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Research Article

Grid-Connected PV System with Quasi-Z-Source Inverter And ANFIS MPPT

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Abstract:

Background of Study: The integration of photovoltaic (PV) systems into the power grid is a key step in the transition toward renewable energy. However, challenges such as inconsistent power output, inefficient energy harvesting, and synchronization with the grid limit their effectiveness. Addressing these issues is crucial for reliable and sustainable solar energy utilization.

Aims and Scope of Paper: This study introduces an ANFIS-based MPPT strategy to boost PV efficiency and grid stability, focusing on intelligent control and advanced inverter systems for seamless AC integration.

Methods: The system uses an ANFIS-based MPPT to dynamically adjust the DC-DC converter's duty cycle, integrates a Switched Quasi-Z-Source Inverter (SQZSI) for voltage boosting and reliability, employs a single-phase VSI with LC filters to produce smooth AC output, and applies a PI controller for grid voltage and frequency synchronization.

Result: The system demonstrated improved energy harvesting efficiency and grid stability. The ANFIS algorithm enabled accurate and rapid tracking of the maximum power point, while the inverter architecture ensured consistent and high-quality power delivery compatible with grid standards.

Coclusion: The combination of ANFIS-based MPPT, SQZSI, and synchronized control provides a reliable and efficient solution for integrating solar energy into the modern power grid. This intelligent, robust system enhances both performance and sustainability in renewable power generation.

Keywords: ANFIS MPPT; Grid-Connected PV; Renewable Energy;Switched Quasi-Z-Source Inverter;

1. INTRODUCTION

As the world moves toward renewable energy, photovoltaic (PV) system integration with the power grid has become essential to contemporary energy infrastructure. Energy storage is a basic technology that is essential to the current power systems' transformation and to the smooth integration of energy sources, power networks, and electricity consumption (J. Li et al., 2024). PV systems use semiconductor materials to directly convert sunlight into electrical energy, providing a sustainable and clean alternative to electricity derived from fossil fuels.

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Applications for these converters include robots, high-voltage DC systems, electric cars, and solar photovoltaic (PV) systems (Lin et al., 2024). For many domestic and commercial applications, a rather high output voltage is needed, yet the energy generated by sources such as fuel cells or solar PV is somewhat low.

However, there are issues with the broad use of PV technology that need to be resolved to guarantee grid efficiency, stability, and dependability. The talk began by providing a quick overview of the definitions of power system stability and their historical development since the 1920s. It was noted that the widespread use of converters with high penetration of renewable energy sources (HPREs) in future power systems will alter numerous stability-related critical parameters (Wu et al., 2023). The erratic and sporadic nature of solar energy is one of the main technical obstacles. PV systems produce electricity based on sunlight availability, which changes with weather and time of day, in contrast to traditional power plants that deliver steady power on demand.

When the power supply matches demand, the electrical grid operates in a stable state. Imbalances between supply and demand can lead to voltage variations, frequency deviations, and even blackouts. Maintaining a balance between supply and consumption helps to keep the grid stable and prevents disruptions in electrical service (Javaid et al., 2024). Furthermore,incontemporary powersystems, the integration of inverter-based generation sources, such as wind farms and solar farms,does not con tribute physical inertia that is characteristic of traditional rotating synchronous generators (Phophongviwat et al., 2024).

The erratic and sporadic nature of solar energy is one of the main technical obstacles (Giglio et al., 2023). PV systems produce electricity based on sunlight availability, which changes with weather and time of day, in contrast to traditional power plants that deliver steady power on demand. In order to prevent voltage breaches, curtailing PV generation is a typical practical option. However, this results in a loss of energy generation, perhaps during the peak PV generating hours of the day. Using voltage regulation tools like step voltage regulators and on-load tap changers might be an additional remedy (Ahmadifar et al., 2023). Grid-tied inverters are essential to this process because they manage power quality and transform DC electricity from PV panels into grid-compatible AC.

An increasing number of individuals are embracing renewable energy solutions. This movement is redefining the whole energy system, decen tralizing power generation and distribution and putting the ability to harness sustainable resources directly into the hands of everyday citizens (Horvat et al., 2024). It's important to note that if the energy suppliers (with risk avoidance) fail to finish the quota work, they would be subject to very large nes. Evidently, they are more prepared to pay for the investment in renewable energy technologies or buy quotas on the Green Power Certification System than people with exceptionally high nes (D. Li & Xu, 2024).

As PV adoption grows, grid congestion becomes a concern, particularly in areas with high PV penetration. Preventing overloading and maintaining stable operation require strategic upgrades to grid infrastructure and thoughtful system planning. Government policies and regulatory frameworks significantly influence PV grid integration. Clear technical standards, investments in grid modernization, and incentives for energy storage adoption are critical to supporting solar energy expansion. PV grid integration is a multifaceted process that demands innovation, policy support, and comprehensive planning.

2. MATERIAL AND METHOD

The proposed approach incorporates a switched quasi-Z-source converter with a photovoltaic (PV) system to improve energy conversion efficiency and facilitate effective integration with the power grid. When utilized in transformerless (non-isolated) grid-tied PV system applications, the aforementioned combination must respect the leakage current reduction restrictions established by reliable standards (Abdelhakeem et al., 2024). It employs pulse width modulation (PWM) to produce control signals for the inverter, which transforms the DC output from the PV source into AC power compatible with the grid. A driver circuit ensures accurate and efficient transmission of the PWM signals to the inverter. To ensure the output waveform meets grid standards, an LC filter is used to smooth the AC signal. To maximize the energy recovered from the PV array, a Maximum Power Point Tracking (MPPT) algorithm based on the Adaptive Neuro-Fuzzy System (ANFS) is also used.

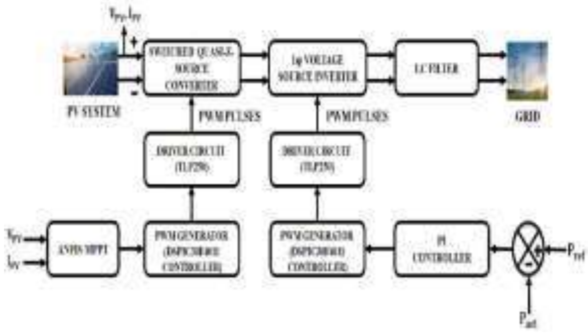

Figure 1. Z source Converter with ANFIS MPPT

The system also includes a proportional-integral (PI) controller to regulate the active power fed into the grid, maintaining synchronization and stability. This configuration enhances overall efficiency, reduces harmonic distortion, and ensures reliable energy supply, making it a robust solution for renewable energy applications.

The Quasi-Z-Source Converter (QZSC) is an innovative power conversion topology that combines the features of both traditional voltage-source and current-source converters, providing unique advantages in energy conversion. This converter utilizes a unique impedance network composed of inductors and capacitors to create a Z-source network, allowing for voltage step-up or step-down capabilities in a single stage without the need for a separate transformer.

2.1 Quasi Z source Converter

The Quasi-Z-Source Converter (QZSC) operates through a distinctive configuration that includes an input voltage source, two inductors, a pair of capacitors, a switch, and diodes.

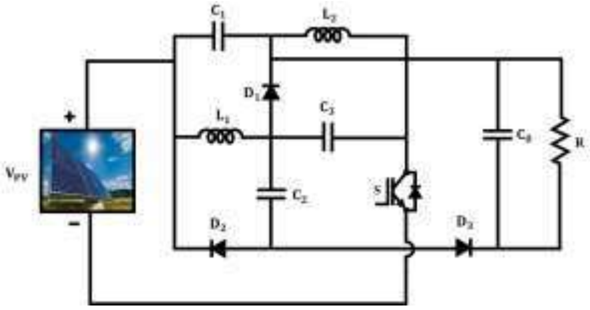

Figure 2. Circuit diagram of Quasi Z source Converter

When the switch is closed, current flows through the inductors, storing energy in their magnetic fields. This stored energy allows the converter to boost the output voltage when the switch opens, transferring the energy to the capacitors and then to the output load. Diodes ensure proper current flow, preventing reverse currents and supporting output voltage regulation.

The QZSC typically functions in continuous conduction mode (CCM), which enhances efficiency and reduces voltage ripple. Advanced control mechanisms adjust the switch's duty cycle based on output feedback, maintaining stable performance under varying loads. Additionally, the converter can support regenerative braking in applications like electric drives, enabling energy recovery and further increasing system efficiency. Through these operations, the QZSC effectively delivers reliable and efficient power conversion for a variety of applications.

2.2 ANFIS MPPT

Adaptive Neuro-Fuzzy Inference System (ANFIS) and Maximum Power Point Tracking (MPPT) are two techniques used in photovoltaic (PV) systems to maximize solar panel power production. By combining fuzzy logic and neural network techniques, it dynamically adjusts a solar panel's operating point to guarantee that it operates at its maximum power point (MPP) under various climatic conditions. First, data is gathered by the ANFIS controller from a variety of sensors including the solar panel itself.

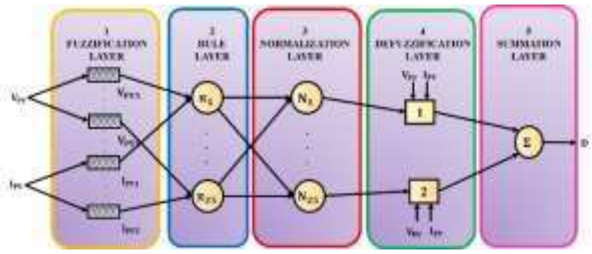

Figure 3. ANFIS based MPPT method

To monitor the PV module's maximum power, the ANFIS-based MPPT technique is suggested. The input variables of ANFIS-based MPPT are the PV cell temperature (T_pv), PV voltage (V_pv), and PV current (I_pv). The ANFIS approach learns the three membership functions for each input parameter. ANFIS MPPT-controlled Switched Quasi-Z-Source Inverter (qZSI) with PI controller for effective grid-connected PV power conversion. By controlling the inverter's output voltage and current and making up for any variations brought on by variations in load or external conditions, it guarantees steady functioning. The PI controller adjusts the duty cycle of the inverter's switches, minimizing errors between the desired and actual output. When integrated with the ANFIS-based Maximum Power Point Tracking (MPPT) algorithm, the PI controller enhances system performance by providing rapid and precise control, ensuring optimal energy conversion and grid synchronization.

Single-phase grid voltage synchronization is a vital process in power electronics and RESs, particularly for the inverters that are interfaced with the electrical grid. The process of synchronization enables smooth power transfer and stable grid operation by matching the voltage, frequency and phase of the generated power to that of the grid power. Moreover, there are also several other techniques that are employed to achieve grid synchronization, which includes Synchronous Reference Frame (SRF), Zero-crossing detection, Instantaneous Power Theory and Fourier Transform-Based methods. These techniques help in precise synchronization despite challenges like harmonics, noise, grid disturbances, and phase jumps. The synchronization process involves initialization, where grid voltage parameters are measured, followed by signal processing through the PLL, control adjustments to match the grid, and continuous monitoring to maintain synchronization.

3. RESULT AND DISCUSSION

Result:

Figure 4. Hardware prototype

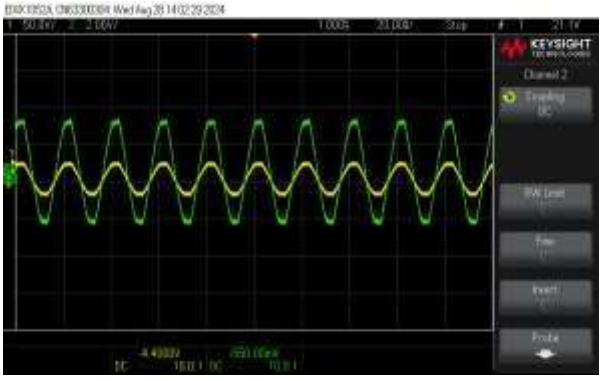

Figure 5. Grid Waveform

The green and yellow waveforms indicate a high-frequency operation, possibly from a DC-DC converter or inverter. The measured values of -4.4V and -550mV DC offset suggest signal analysis related to power conversion, filtering, or control applications.

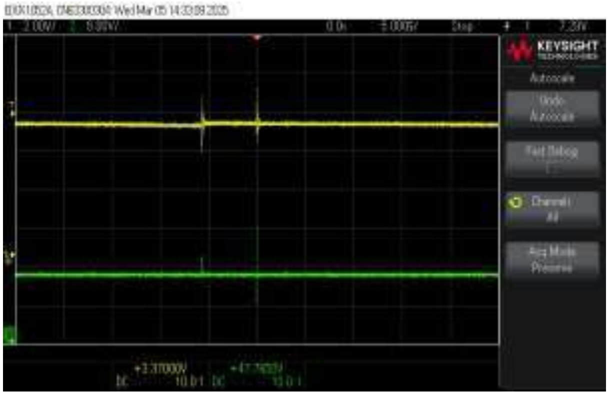

Figure 6. Input And Output Voltage Waveform

The yellow and green waveforms indicate transient events or noise spikes in a power electronics circuit. The voltage readings of 3.37V and 47.77V suggest the monitoring of a DC power supply or converter output.

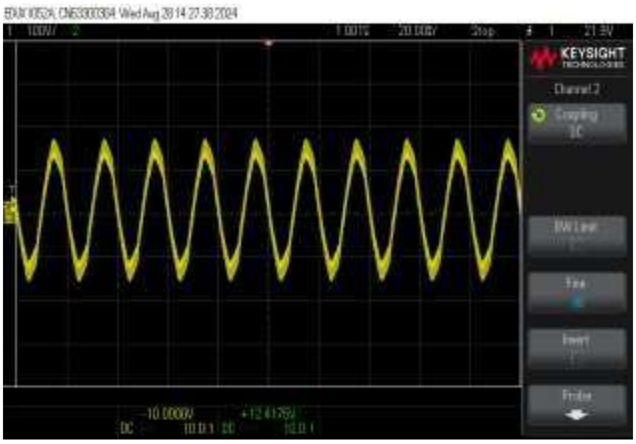

Figure 7. LC Filter Waveform

The measured voltage ranges from -10V to 12.42V, suggesting an AC signal with a DC offset. The waveform appears stable and periodic, indicating it could be from a power electronics system, such as an inverter or resonant converter. The DC coupling setting suggests the measurement includes both AC and DC components. This type of waveform is commonly observed in applications involving AC-DC conversion, renewable energy systems, or electric vehicle power management.

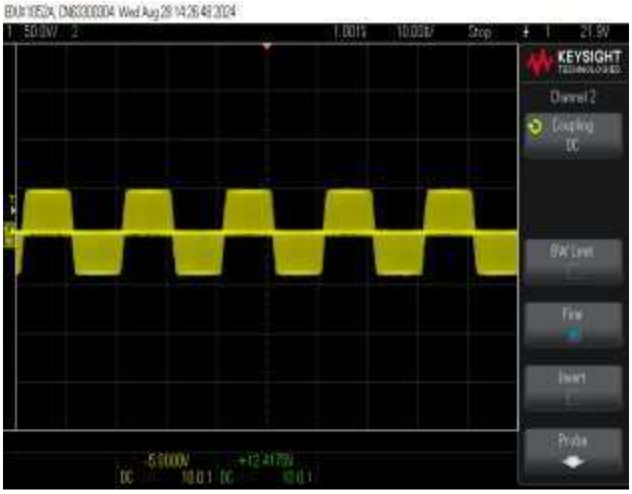

Figure 8. Single Phase VSI

It displays a square wave signal with a DC coupling mode. The waveform has a peak-to-peak voltage range from approximately -5V to +12.4175V. The symmetrical nature of the waveform suggests it may be a pulse-width modulated (PWM) signal or a clock signal in a digital circuit. This type of signal is commonly found in switching power supplies, communication protocols, or motor control circuits. fficiency and operational resilience.The integration of ANFIS enables the MPPT mechanism to respond dynamically to changing environmental conditions, ensuring optimal solar power extraction throughout the day. The qZSI structure enhances voltage regulation and minimizes harmonic distortion, making it well-suited for seamless grid integration. Moreover, the system design supports effective energy management by reducing power losses and boosting overall performance.In summary, this research emphasizes the value of merging advanced control methodologies with modern inverter technologies to achieve more efficient, dependable, and eco-friendly energy solutions. As the global shift toward renewable energy accelerates, the insights from this study contribute to the advancement of solar energy systems, supporting a cleaner and more sustainable future.

Discussion :

The detection of copper ions in aqueous solutions is critically important due to their harmful effects on both human health and the environment. High levels of copper exposure can cause serious health problems, and copper is toxic to aquatic organisms. However, existing detection methods are often expensive and complex, limiting their practicality for routine use. This study addresses these limitations by exploring the potential of beetroot extracts containing betanin as environmentally friendly fluorescence probes to detect copper ions.

The strong fluorescence behavior of the pure beetroot dye, as indicated by the PL analysis, reinforces its potential as a viable fluorescence probe for sensitive and accurate detection of copper ions in aqueous solutions. The FTIR analysis further characterized the beetroot powder, with observed peaks indicating the presence of hydroxyl, carbonyl, and amine groups, consistent with compounds such as anthocyanins and betanin, which contribute to its red color.

he UV-vis characterization demonstrated that both 0.01 mol and 0.005 mol beetroot dye solutions exhibited distinct absorption peaks, with the higher concentration showing greater absorbance. This directly correlates with the concentration of betanin and other associated compounds in the solution. A crucial finding was the gradual decrease in absorbance intensity and the visible fading of the solution's color with increasing copper ion concentration. This suggests an interaction between the betanin dye and copper ions that directly affects the dye's optical properties, forming the basis for its use as a copper ion sensor.

The linear correlation between copper concentration and betanin absorbance ($R^2 = 0.792$) confirms betanin's potential as a responsive optical sensor for copper ions. The calculated detection sensitivity of $-6.21828\times10-4$ A.U./ppm further highlights betanin's high potential, as even small changes in copper concentration lead to noticeable variations in absorbance. The relatively steep slope of the absorbance-concentration graph supports the dye's suitability for sensitive copper ion detection.

In conclusion, this study confirms that betanin from beet extract can be used as an effective, low-cost, and environmentally friendly fluorescence probe in detecting copper ions. These findings contribute to the development of safer and more sustainable metal ion detection methods with potential applications in environmental, industrial, and biomedical research. The observed interaction between the dye and copper ions led to a reduction in the dye's absorption capacity as copper concentration increased. The 0.01 mol dye solution exhibited a strong linear correlation between copper ion concentration and absorbance.

4. CONCLUSION

The implementation of the Switched Quasi-Z-Source Inverter (SQZSI) along with MPPT's Adaptive Neuro-Fuzzy Inference System (ANFIS) significantly improves the power conversion efficiency in grid-connected PV systems. Through more efficient voltage control, this combination of technologies lowers harmonic distortion, increases the reliability of power injection into the grid, and maximizes power harvesting from solar panels. Furthermore, in the face of shifting external factors like temperature and irradiance, the created system provides excellent reliability. With the integration of artificial intelligence-based MPPT algorithms, the system is able to dynamically adjust to the power changes generated by PV, ensuring optimal operation throughout the day. This research provides an innovative solution to the challenge of integrating PV into the modern power grid and opens up opportunities for the development of more efficient and sustainable inverter technology. The results obtained can be used as a basis for further research in the field of renewable energy and AI-based electric power systems.

5. ACKNOWLEDGEMENT

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6. AUTHOR CONTRIBUTION STATEMENT

All the authors involved in this study J. Raji, S. Lakshmi, and S. Prakash contributed significantly to the development of the concept, system design, data analysis, and writing and editing of this article. The authors worked together to ensure that this study provides an innovative solution for grid-connected PV systems with Quasi-Z-Source inverters and ANFIS-based MPPT algorithms. In addition, the author also plays a role in simulation and testing of systems to improve the efficiency and reliability of renewable energy for the integration of modern power grids.

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