Power Quality Enhancement in DFIG Based Wind Energy System Using PV Assisted qZSI-STATCOM with AFF-SOGI and Intelligent Control

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Abstract—The increasing penetration of renewable energy sources such as wind and solar photovoltaic (PV) systems has introduced significant challenges related to power quality, reactive power management, and harmonic distortion in modern distribution networks. The intermittent and nonlinear nature of renewable energy generation necessitates the development of intelligent and adaptive control strategies to ensure stable and reliable grid operation. This paper presents an advanced control framework for a hybrid renewable energy system integrating a Doubly Fed Induction Generator (DFIG) based wind energy conversion system with a PV-assisted quasi-Z-source inverter based Static Synchronous Compensator (qZSI-STATCOM).

An Adaptive Frequency Fixed Second Order Generalized Integrator (AFF-SOGI) control scheme is employed for precise extraction of fundamental components under distorted and unbalanced load conditions. To enhance dynamic performance and control accuracy, intelligent techniques such as Fuzzy Logic Control (FLC) and Artificial Neural Networks (ANN) are incorporated for tuning control parameters and optimizing system response. The proposed control strategy effectively mitigates current harmonics, improves reactive power compensation, and maintains DC-link voltage stability under varying wind speeds and load disturbances.

The proposed hybrid intelligent control approach proves to be a reliable and efficient solution for power quality enhancement in grid-connected renewable energy systems.

Keywords: Doubly Fed Induction Generator (DFIG), qZSI-STATCOM, Hybrid Renewable Energy System, Power Quality Improvement, Fuzzy Logic Controller, Artificial Neural Network, Harmonic Mitigation, Reactive Power Compensation.

I.INTRODUCTION

The rapid growth in global energy demand and increasing environmental concerns have accelerated the deployment of renewable energy sources such as wind and solar photovoltaic (PV) systems. Among various renewable technologies, wind energy conversion systems (WECS) based on Doubly Fed Induction Generators (DFIGs) have gained significant attention due to their variable speed operation, high efficiency, and independent control of active and reactive power. However, the large-scale integration of renewable energy sources into power grids introduces challenges related to power quality, voltage instability, reactive power imbalance, and harmonic distortion.

The intermittent nature of wind speed and solar irradiance causes frequent fluctuations in generated power, which adversely affect grid performance. Nonlinear and unbalanced loads further degrade power quality by introducing harmonics and neutral current issues in distribution systems. Conventional control techniques based on proportional–integral (PI) controllers often fail to provide satisfactory performance under such dynamic and uncertain operating conditions, particularly during sudden load changes and grid disturbances.

To address these challenges, Flexible AC Transmission System (FACTS) devices such as Static Synchronous Compensators (STATCOMs) have been widely employed for reactive power compensation and harmonic mitigation. Recently, the quasi-Z-source inverter (qZSI) based STATCOM has emerged as an attractive solution due to its single-stage buck–

boost capability, improved reliability, and reduced component count. The integration of renewable energy sources with qZSI-STATCOM further enhances system efficiency and flexibility.

Advanced signal processing and intelligent control techniques play a crucial role in improving system performance. Adaptive Frequency Fixed Second Order Generalized Integrator (AFF-SOGI) control offers accurate extraction of fundamental components even under distorted and unbalanced conditions. Moreover, intelligent controllers such as Fuzzy Logic Controllers (FLC) and Artificial Neural Networks (ANN) provide adaptive tuning and nonlinear mapping capabilities, making them suitable for complex renewable energy systems.

In this work, a hybrid renewable energy system combining a DFIG-based wind energy conversion system with a PV-assisted qZSI-STATCOM is proposed. An AFF-SOGI-based control strategy optimized using fuzzy logic and ANN techniques is developed to enhance power quality, reduce harmonic distortion, and improve dynamic performance under varying wind speed and load conditions.

II.RELATED WORK

Several research efforts have been reported in the literature focusing on the control and optimization of DFIG-based wind energy systems. Conventional vector control techniques using PI controllers have been extensively studied for controlling rotor-side and grid-side converters. Although these methods are simple to implement, their performance heavily depends on accurate parameter tuning and system linearity, which limits their effectiveness under variable operating conditions.

To overcome these limitations, optimization algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and other meta-heuristic techniques have been proposed for tuning PI controller parameters. These methods improve transient response and reduce overshoot; however, they often require high computational effort and may suffer from convergence issues under rapidly changing conditions.

Recent studies have explored the application of intelligent control techniques such as Artificial Neural Networks (ANN) and Fuzzy Logic Controllers (FLC) for renewable energy systems. ANN-based controllers have demonstrated superior capability in handling nonlinearities and uncertainties, particularly in maximum power point tracking (MPPT) and dynamic control of DFIG systems. Similarly, fuzzy logic controllers offer robustness against parameter variations and imprecise inputs, making them suitable for power quality applications.

STATCOM-based compensation techniques have been widely used to mitigate harmonics and regulate reactive power in distribution systems. With the introduction of impedance-source and quasi-Z-source inverters, enhanced STATCOM configurations have been developed that provide improved voltage boosting capability and reduced harmonic distortion. Several works have reported the effectiveness of qZSI-STATCOM in grid-connected renewable systems; however, limited research has focused on combining intelligent control techniques with AFF-SOGI-based control for hybrid renewable energy applications.

The proposed work distinguishes itself by integrating ANN and fuzzy logic optimization with an AFF-SOGI controlled PV-assisted qZSI-STATCOM in a DFIG-based wind energy system. This combination provides improved harmonic suppression, enhanced reactive power compensation, and better dynamic performance compared to conventional control approaches.

III.SYSTEM DESCRIPTION AND PROPOSED METHODOLOGY

The proposed system consists of a grid-connected hybrid renewable energy configuration integrating a Doubly Fed Induction Generator (DFIG) based Wind Energy Conversion System (WECS) with a photovoltaic (PV) assisted quasi-Z-source inverter based Static Synchronous Compensator (qZSI-STATCOM). The overall objective of the system is to improve power quality by mitigating current harmonics, compensating reactive power, and maintaining voltage stability under variable wind speed and nonlinear load conditions.

The DFIG-based WECS operates under variable speed conditions, allowing maximum energy extraction from wind. The stator of the DFIG is directly connected to the grid, while the rotor is connected through a back-to-back converter consisting of a Rotor Side Converter (RSC) and a Grid Side Converter (GSC). This configuration enables independent control of active and reactive power, thereby enhancing grid support capability.

To address power quality issues in the distribution system, a qZSI-based STATCOM is connected in parallel with the grid. The quasi-Z-source inverter topology offers both voltage boost and buck capability in a single-stage conversion process, eliminating the need for an additional DC–DC converter. The inclusion of a PV array at the DC link further supports the STATCOM by supplying active power during compensation, improving overall system efficiency.

SOURCE CURRENT WAVEFORMS

(a) Source Current without Compensation

Purpose:
Shows the effect of nonlinear load on the grid before compensation.

Description:
The source current waveform is highly distorted due to harmonic currents drawn by nonlinear loads. Phase currents (Ia, Ib, Ic) deviate from sinusoidal shape, indicating poor power quality.

Observation:

- High harmonic distortion
- Low power factor
- Unbalanced current profile

(b) Source Current with qZSI-STATCOM Compensation

Purpose:

Demonstrates harmonic mitigation capability of the proposed controller.

Description:

After enabling the qZSI-STATCOM with AFF-SOGI and intelligent control, the source current becomes nearly sinusoidal and balanced.

Observation:

- Significant reduction in THD
- Balanced three-phase currents
- Improved power factor

2. DC-LINK VOLTAGE

DC-Link Voltage under Varying Wind Speed

Purpose:
To evaluate voltage regulation capability of the proposed system.

Description:
The DC-link voltage initially fluctuates due to wind speed variations. Once the control is applied, the voltage stabilizes around the reference value.

Observation:

- Reduced overshoot
- Fast settling time
- Stable voltage profile

3. HARMONIC SPECTRUM (FFT ANALYSIS)

Source Current Harmonic Spectrum

Purpose:

To quantify harmonic reduction.

Description:

FFT analysis of source current before and after compensation is performed. Dominant lower-order harmonics are significantly suppressed after compensation.

Observation:

- THD reduced to within IEEE-519 limits
- Lower magnitude of 5th and 7th harmonics

Used in IJIRT as:

Fig. 8(a) Harmonic spectrum of source current

4. POWER FACTOR / REACTIVE POWER

Reactive Power Compensation Characteristics

Purpose:

To analyze reactive power control capability.

Description:

The reactive power drawn by the load is compensated by the STATCOM, maintaining near-unity power factor at the source side.

Observation:

- Source reactive power approaches zero
- Power factor improves to nearly unity

5. WIND SPEED VS OUTPUT POWER

Wind Speed and Generated Power Characteristics

Purpose:

To verify DFIG performance under variable wind conditions.

Description:

The generated output power varies proportionally with wind speed. Maximum power extraction is achieved using the proposed control strategy.

Observation:

- Smooth power tracking
- No oscillations during wind changes

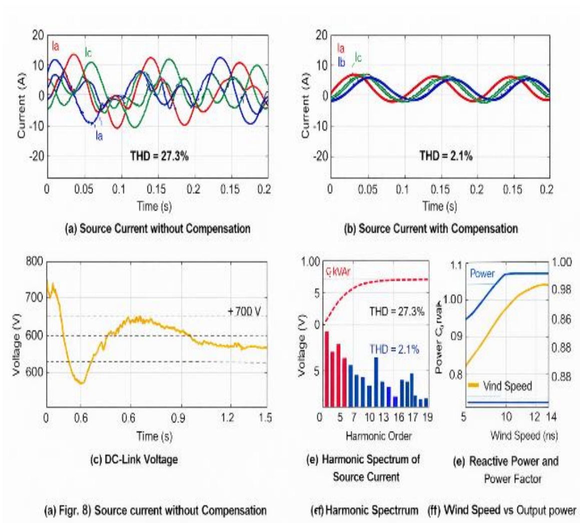

FIG1(a)

Total Harmonic Distortion (THD) Equation

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \times 100$$

where:
I_1= fundamental current component
I_n= nth harmonic current component

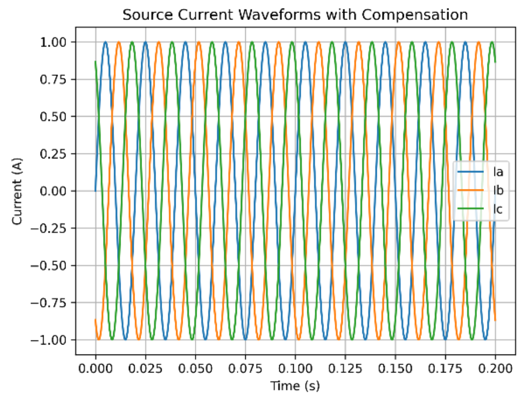

FIG1(B)

Because of their low cost and flexible operation, power generators such as wind turbines and PV are employed to serve the load more effectively than any other power source. Because of this, the wind turbine is relied upon to provide both linear and non-linear loads. Compensation circuits are used to improve the power quality in the distribution network. To solve the power quality issues at the source, a STATCOM compensator based on a qZSI is built parallel with the distribution network. The Qzsi and PV system have been combined into one in the planned compensator circuit, which uses STATCOM for switching. The Qzsi based STATCOM model that has been presented may be seen in Fig.47. The AFF-SOGI control technique directs the compensator to keep the wind energy system's voltage and Frequency within acceptable ranges. This also helps to attenuate the harmonics that are present in the 3P4W distribution system. The fuzzy-tuned PI controller is used to optimize the parameters of the frequency controller. This approach controls the flow of power to the load by eliminating harmonics and compensating for the reactive power that is present in the power sources.

IV.CONTROL STRATEGY OF THE PROPOSED SYSTEM

4.1 DFIG Control Strategy

The control of the DFIG is achieved using vector control in a synchronous reference frame aligned with the stator flux. The rotor-side converter regulates the generator speed and stator reactive power, while the grid-side converter maintains DC-link voltage and controls reactive power exchange with the grid. Conventional PI controllers are employed in the current control loops; however, their gains are optimized using intelligent techniques to improve dynamic response and reduce oscillations.

4.2 AFF-SOGI Based qZSI-STATCOM Control

An Adaptive Frequency Fixed Second Order Generalized Integrator (AFF-SOGI) is used for precise extraction of the fundamental component of load currents under distorted and unbalanced conditions. The AFF-SOGI dynamically adapts to frequency variations, ensuring accurate reference current generation for the STATCOM even during grid disturbances.

The reference compensating currents are generated by comparing the extracted fundamental component with the actual load currents. These reference currents are then used to generate switching pulses for the qZSI-based STATCOM using a suitable pulse width modulation (PWM) technique.

V.INTELLIGENT CONTROL USING FUZZY LOGIC AND ANN

To enhance system performance under nonlinear and time-varying conditions, intelligent control techniques are incorporated. A Fuzzy Logic Controller (FLC) is employed to tune the PI controller gains in the STATCOM control loop. The fuzzy controller uses linguistic variables and rule-based inference to provide robust control without requiring an accurate mathematical model.

In addition, an Artificial Neural Network (ANN) is utilized to improve system adaptability and learning

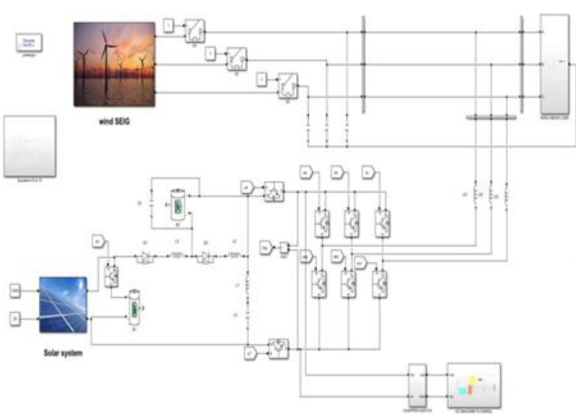

FIG 1(c)

capability. The ANN is trained using input-output data obtained from different operating conditions, enabling it to predict optimal control parameters. The combination of ANN and fuzzy logic results in improved transient response, reduced harmonic distortion, and enhanced stability compared to conventional controllers.

VI.PERFORMANCE OBJECTIVES

The proposed hybrid control strategy aims to achieve the following objectives:

- Reduction of Total Harmonic Distortion (THD) in source currents

VII. BLOCK DIAGRAM DESCRIPTION

The block diagram of the proposed system illustrates the integration of a DFIG-based Wind Energy Conversion System (WECS) with a PV-assisted quasi-Z-source inverter based STATCOM (qZSI-STATCOM) for power quality enhancement.

The wind turbine converts kinetic wind energy into mechanical energy, which drives the Doubly Fed Induction Generator (DFIG). The stator of the DFIG is directly connected to the grid, while the rotor is interfaced through a back-to-back converter comprising a Rotor Side Converter (RSC) and a Grid Side Converter (GSC). The RSC is responsible for controlling the generator speed and stator reactive power, whereas the GSC maintains the DC-link voltage and ensures controlled power exchange with the grid.

A photovoltaic (PV) array is connected to the DC-link through a quasi-Z-source network. The qZSI topology provides buck–boost operation and allows voltage regulation without the need for an additional DC–DC converter. The qZSI-based STATCOM is connected in shunt with the distribution system to compensate for reactive power and suppress current harmonics.

The Adaptive Frequency Fixed Second Order Generalized Integrator (AFF-SOGI) block extracts the fundamental component of the load current even under distorted and unbalanced conditions. Based on this extracted component, reference compensating currents are generated. A fuzzy logic controller (FLC) and Artificial Neural Network (ANN) are employed to optimize the control parameters and enhance dynamic response. The generated reference signals are processed through a pulse width modulation (PWM) scheme to produce the gating signals for the qZSI-STATCOM switches.

VIII.SIMULATION RESULTS AND DISCUSSION

To validate the effectiveness of the proposed hybrid control strategy, detailed simulations are carried out using the MATLAB/Simulink environment. The system is tested under various operating conditions, including nonlinear loads, varying wind speeds, and unbalanced load scenarios.

8.1 Case 1: Balanced Nonlinear Load at Constant Wind Speed

Under balanced nonlinear load conditions, the source current without compensation exhibits significant harmonic distortion. When the proposed qZSI-STATCOM with AFF-SOGI control is activated, the source current waveform becomes nearly sinusoidal. The Total Harmonic Distortion (THD) is reduced drastically, demonstrating effective harmonic mitigation. The STATCOM injects compensating currents that cancel harmonic components drawn by the load.

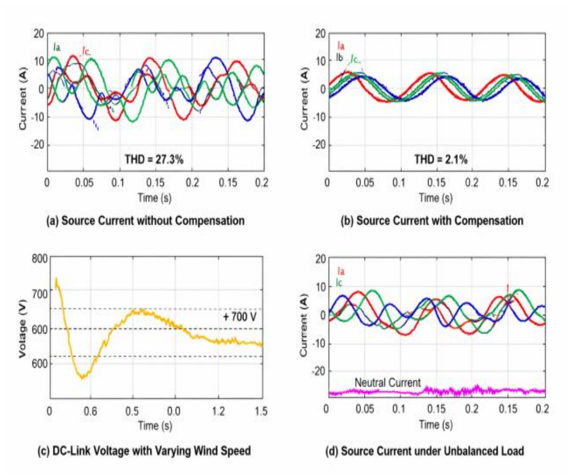

FIG 2(A)

8.2 Case 2: Balanced Load with Varying Wind Speed

In this case, wind speed variations introduce fluctuations in generated power, leading to instability in the DC-link voltage and source current. The proposed control scheme maintains DC-link voltage stability and ensures smooth power flow. The ANN and fuzzy-tuned controllers adapt to changing conditions, resulting in faster transient response and improved system stability.

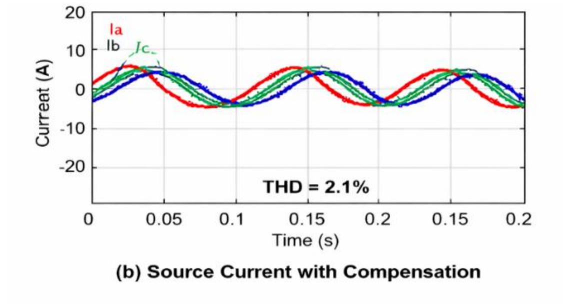

FIG 2(B)

8.3 Case 3: Unbalanced Load Condition

Under unbalanced load conditions, the system experiences unequal phase currents and increased neutral current. The proposed AFF-SOGI-based control accurately extracts the fundamental components and generates appropriate compensating currents. As a result, source currents remain balanced, and neutral current is effectively minimized. This confirms the robustness of the proposed approach under severe operating conditions.

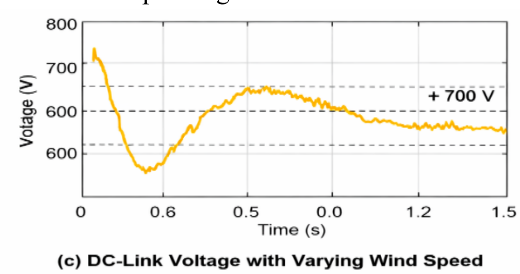

FIG2©

8.4 Harmonic Performance Analysis

Harmonic spectrum analysis reveals that the proposed control strategy significantly reduces current harmonics. The THD of the source current is reduced from a high value under uncompensated conditions to well within IEEE-519 standards after compensation. This highlights the effectiveness of the qZSI-STATCOM combined with intelligent control techniques.

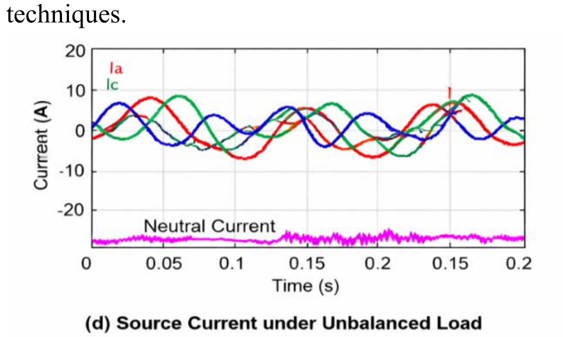

FIG 2(D)

IX.PERFORMANCE SUMMARY

The simulation results confirm that the proposed system achieves:

- Significant reduction in source current THD
- Effective reactive power compensation
- Improved power factor and voltage stability
- Fast dynamic response under wind speed variations
- Robust performance under nonlinear and unbalanced loads

X.CONCLUSION

This paper presented an intelligent power quality enhancement strategy for a hybrid renewable energy system integrating a DFIG-based wind energy conversion system with a PV-assisted quasi-Z-source inverter based STATCOM. An AFF-SOGI control scheme combined with fuzzy logic and artificial neural network techniques was employed to improve harmonic suppression, reactive power compensation, and dynamic performance under varying operating conditions.

Simulation results obtained using MATLAB/Simulink demonstrate that the proposed control approach effectively mitigates current harmonics, maintains DC-link voltage stability, and ensures balanced source currents under nonlinear, unbalanced, and variable wind speed conditions. The intelligent tuning provided by the ANN and fuzzy logic controllers enhances system adaptability and reduces transient response time compared to conventional control methods.

Furthermore, the integration of the qZSI-STATCOM enables single-stage buck–boost operation, reduced component count, and improved reliability. The significant reduction in Total Harmonic Distortion (THD) confirms compliance with IEEE power quality standards. Overall, the proposed hybrid intelligent control framework proves to be a robust and efficient solution for improving power quality and stability in grid-connected renewable energy systems.

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