Power Quality Improvement of a Grid Connected Wind Energy Conversion System Using PID Controlled STATCOM

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Keywords: Wind Energy Conversion System (WECS), Power Quality, STATCOM, Voltage Stability, Harmonics, Reactive Power.

Abstract: This research focuses on using a PID-controlled static synchronous compensator (STATCOM) to improve the power quality of grid-connected wind energy conversion systems (WECS). Because wind energy is intermittent, integrating wind energy systems into the grid frequently results in power quality problems such reactive power imbalance, voltage fluctuations, and harmonic distortions. With the help of a Proportional-Integral-Derivative (PID) controller, the STATCOM successfully reduces these power quality problems. The effectiveness of the suggested strategy in preserving grid stability and guaranteeing adherence to grid codes is confirmed by simulation results.

1 INTRODUCTION

Power quality issues have grown significantly as a result of the electrical grid's increasing incorporation of renewable energy sources like wind. Because wind is erratic, wind energy conversion systems (WECS) are by their very nature variable. The overall quality of the grid's electricity can be adversely affected by this unpredictability, which can result in reactive power imbalance, harmonic distortions, and voltage instability. One popular method for enhancing power quality in renewable energy systems is the incorporation of a Static Synchronous Compensator (STATCOM). In order to lessen power quality problems, STATCOM offers voltage management and reactive power support. However, the control approach used determines how effective it is.

In order to improve dynamic responsiveness and preserve power quality in the face of fluctuating wind conditions, this study suggests using a Proportional-Integral-Derivative (PID) controller for STATCOM control. The MATLAB/Simulink simulations are used to assess the suggested system.

2 WIND ENERGY CONVERSION SYSTEM

This section provides an overview of the components and operation of a typical wind energy conversion system (WECS). It includes:

- **Wind Turbine**: Converts wind energy into mechanical energy.
- **Generator**: Typically, an induction or synchronous generator, which converts mechanical energy into electrical energy.
- **Power Electronics Interface**: Converts the generated electricity into a form suitable for grid connection (DC to AC conversion).
- **Grid Connection**: Details the interface with the grid, focusing on the power quality challenges such as harmonics, voltage sags, and reactive power management.

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3 QUALITY ISSUES IN WIND POWER SYSTEMS

Because wind is erratic and intermittent, wind energy systems present serious power quality issues when they are incorporated into the grid. The main problems are harmonic distortions brought on by power electronic converters used in wind turbines and voltage changes caused by fluctuating wind speeds. Reactive power imbalance also happens, which causes voltage instability and power system inefficiencies. In order to preserve grid dependability, compensating devices such as STATCOM for voltage control, harmonic filtering, and reactive power compensation are required because these power quality issues can have a detrimental effect on the grid's stability and performance. This section highlights the primary power quality issues associated with grid-connected WECS:

(i) Voltage Fluctuations: Caused by variable wind speeds.

(ii) Harmonic Distortions: Introduced by power electronic converters.

(iii) Reactive Power Imbalance: Results in voltage instability and reduced grid efficiency.

The reactive power QQQ provided or absorbed by the STATCOM is given by:

$$Q = V_{bus} \cdot (V_{ref} - V_{measured})/X \tag{1}$$

A discussion on the impact of these issues on grid stability and the importance of maintaining power quality standards for grid compliance is included.

4 STATCOM FOR POWER QUALITY IMPROVEMENT

A Static Synchronous Compensator (STATCOM) is an advanced power electronics device used to enhance power quality in grid-connected systems. It provides reactive power compensation by either absorbing or injecting reactive power, stabilizing grid voltage levels under fluctuating load conditions. In wind energy systems, STATCOM mitigates issues like voltage fluctuations, harmonic distortions, and reactive power imbalance caused by variable wind speeds. With its fast response, STATCOM improves voltage regulation, reduces total harmonic distortion (THD), and enhances overall grid stability. When controlled using strategies like PID control, STATCOM becomes highly effective in maintaining consistent power quality in renewable energy integration.

The Total Harmonic Distortion (THD) is calculated as:

$$THD = \frac{\sqrt{V_{2+}^2 V_{3+}^2 \dots + V_n^2}}{V_1} \times 100\% \tag{2}$$

Principle of Operation: STATCOM is a shunt device that injects or absorbs reactive power to stabilize voltage levels. The benefits of STATCOM: Fast response, voltage stabilization, harmonic filtering, and reactive power compensation.

This section explains how STATCOM can improve the overall stability of the wind energy system when connected to the grid.

5 DESIGNS OF STATCOM

The PID controller design for STATCOM enhances its ability to stabilize grid voltage and improve power quality by precisely regulating reactive power output. The Proportional (P) component corrects the voltage error based on the magnitude, the Integral (I) component addresses accumulated past errors to eliminate steady-state offset, and the Derivative (D) component predicts future errors to improve system stability. Proper tuning of these gains ensures fast response and minimal overshoot. In wind energy systems, PID-controlled STATCOM dynamically adjusts reactive power compensation, mitigating voltage fluctuations and harmonics, resulting in enhanced grid stability and improved power quality under varying wind conditions.

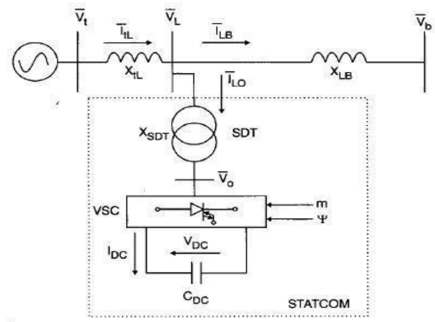

Figure 1: STATCOM Diagram.

5.1 PID Controller Design for STATCOM

Output of PID controller, u(t) for regulating reactive power expressed

$$u(t) = K_{p^e}(t) + K_i \int \quad e(t)dt + K_d \frac{de(t)}{dt} \qquad (3)$$

The design of the PID controller for the STATCOM is discussed in this section:

5.2 PID Control Mechanism

Overview of how the PID controller adjusts the reactive power output of the STATCOM to maintain the desired voltage level and power quality.

5.3 Tuning of PID Parameters

Explanation of the tuning process for the proportional (P), integral (I), and derivative (D) gains to optimize system performance.

5.4 Methods for Tuning PID Controllers:

There are several methods to tune the PID controller, ranging from manual trial-and-error to more systematic approaches.

5.4.1 Manual Tuning (Trial and Error)

This method is simple but requires a good understanding of the system and a lot of experimentation.

(i) Start with $K_i = 0$ and $K_d = 0$

Increase K_p until the system responds quickly without excessive oscillation. When the system oscillates or takes too long to reach the setpoint, reduce K_p

Add Integral Action (K_i):

Once the proportional gain is set, add a small amount of to K_i eliminate steady-state error. Increasing the value of K_i improves steady-state accuracy but may induce oscillations if it's too large.

Adjust Derivative Action (Adjust K_d):

Finally, adjust K_d to reduce oscillations or overshoot. A small amount of K_d can smooth the response. The method works for relatively simple systems but may not give optimal performance in all cases.

5.4.2 Ziegler-Nichols Method

The Ziegler-Nichols method is a popular heuristic approach based on the system's response to a step input.

$$\text{Set } K_i = 0 \text{ and } K_d = 0 \qquad (4)$$

- Increase K_p until the system oscillates consistently with a constant amplitude (this is called the ultimate gain, K_u
- Measure the period of oscillation (denoted K_u)

1. Use the following empirical formulas to calculate the PID parameters:
   - For a P controller:

$$K_p = 0.5 \,.\, K_u \qquad (5)$$

For a PI controller:

$$K_i = 0.45 \,.\, K_u \,, K_i = 1.2 \,.\, \frac{K_p}{P_u} \qquad (6)$$

- For a PID controller:

$$K_i = 0.6 \,.\, K_u \,, K_i = 2 \,.\, \frac{K_p}{P_u} \,.\, K_d = K_p \,.\, \frac{P_u}{8} \qquad (7)$$

Control Objectives: Ensure voltage stability, minimize harmonic distortions, and balance reactive power under varying wind conditions.

6 SYSTEM REQUIREMENTS

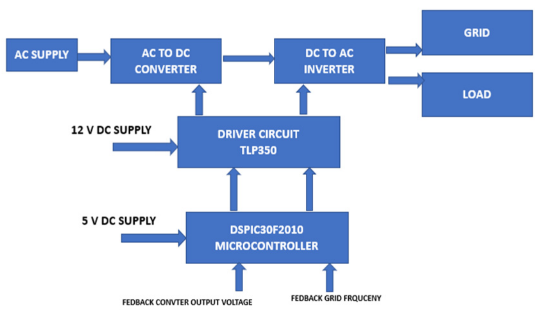

Figure 2: Block Diagram.

The block diagram illustrates the interconnected components essential for enhancing power quality in renewable energy integration. At the core, the Wind Energy Conversion System (WECS) consists of a wind turbine that converts kinetic energy from the wind into mechanical energy, which is then transformed into electrical energy by a generator, typically a Doubly-Fed Induction Generator (DFIG) or Permanent Magnet Synchronous Generator (PMSG). This output is processed through power electronics converters to stabilize the voltage and frequency for grid compatibility. The electrical output is connected to the utility grid, where it is continuously monitored for power quality metrics, such as voltage levels and Total Harmonic Distortion (THD). The data from the grid is fed into a PID controller, which adjusts the operation of a Static Synchronous Compensator (STATCOM) to manage reactive power. The STATCOM can either inject or absorb reactive power as needed, ensuring voltage stability and improving the overall power factor. Through this feedback loop, the PID controller optimizes the STATCOM's response to fluctuations in wind energy generation and grid demand, leading to improved power quality and a more reliable energy supply for the grid.

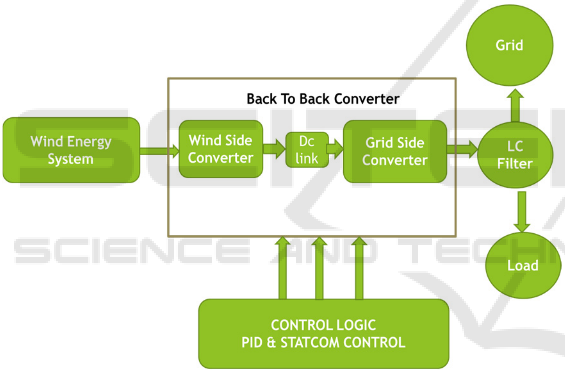

Figure 3: Simulation setup.

The simulation is typically conducted using MATLAB/Simulink, which provides a robust platform for modeling dynamic systems in power electronics and renewable energy applications. The Wind Energy Conversion System (WECS) is modeled to include a wind turbine that simulates the relationship between wind speed and power output, along with a generator (such as a Doubly-Fed Induction Generator or Permanent Magnet Synchronous Generator) that converts mechanical energy into electrical energy. Power electronic converters are incorporated to manage the conversion of the variable output into a stable form suitable for grid connection.

The grid model reflects the reference voltage and load dynamics, while the Static Synchronous Compensator (STATCOM) is modeled to inject or absorb reactive power as needed. The PID controller is integrated to regulate the STATCOM's output based on grid voltage requirements, with tuning parameters optimized during the simulation for enhanced performance. Various scenarios are simulated, such as changing wind speeds and sudden load fluctuations, to evaluate the system's response and resilience to disturbances. Key power quality indicators, including voltage levels and Total Harmonic Distortion (THD), are monitored and analyzed, leading to visualizations that illustrate the effectiveness of the control strategies. Overall, the simulation serves as a vital tool for understanding the interactions within the system and preparing for successful real-world deployment.

7 SIMULATION MODEL DIAGRAM

The simulation model is shown in Fig. 4.

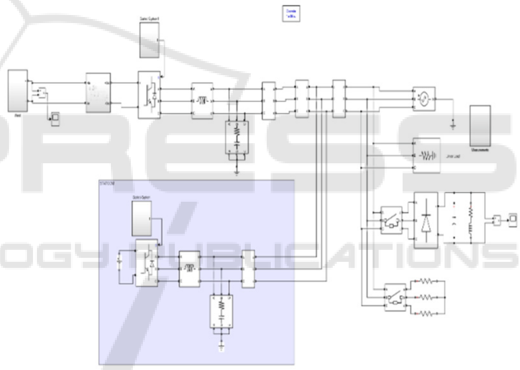

Figure 4: Simulation model.

7.1 Wind System

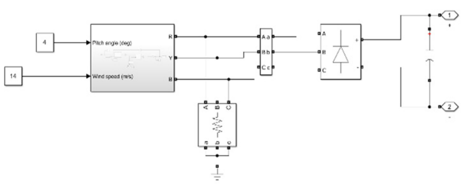

Figure 5: Simulation subsystem model.

7.2 Simulation and Results

The simulation results of the PID-controlled STATCOM in a grid-connected wind energy conversion system demonstrate significant improvements in power quality. Voltage stability is achieved as the STATCOM effectively compensates for fluctuations caused by variable wind speeds, maintaining voltage within desired limits. The **Total Harmonic Distortion (THD)** is reduced, ensuring compliance with grid standards. Reactive power is balanced, minimizing voltage dips and enhancing system efficiency. Comparative graphs show the system’s performance with and without STATCOM, where the PID-controlled STATCOM leads to faster dynamic response, minimal oscillations, and better overall power quality, validating the effectiveness of the proposed control strategy.

7.3 Voltage Waveforms

Stability: The simulation typically shows improved voltage stability at the grid connection point. Voltage waveforms exhibit reduced fluctuations compared to scenarios without the STATCOM, demonstrating the compensator’s effectiveness in maintaining voltage levels. Response to Changes: During sudden changes in load or wind speed, the voltage waveforms quickly stabilize due to the reactive power support provided by the STATCOM, showcasing the system's dynamic response capabilities.

7.4 Reactive Power Profiles:

Reactive Power Compensation: The STATCOM is observed to effectively inject or absorb reactive power as needed, keeping the grid voltage within acceptable limits. The reactive power profile indicates the compensator's output in response to varying load conditions, highlighting its role in balancing reactive power demand.

Control Performance: The PID controller's ability to adjust STATCOM output in real-time is evidenced by smooth transitions in reactive power, leading to minimal overshoot and oscillations. For reactive power regulation in a STATCOM, a PID controller is a common and efficient solution. PID controllers help keep the power grid's voltage stable by modifying reactive power injection or absorption in response to voltage deviation. The stability and best performance of the system depend on proper simulation and adjustment.

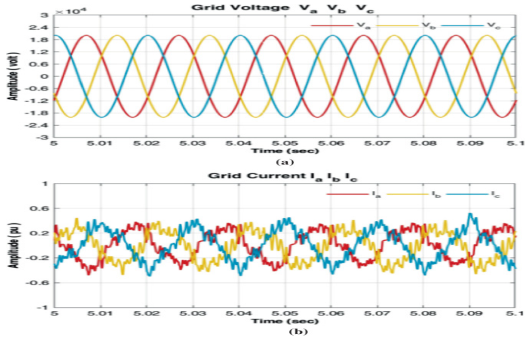

Figure 6: Simulation output.

7.5 Power Factor Improvement:

Before and After Comparison: The simulation results typically reveal a significant improvement in the power factor of the system. Without the STATCOM, the power factor may fall below acceptable levels, indicating poor utilization of electrical power. With the STATCOM operational, the power factor approaches unity, suggesting enhanced efficiency in energy consumption. Harmonic Distortion Reduction: The implementation of the STATCOM also contributes to a reduction in Total Harmonic Distortion (THD) in the current waveforms, further improving the overall power quality.

7.6 Harmonic Analysis:

THD Levels: The simulation may show a reduction in THD levels of the voltage and current waveforms after incorporating the STATCOM. This reduction indicates improved harmonic compensation, leading to cleaner power quality supplied to the grid.

Compliance with Standards: Results often demonstrate that THD levels meet regulatory standards, ensuring that the system can operate reliably within the grid infrastructure.

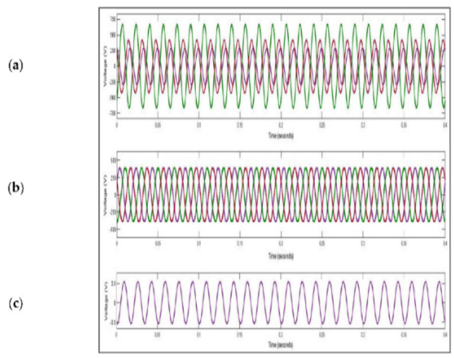

Figure 7: Simulation output waveform.

7.7 Transient Response

Dynamic Behavior: The simulation results provide insight into the transient response of the system during disturbances, such as sudden wind speed variations or load changes. The STATCOM's quick response time, facilitated by the PID controller, helps mitigate voltage dips and surges effectively.

Settling Time: The settling time for voltage and reactive power to stabilize after disturbances is significantly reduced, showcasing the PID controller's effectiveness in optimizing system performance.

Simulation Setup: Description of the wind energy conversion system model, the STATCOM with PID controller, and the grid interface.

Performance Evaluation: The key metrics for evaluating the system's performance, such as voltage stability, total harmonic distortion (THD), and reactive power compensation. For voltage, the usual Total Harmonic Distortion (THD) level is between 1% and less than 10%. If there are numerous harmonics present, the THD value for current could be greater than 100%. Thus, 5% for THD and 3% for any single harmonic are the voltage harmonic limitations. It is significant to remember that the values and recommendations presented in this standard are entirely optional. However, maintaining low THD values on a system will also guarantee that the equipment operates correctly and lasts longer.

Results: Graphical representation of the simulation results, showing improvements in voltage regulation, reduction in harmonics, and enhanced reactive power control.

Table 1: Output Parameters.

Requirement	Voltage	Current
Inverter 1	311	16
Inverter 2	311	16
Grid	311	36

8 DISCUSSIONS

8.1 Impact of PID Controlled STATCOM

Discussion on the observed improvements in power quality, focusing on reduced voltage fluctuations, better reactive power management, and lower harmonic distortion.

8.2 Comparison with Other Controllers

Brief comparison with other control strategies (e.g., PI control, Fuzzy Logic control) and how the PID controller provides a better dynamic response and tuning simplicity.

9 CONCLUSIONS

This paper presents an effective solution for power quality improvement in grid-connected wind energy systems using a PID-controlled STATCOM. The simulation results demonstrate that the proposed system enhances voltage stability, reduces harmonics, and improves overall grid compliance under varying wind conditions. The PID controller offers a simple yet efficient way to control the STATCOM, making it suitable for integration into renewable energy systems.

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