

Renewable Energy Adaptive Voltage Control Using STATCOM in Wind Farm Integrated Grid System

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ABSTRACT: The intermittent nature of renewable energy can make it difficult to integrate renewable energy sources especially wind power into traditional electrical systems. The grid performs worse as a result of this instability, particularly when it comes to sustaining voltage and frequency. In response, the International Electrotechnical Commission (IEC) created the IEC 61400 standard to guarantee wind turbine performance and power quality. This standard addresses issues like voltage control, active and reactive power management which are critical when wind-generated electricity is fed into the grid. To mitigate these challenges and improve system stability, various Flexible Alternating Current (AC) Transmission System (FACTS) devices are employed. A key device in this context is the Static Synchronous Compensator (STATCOM), which helps manage voltage and power quality issues. In this paper, the authors propose a STATCOM model to enhance the power quality when feeding wind-generated electricity into the grid. The STATCOM is integrated between the Induction Fed Induction Generator (IFIG) of the wind turbine and the grid, with an option for energy storage. Using MATLAB Simulink for simulation, the proposed model aims to maintain system stability.

Keywords: Renewable Energy, Wind System, STATCOM, FACTS device, IFIG,

1. Introduction

The growing demand for clean and sustainable energy has accelerated the integration of renewable sources like wind power into modern power grids [1]. While wind energy offers numerous environmental and economic benefits, its inherent variability poses challenges to grid stability, especially in terms of maintaining consistent voltage levels. In a wind farm integrated grid system, fluctuations in wind speed can cause rapid changes in power output, leading to voltage instability, poor power quality, and potential disruptions in grid operation [2-3]. To address these issues, advanced power electronic solutions like the STATCOM are employed. STATCOM is a key component of FACTS that provides fast and adaptive voltage control by dynamically managing reactive power [4]. This

technology plays a vital role in stabilizing voltage, improving power quality, and ensuring reliable integration of wind energy into the electrical grid. As the global transition to renewable energy continues, adaptive voltage control using STATCOM becomes increasingly important for maintaining a resilient and efficient power system [5-6]. It is used in modern power systems for voltage regulation and reactive power compensation. It enables it to maintain constant voltage levels even under fluctuating load or generation conditions [7]. Unlike traditional reactive power compensators, it offers faster dynamic response, better performance under low-voltage conditions, and improved power quality [8]. As the demand for flexible and intelligent grid solutions increases, STATCOM has become a vital component in the evolution of smarter and more resilient electrical

networks. The integration of wind energy into modern power grids is essential for achieving a cleaner, more sustainable energy future [9]. However, the variability and intermittency of wind power present significant challenges to grid stability, particularly in maintaining consistent voltage levels. As a type of shunt-connected FACTS device, STATCOM plays a crucial role in improving the stability, reliability, and efficiency of electricity transmission and distribution networks [10]. Therefore, the renewable energy adaptive voltage control using STATCOM for grid stability in a wind farm-integrated grid system. This work addresses the following goals:

- To enhance the flexibility, controllability, and overall efficiency, IFIG is utilized.
- To improve voltage and frequency stability during fault conditions to ensure reliable operation of the grid, FACT is applied.
- To Provide fast and precise reactive power support to balance system demands and improve power factor, STATCOM is developed.

The following list shows the order in which the paper is presented: Recent work is covered in Section II. The proposed work is described in detail in Section III. Section IV presents the findings. A conclusion is given in Section V.

2. Recent Works

Hikmat Basnet *et al* (2024) [11] have presented a Proportional-Integral (PI) controllers in energy-storage-equipped STATCOM application. It allowing normal operational currents to flow freely, improving system stability and performance.

Zoran Miletic *et al* (2024) [12] have developed a three-phase four-wire five-level E-type STATCOM inverter for improved power

conversion efficiency. It designs return to the superconducting state automatically after the fault is cleared, minimizing downtime. However, it expensive to manufacture and install due to the cost of superconducting materials and cooling systems.

Ajinkya J. Sonawane *et al* (2023) [13] have presented a synchronverter based PV system as STATCOM for enhanced grid stability. It has decades of field-proven effectiveness in improving small-signal stability in large interconnected power grids. Accurate models of the generator and the power system are necessary to design and test is resource-intensive.

Abdallah Fouad *et al* (2024) [14] have developed a dandelion optimizer based the hybrid fractional-order PI and PI controlled STATCOM for enhancing grid-connected DFIG systems. It responds quickly to rotor speed or power angle deviations, contributing to system resilience. Improper tuning of PSS parameters is worsening system stability or cause poor performance during disturbances.

Muhammad Sarwar *et al* (2023) [15] have proposed a grid-connected wind power generation system using Power System Stabilizer (PSS) and Resistive Superconductor Fault Current Limiter (R-SFCL) for stability enhancement. It reacts almost instantaneously to a fault, reducing the risk of damage to equipment. Further, it helps manage high fault currents in interconnected grids, especially in modern systems with distributed energy resources. However, it requires continuous cooling to maintain superconductivity, adding complexity and maintenance needs.

3. Proposed Work Explanation

In Figure 1, the proposed block diagram is presented.

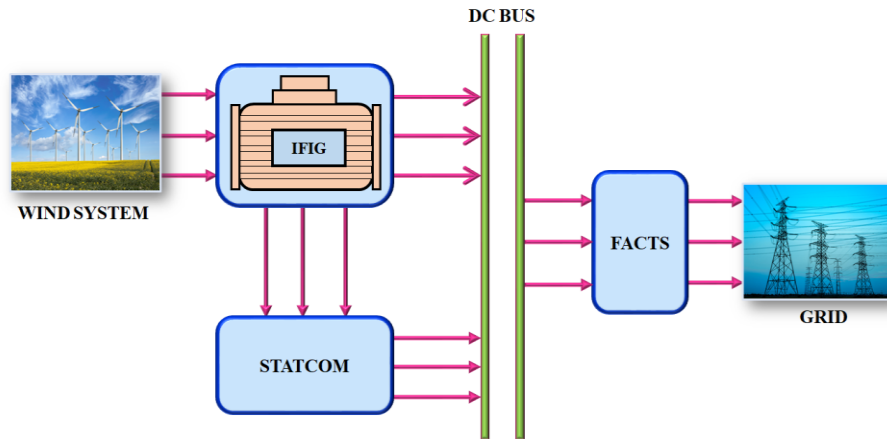


Figure 1: Block Diagram for Proposed System

The wind energy is allowed to an IFIG system. In IFIG, the kinetic energy generated from the wind energy is converted to electrical energy. The STATCOM is integrated between the induction IFIG of the wind turbine and the grid, with an option for energy storage. The IFIG output is fed into a STATCOM, which is used to manage the voltage and power quality. Then the STATCOM and IFIG are connected to the DC bus and FACTS device. In the final stage, a FACTS helps in reducing harmonics indirectly by ensuring that the control signals, which contribute to the better-improved system stability, are fed to the grid system.

3.1 Wind System

One type of renewable energy system that uses wind energy to create electricity is a wind farm

system. It usually comprises of several wind turbines positioned strategically in a region with steady wind. Each turbine captures the kinetic energy of the wind using large blades, which spin a rotor connected to a generator. Wind energy systems are environmentally friendly, producing no greenhouse gas emissions during operation, and it provides fossil fuels with a viable substitute.

3.2 Induction Fed Induction Generator

An IFIG is a type of electrical generator that uses two induction machines in tandem, where one induction machine feeds the rotor of another induction machine that operates as a generator. This configuration is primarily used in advanced wind energy systems to improve efficiency and control over the power output.

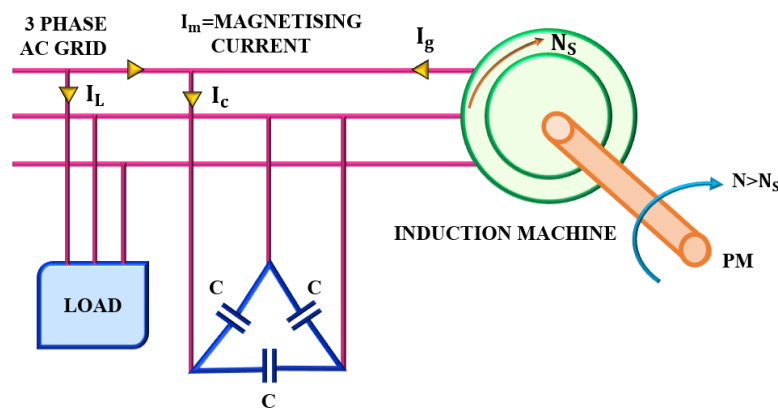


Figure 2: The IFIG Model

Figure. 2 displays the structure of the IFIG model. It acts as a motor and is used to control the speed and slip of the second machine, which is the main

generator. The main induction generator is connected to the wind turbine and generates power from the rotor movement caused by wind. The

feeder motor controls the rotor current of the generator, enabling variable speed operation while still delivering power at a constant frequency to the grid. It allows more precise control of active and reactive power, making it suitable for large-scale or grid-connected wind farms.

3.3 Flexible AC Transmission System

It refers to a collection of technologies that enhance the controllability, stability, and power transfer capability of an AC power network. These systems use high-speed, high-power electronic devices to manage voltage, impedance, and phase angle in real time, allowing for more efficient and reliable operation of the electrical grid.

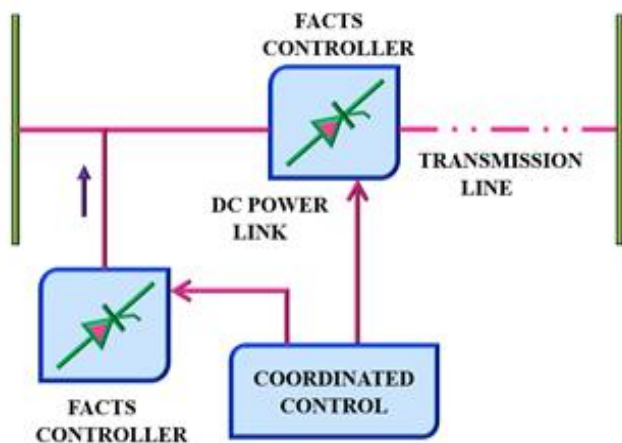


Figure 3: The structure of FACTS

Figure 3 depicted the FACTS structure. It helps control the direction and amount of power flow through transmission lines, improving overall efficiency. By optimizing the use of existing lines, it allows more power to be transmitted without building new infrastructure.

3.4 Statcom

A STATCOM is a shunt-connected device used in power systems to regulate voltage levels and enhance stability by providing fast and flexible reactive power compensation. It helps maintain a stable voltage level at the grid connection point, especially when wind speed fluctuates and causes voltage drops or spikes. It works using a Voltage Source Converter (VSC) that generates a controllable AC voltage from a DC source.

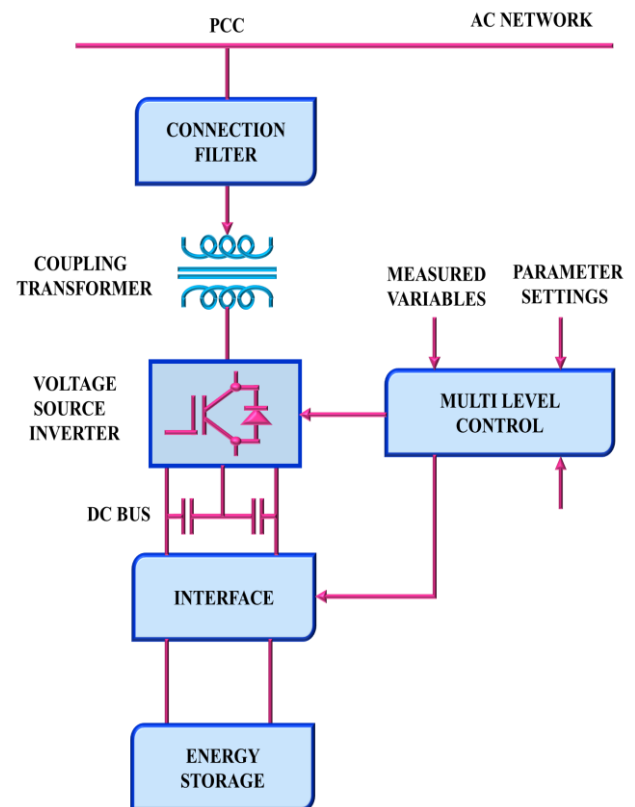


Figure 4: The Architecture of STATCOM

As shown in Figure 4, the architecture of STATCOM. When the system voltage drops, the STATCOM injects reactive power into the grid to boost voltage, when the voltage is too high, it absorbs reactive power to bring it down. Because it has a fast response time and can operate effectively even during low-voltage conditions, STATCOM is widely used in modern electrical grids for dynamic voltage support, especially in areas with fluctuating loads or where renewable energy sources like wind or solar are integrated. Compared to older technologies like Static Var Compensator (SVC), and it offers quicker control, better performance, and a smaller footprint. Further, it reduces voltage flickers, harmonics, and other disturbances, ensuring clean and stable power is delivered from the wind farm to the grid.

4. Results and Discussion

In this work, renewable energy adaptive voltage control using the STATCOM technique is proposed in a wind farm integrated grid system and implemented using MATLAB software, and the obtained outcomes are provided.

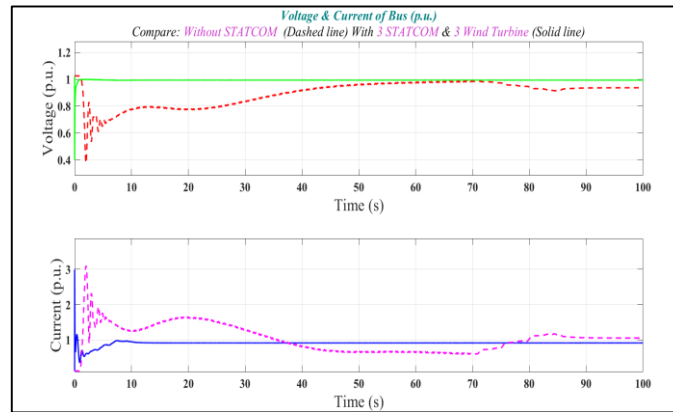


Figure 5: Voltage and Current Waveforms of Bus

Figure 5 displays the voltage and current waveforms of the bus. In the voltage waveform, the voltage is dropped between the without STATCOM and with STATCOM. In this case, with STATCOM and a turbine voltage of 1 pu, and

without STATCOM, a voltage of below 1 pu is attained. Similarly, the current waveforms, with STATCOM and turbine current of 1 pu and without STATCOM of above 1 pu, are achieved.

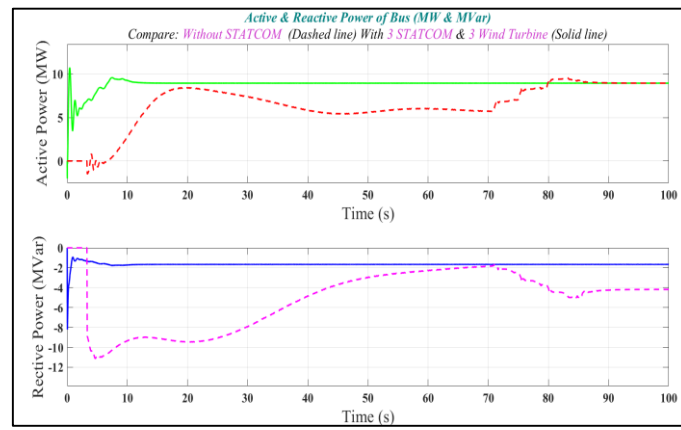


Figure 6: Active and Reactive Power Waveforms of Bus

Figure 6 demonstrates the active and reactive power waveforms of the bus. The active power waveform illustrates that with STATCOM, power is obtained at 9 MW, and without STATCOM, power is consistently obtained at 8 MW. In

reactive power waveforms, with STATCOM power of -2 (MVar) and without STATCOM power of -2 (MVar) are obtained with some oscillations.

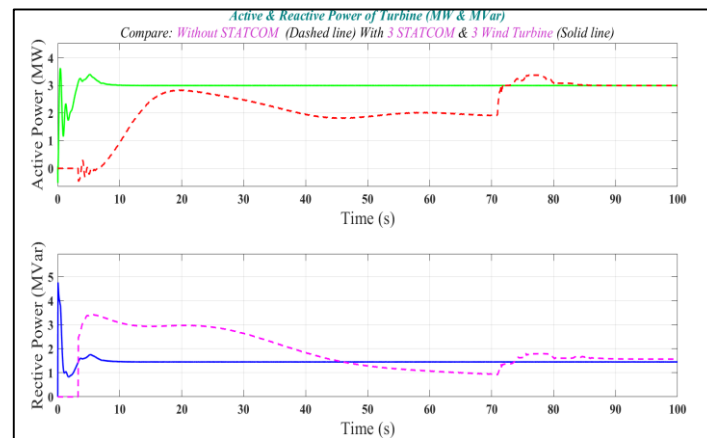


Figure 7: Active and Reactive Power Waveforms of Turbine

The turbine's active and reactive power waveforms are shown in Figure 6. The active power waveform shows that power is reliably produced at 3 MW without STATCOM and at 3.5

MW with STATCOM. Waveforms of reactive power generated with and without a STATCOM power of 2.5 (MVar) indicate some oscillations.

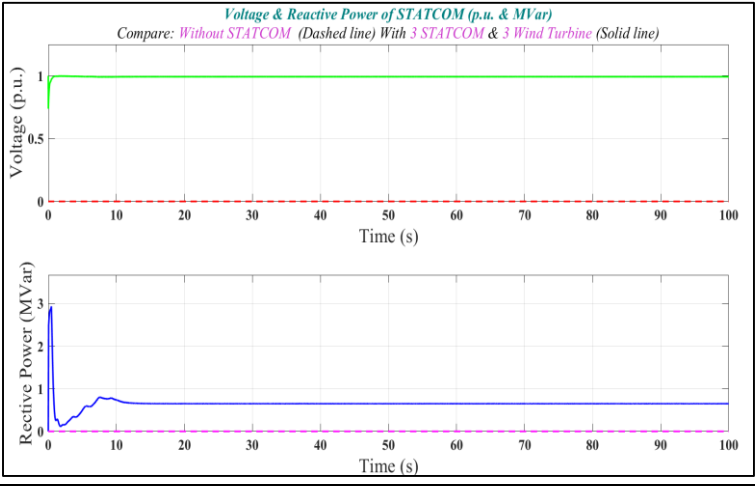


Figure 8: Voltage and Reactive Power Waveforms of STATCOM.

The voltage and reactive power waveforms of STATCOM are clearly seen in Figure 8. Between the voltage waveforms without STATCOM, the voltage is lowered. In this instance, a with STATCOM voltage of 1 pu is reached. Likewise, reactive power waveforms are obtained with a STATCOM of 0.8 pu and without a turbine current and STATCOM of 0 (MVar).

Table 1: Performance of Comparative Analysis

Classifications	Efficiency%
R-SFCL -STATCOM [15]	87
E - STATCOM [11]	91
5 Level E Type STATCOM [12]	93
Proposed STATCOM Model	97

Table 1 shows an analysis of the comparatives of the different STATCOM types and the proposed work. The proposed STATCOM model produces better results in terms of classification than different techniques.

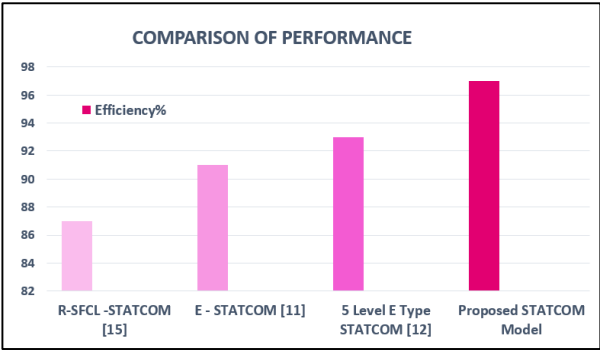


Figure 9: Comparison of the Model's Performance

Figure 10 illustrates a comparison of different classifications of RMSE and MAE values. In the graph, the proposed classification is RMSE of 6.11% and MAE of 2.80%. Previous classifications of DNN provide a highest RMSE value of 18.93% and an MSE value of 15.64%, respectively. The second classification RMSE value, CNN-LSTM of 13.76%, and MAE value of 10.58% are attained. The third classification of CNN-LSTM, RMSE value of 9.20%, and MAE value of 7.83 % are achieved.

5. Conclusion

This paper presents renewable energy adaptive voltage control using STATCOM for grid stability in a wind farm-integrated grid system. In this work, STATCOM is used to offer an effective

solution for adaptive voltage control in wind farm integrated grid systems. With its rapid response time and dynamic reactive power compensation capabilities, STATCOM ensures voltage stability, improves power quality, and supports grid reliability even under fluctuating wind conditions. By enabling better compliance with grid codes and enhancing the performance of wind farms, STATCOM plays a crucial role in the efficient and reliable integration of renewable energy into the power grid, paving the way toward a more resilient and low-carbon energy infrastructure.

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