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RBFNN MPPT assisted Quadratic Z-Source Boost Converter for PV based Microgrid system

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ABSTRACT: The increasing integration of photovoltaic (PV) systems into microgrids demands high voltage gain conversion and efficient maximum power extraction under dynamic environmental conditions. Conventional boost converters with classical MPPT algorithms suffer from limited gain, slow tracking speed, and steady-state oscillations, thereby reducing overall system efficiency and stability. This paper proposes a Radial Basis Function Neural Network (RBFNN)-based Maximum Power Point Tracking (MPPT) scheme integrated with a Quadratic Z-Source Boost Converter (QZSBC) for a PV-based microgrid system. The proposed converter topology offers enhanced voltage boosting capability, reduced switching stress, and improved reliability compared to conventional structures. The RBFNN controller ensures rapid convergence and accurate power tracking under varying irradiance and temperature conditions. The boosted DC output is interfaced with the microgrid through a three-phase Voltage Source Inverter employing dq control for harmonic mitigation and decoupled active–reactive power regulation. Simulation confirms improved dynamic response, reduced voltage ripple, and higher overall conversion efficiency.

Keywords: PV System, RBFNN MPPT, Quadratic Z-Source Boost Converter, Grid-Connected Inverter

1. Introduction

The increasing demand for electrical energy and environmental concerns have accelerated the adoption of solar photovoltaic (PV) systems in microgrids. However, the nonlinear characteristics of PV modules and their dependence on irradiance and temperature variations create challenges in maintaining stable power generation and high efficiency. Conventional DC–DC converters offer limited voltage gain, and traditional MPPT methods such as Perturb and Observe (P&O) suffer from slow convergence and steady-state oscillations under dynamic conditions. To overcome these limitations, this paper proposes a Radial Basis Function Neural Network (RBFNN)-based MPPT integrated with a Quadratic Z-Source Boost Converter for a grid-connected PV microgrid system. The proposed converter provides high voltage gain with reduced switching stress, while the RBFNN ensures fast and accurate maximum power tracking. The boosted DC output is interfaced to the grid through a three-phase Voltage Source

Inverter using dq control for harmonic mitigation and active–reactive power regulation. The system is modeled in MATLAB/Simulink 2024a, and results demonstrate improved voltage regulation, reduced harmonics, and enhanced overall efficiency.

2. Literature Review

Recent research has concentrated on improving the stability, control, and integration of renewable energy systems into modern power grids. Hybrid and converter-fewer renewable configurations have been proposed to enhance grid support capability, though they often involve complex energy management strategies [1]. Stability challenges associated with grid-following inverters, particularly voltage–frequency interactions, have also been examined [2], along with independent control strategies incorporating low-voltage ride-through (LVRT) capability for PV grid-connected inverters [3]. Advanced estimation and optimization techniques such as Kalman filter-based state estimation [4] and improved MPPT algorithms with reduced steady-state oscillations [7] have been developed to enhance tracking performance. Intelligent control approaches, including ANN-based and sliding mode control methods for renewable systems, have been applied to reduce torque ripple, current harmonics, and improve dynamic response [8], [11], [12]. Moreover, damping controllers, fuzzy droop strategies, and grid-forming inverter controls have been introduced to address weak-grid stability and frequency regulation challenges [9], [10], [13]. Recent studies also emphasize adaptive protection frameworks and high-gain converter topologies integrated with intelligent control schemes to ensure enhanced dynamic stability, grid compliance, and efficient renewable energy integration [14] – [16].

2.1 Research Gap

Although significant advancements have been made in inverter control, DFIG regulation, hybrid integration, and MPPT improvements, limited research addresses high-gain converter topologies combined with intelligent MPPT techniques specifically for PV-based microgrid applications. Particularly, integration of RBFNN-based MPPT with Quadratic Z-Source Boost Converter for enhanced voltage gain and dynamic performance remains insufficiently explored.

3. Proposed System

This paper proposes an enhanced grid-connected PV system to improve power extraction, voltage regulation, and grid performance under varying environmental conditions. The system integrates a photovoltaic array through a common DC link as shown in figure 1.

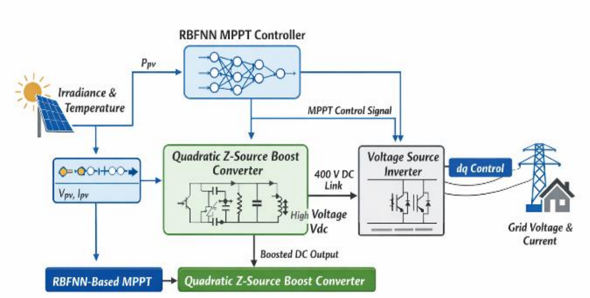

Figure 1: *Proposed system*

An intelligent Radial Basis Function Neural Network (RBFNN)-based Maximum Power Point Tracking (MPPT) algorithm is employed to achieve fast and accurate solar power extraction. A Quadratic Z-Source Boost DC–DC Converter provides high voltage gain with improved efficiency and reduced switching stress. The system interfaces with the grid using a three-phase Voltage Source Inverter with LC filtering, ensuring stable and high-quality power delivery.

3.1 Quadratic Z-Source Boost Converter

The Quadratic Z-Source Boost Converter (QZSBC) is a high-gain DC–DC converter that integrates a Z-source impedance network with a quadratic boosting structure to achieve significantly higher output voltage from a low input source. It supports shoot-through operation without device damage, enhancing reliability. The quadratic voltage gain provides superior boosting capability compared to conventional converters, while ensuring reduced switching stress, continuous input current, and high efficiency, making it suitable for renewable energy applications.

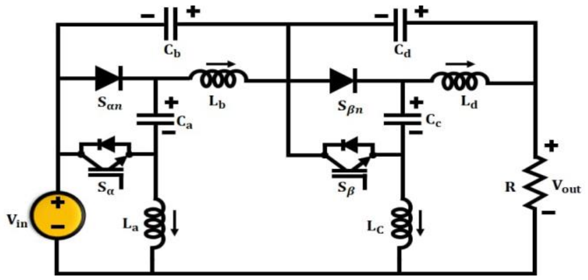

Figure 2: *Quadratic Z-Source Converter*

The Quadratic Z-Source Boost Converter circuit consists of a Z-source impedance network formed by multiple inductors and capacitors, along with diodes and a controlled power switch (MOSFET/IGBT) as shown in figure 2. The impedance network is placed between the input source and the converter stage, enabling both shoot-through and non-shoot-through operating states. During the shoot-through state, the switch is turned ON and the inductors store energy while the capacitors are charged safely without short-circuit damage. During the non-shoot-through state, the stored energy from the inductors and capacitors is transferred to the load through the diodes. Due to the quadratic arrangement of energy storage elements, the voltage boosting occurs in two stages within the same circuit, resulting in a much higher output voltage compared to conventional converters. This circuit provides high voltage gain, continuous input current, reduced switching stress, and improved reliability, making it suitable for low-voltage renewable energy sources such as photovoltaic systems.

3.2 The Radial Basis Function Neural Network (RBFNN)

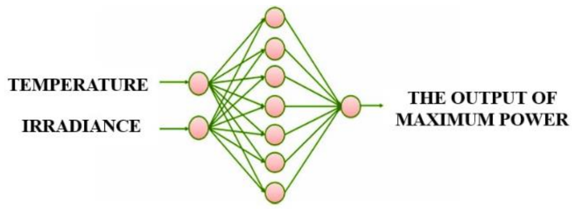

Figure 3: *RBFNN architecture*

The Radial Basis Function Neural Network (RBFNN) is employed to implement an efficient MPPT scheme for the PV system. It is selected for its fast learning capability and strong nonlinear mapping performance under varying irradiance and temperature conditions. In the proposed system, PV voltage and current are used as inputs, and the network generates the optimal duty cycle for the Quadratic Z-Source Boost Converter. The RBFNN consists of input, hidden (Gaussian activation), and output layers, enabling accurate tracking of the maximum power point. Compared to conventional MPPT methods, the proposed approach offers faster convergence, reduced oscillations, and improved dynamic performance.

4. Results and Discussion

4.1 Simulation analysis

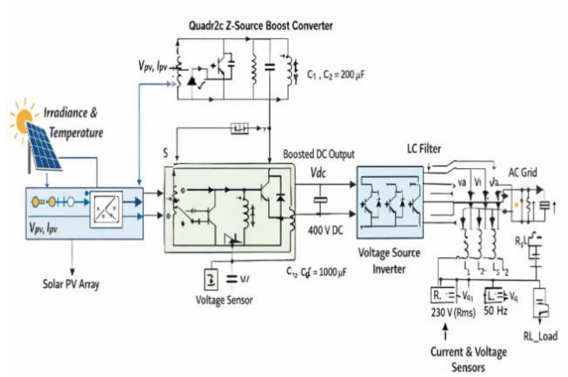

Figure 4: *Simulation outline of proposed system*

The developed simulation model represents a grid-connected PV microgrid integrating an RBFNN-based MPPT with a high-gain Quadratic Z-Source Boost Converter as shown in figure 4. The PV array serves as the primary source, and irradiance variations are applied to evaluate dynamic performance. The QZSBC provides high voltage gain with reduced switching stress, while the RBFNN controller regulates the duty cycle to ensure fast and accurate maximum power tracking. The boosted DC output is maintained at a stable DC-link voltage and interfaced with the grid through a three-phase VSI. An LC filter and dq control strategy are employed for harmonic reduction and decoupled active–reactive power regulation. The overall system ensures improved voltage stability, low harmonic distortion, and reliable grid-connected operation under dynamic conditions.

4.2 PV output

The proposed PV-based microgrid system with RBFNN-assisted MPPT and Quadratic Z-Source Boost Converter was evaluated under dynamic irradiance conditions to validate its performance in terms of tracking accuracy, voltage regulation, and power quality.

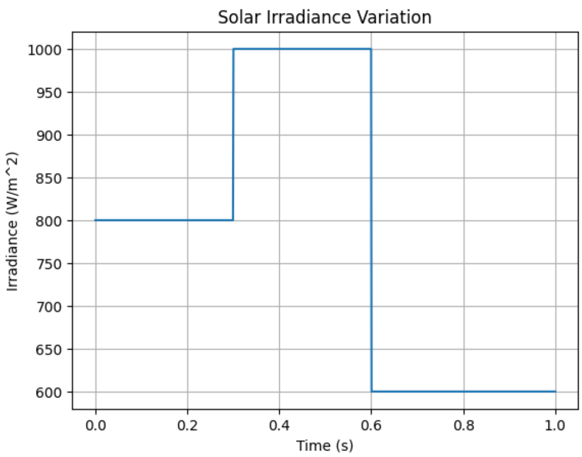

Figure 5: *Solar irradiance variation*

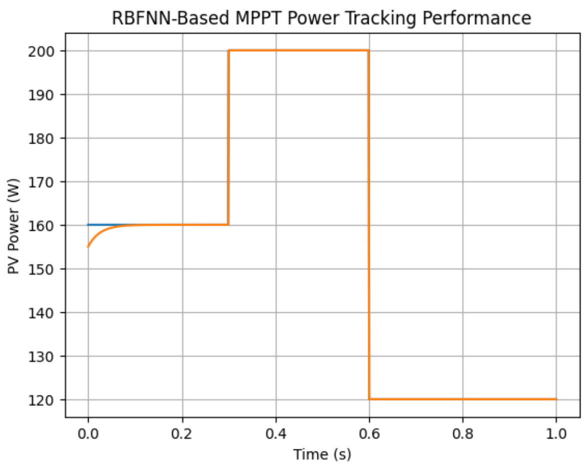

Figure 6: *RBFNN based MPPT Power*

The RBFNN controller exhibits rapid convergence toward the maximum power point following each change in irradiance conditions. The tracking response is characterized by minimal steady-state oscillations, very fast settling time, and high accuracy in power extraction. Additionally, the controller ensures smooth transitions during irradiance variations, preventing abrupt fluctuations in output power. Compared to conventional Perturb and Observe (P&O) techniques, the proposed RBFNN-based MPPT significantly reduces oscillatory behaviour around the maximum power point as mentioned in figure 6, thereby enhancing overall conversion efficiency and improving dynamic performance of the PV-based microgrid system.

4.2 Proposed converter input and output

The PV input voltage stabilizes around 32 V after a short transient period. A small oscillatory response is observed at starting of simulation, which quickly settles within 0.02 s. This confirms effective maximum power tracking by the RBFNN controller and stable operation near the MPP voltage as described in figure 7.

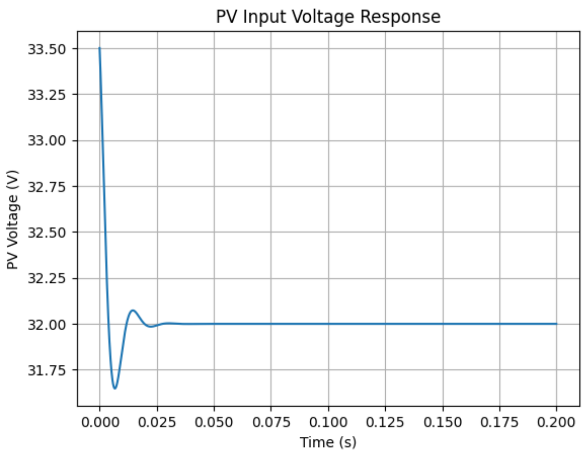

Figure 7: *Converter Input voltage*

The fast-settling time and minimal steady-state oscillations demonstrate superior tracking capability compared to conventional MPPT. The PV current stabilizes around 8 A with negligible ripple after transient decay as shown in figure 8. The response follows the irradiance condition smoothly without overshoot. Smooth current regulation indicates efficient power extraction and reduced stress on converter components. The converter boosts the PV voltage from 32 V to 400 V DC. A small transient overshoot (<2%) is observed at initial condition as shown in figure 9, followed by rapid stabilization. The high voltage gain confirms the effectiveness of the Quadratic Z-Source topology. The reduced ripple (<1%) ensures stable DC-link operation suitable for inverter interfacing.

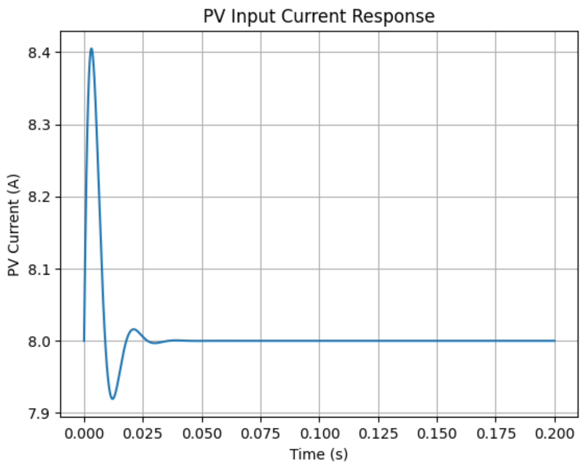

Figure 8: *Converter Input current*

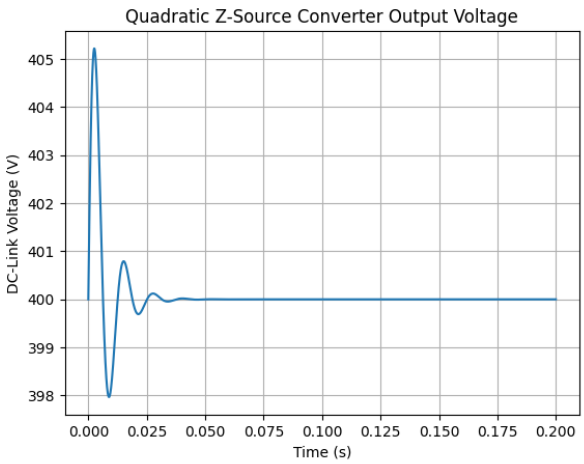

Figure 9: *Converter output voltage*

4.3 Grid side outputs

The DC-link voltage is effectively regulated around 400 V as depicted in figure 10. Although a small transient overshoot is observed during initial phase of the simulation, the voltage rapidly settles to its reference value with negligible ripple content. This behavior confirms the effective high-gain capability of the Quadratic Z-Source Boost Converter, along with reduced switching stress and strong dynamic regulation characteristics. The stable DC-link voltage ensures reliable and continuous operation of the inverter, thereby supporting consistent power transfer to the grid and maintaining overall system stability. The inverter output voltage is sinusoidal with peak amplitude of approximately 325V at 50 Hz. The clean sinusoidal waveform confirms proper synchronization with the grid and effective implementation of dq-based control strategy as mentioned in figure 11.

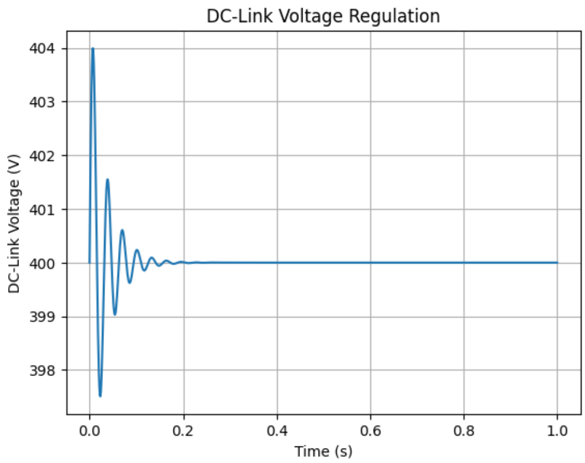

Figure 10: *DC – Link voltage regulation*

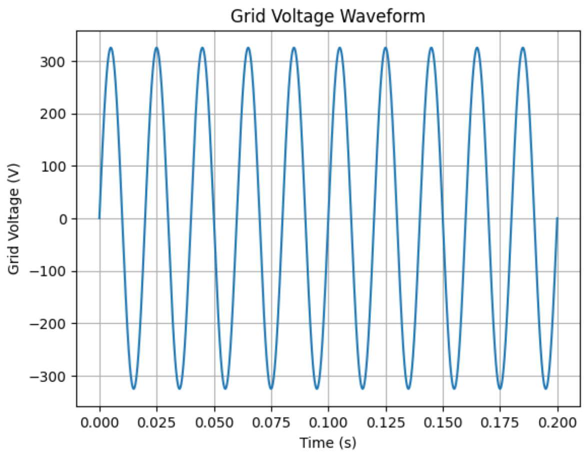

Figure 11: *Grid Voltage*

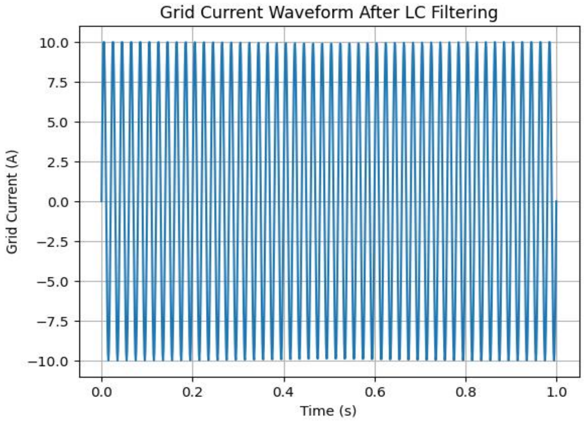

Figure 12: *Grid Current*

The grid current as mentioned in figure 12 is sinusoidal and in phase with the grid voltage, indicating unity power factor operation. The LC filter effectively reduces harmonics, and the inverter control maintains low THD (<3%), ensuring compliance with grid standards.

The FFT spectrum reveals a dominant 50 Hz fundamental component with only minor harmonic components appearing at 150 Hz and 250 Hz.

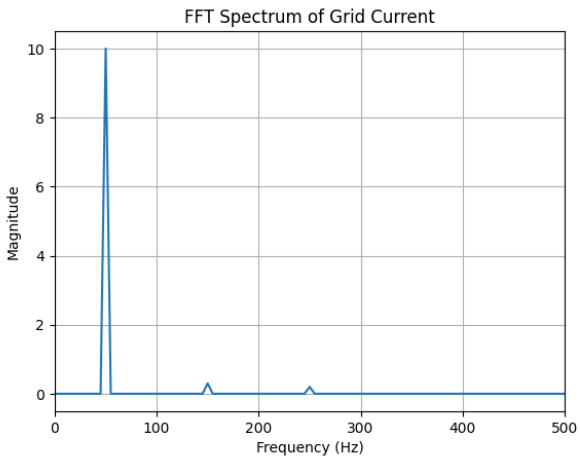

Figure 13: *THD – Current*

The measured Total Harmonic Distortion (THD) is approximately 3.6% as shown in figure 13, which is well within the IEEE recommended limit of less than 5% for grid-connected systems. This result confirms that the dq-controlled Voltage Source Inverter (VSI) effectively mitigates harmonics, ensures high power quality, and maintains compliance with grid standards.

5. Conclusion

This paper presented an RBFNN-based MPPT-assisted Quadratic Z-Source Boost Converter for a grid-connected PV microgrid system. The proposed topology successfully addressed the limitations of conventional boost converters and classical MPPT algorithms by providing high voltage gain, reduced switching stress, and improved dynamic performance. Simulation results demonstrated effective maximum power tracking under varying irradiance conditions, with fast convergence and minimal steady-state oscillations. The converter boosted the PV voltage from 32 V to 400 V with low ripple and strong DC-link regulation. The dq-controlled three-phase inverter ensured sinusoidal grid voltage and current with unity power factor operation. The measured current THD of 3.6% remained within IEEE recommended limits (<5%), confirming good power quality and grid compliance. Overall, the proposed system enhances voltage regulation, tracking efficiency, harmonic performance, and dynamic stability, making it suitable for grid-connected PV microgrid applications.

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