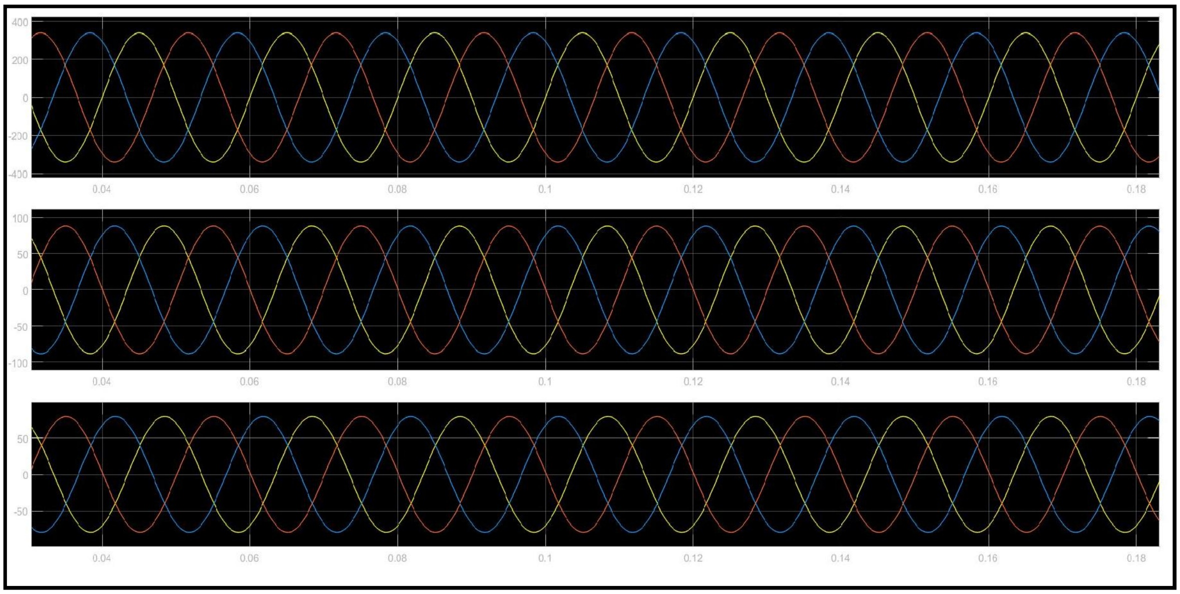

Fig. 5.3 Source Voltage, Source Current , Load Voltage.

For the adjustments in power system (for example, increment in loading, generator achieving reactive power limits [10] etc.), voltage stability has been a great concern for power system utilities. Induction generator (IG) based wind turbine has been used because it can recover *energy* with relatively simple control and it is also cost-effective. Though the active power produced by consistent speed, wind turbines is fluctuated because of the impacts of disturbance, the wind slope, the tower shadow and the reactive power request of these squirrel-cage induction generators have additionally changed. Voltage fluctuation can be caused at the point of normal coupling (PCC) due to the active and reactive power variations.

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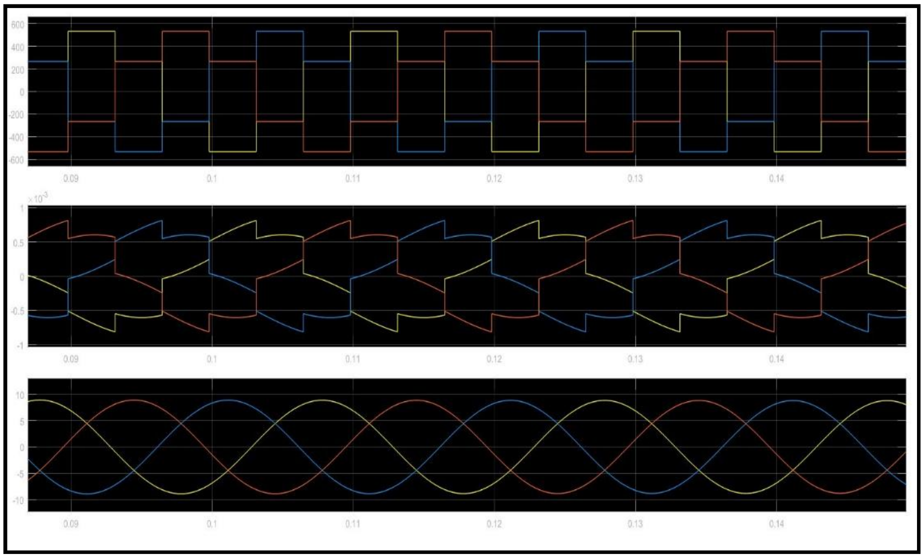

Fig.5.4 STATCOM Voltage, Injected Voltage, Wind Current.

Fig. 4.4 shows a controlled voltage profile after a certain load variation, and, therefore, a variation in load current can also be seen. After every switching operation in the MG system, the voltage profile is maintained with the PID Controller. Voltage control loop with PID controller has been used to control STATCOM. A Pulse Width Modulation (PWM) method has been adopted as the control strategy of STATCOM. Different comparative study regarding stabilization of a wind farm has been performed using different approach (i.e. wind farm with capacitor bank and STATCOM or using STATCOM along with Proportional– integral–derivative (PID) controller) during wind speed change. Comparison of result shows that STATCOM with PID controller offers better performance with enhanced stability.

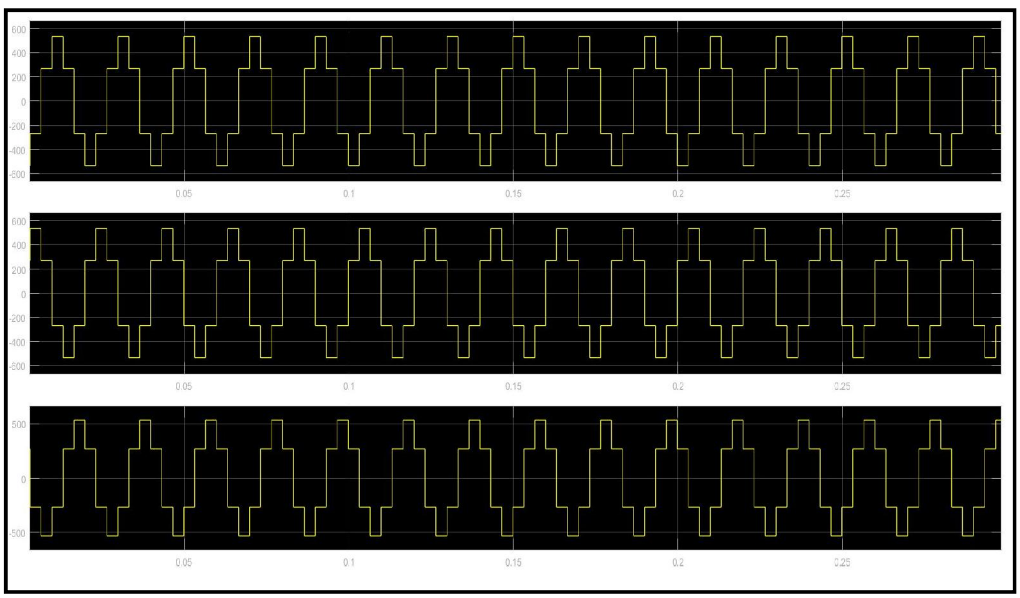

Fig.5.5 % Level PWM Technique using generate Pulses

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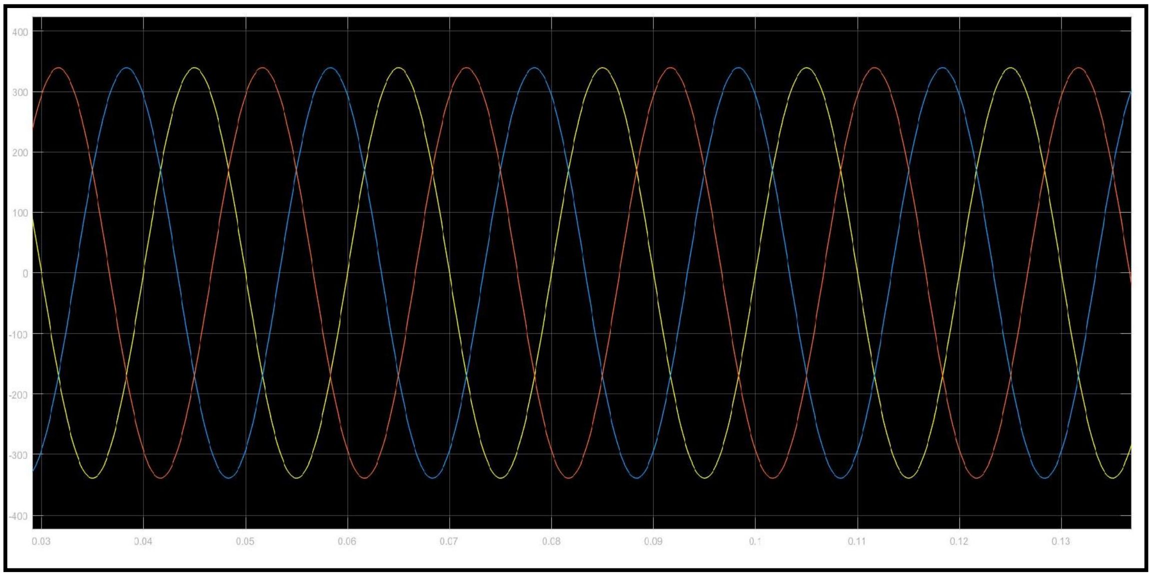

Fig.5.6 Grid Voltage

Despite the fact that Capacitor bank is utilized to keep up reactive power at consistent state, it can't legitimately be controlled to keep the voltage steady. In wind farms, STATCOM provides the voltage which is more stable and it is also cost-effective. With the ever-increasing use of renewable energy [11, 12] resources, the use of STATCOM has become absolutely essential grid-connected wind farm stability has been upgraded by mitigating voltage fluctuation and attaining reactive power compensation using Static Synchronous Compensator (STATCOM).

VI. CONCLUSION

This study deals with the stability analysis of the STATCOM. Voltage control loop with PID controller and Pulse Width Modulation (PWM) has been used for controlling purpose of the STATCOM. The results indicates that the STATCOM is more effective to stabilize the RMS voltage and terminal voltage over capacitor bank. STATCOM along with PID controller can effectively stabilize the wind farm voltage more smoothly than capacitor bank by providing sufficient reactive power to the wind farm. So the STATCOM system is more efficient. Finally, the stability of a grid-connected wind farm has been enhanced by mitigating voltage fluctuation and attaining reactive power compensation using STATCOM and PID controller.

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