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Intelligent Power Management using MPPT-Controlled Buck-Boost Converter for Hybrid Solar-Fuel Cell Systems in Single and Three-Phase Applications

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ABSTRACT

This study presents an intelligent power management framework for a hybrid solar photovoltaic (PV) and fuel cell system using a Maximum Power Point Tracking (MPPT)-controlled Buck-Boost Converter. The proposed system is engineered for dual operation in both single-phase and three-phase load environments, ensuring efficient voltage regulation under dynamic irradiance and load conditions. The core innovation lies in integrating real-time sensing of irradiance, temperature, and voltage levels with adaptive MPPT techniques (Incremental Conductance and P&O), executed via a microcontroller-driven control strategy. MATLAB/Simulink simulations validate the performance in terms of efficiency, output ripple, and transient response. The results confirm superior regulation, high efficiency (over 93.5%), and seamless load adaptability. The proposed approach is particularly effective for standalone and microgrid applications demanding consistent performance under variable input and environmental factors.

Keywords: Hybrid Renewable Energy, Solar PV, Fuel Cell Integration, MPPT Control, Buck-Boost Converter, Adaptive Power Management, Real-Time Control, Microgrid Applications

1. Introduction

The global shift toward clean and sustainable energy has accelerated the integration of renewable energy sources such as solar photovoltaic (PV) panels and hydrogen-based fuel cells. While these sources offer substantial environmental benefits, their real-world application introduces new challenges due to their inherent variability and non-linear performance under fluctuating environmental conditions. Solar irradiance, temperature, and dynamic load changes lead to voltage and current inconsistencies, thereby necessitating intelligent power conditioning systems that ensure stable and efficient energy delivery[1-3].

Hybrid renewable energy systems combining solar PV and fuel cells have emerged as a robust solution to address the intermittency of solar energy. While the PV system serves as the primary energy source, the fuel cell provides backup support during low irradiance or peak demand periods. However, the varying output characteristics of these sources demand efficient power conversion mechanisms to maintain voltage stability across varying supply and load conditions[4-6].

A Buck-Boost Converter, being capable of both stepping up and stepping down voltages, is well-suited for such hybrid applications. When augmented with a Maximum Power Point Tracking (MPPT) controller, this converter can intelligently extract maximum available power from solar PV panels, regardless of external fluctuations. The MPPT technique, based on algorithms such as Incremental Conductance and Perturb & Observe, dynamically adjusts the converter's duty cycle to operate the PV panel at its optimal power point[7-10].

This research focuses on an MPPT-controlled Buck-Boost Converter designed to function in both single-phase and three-phase power delivery environments. The system integrates real-time monitoring of critical environmental and electrical parameters, employing a microcontroller-based control strategy to maximize energy extraction, minimize power loss, and ensure seamless hybrid power flow. Simulations are conducted in MATLAB/Simulink to analyze the converter’s dynamic response, efficiency, voltage ripple, and transient performance[11-14].

The proposed architecture aims to bridge the existing gap in power quality and management for hybrid renewable systems, presenting a versatile and intelligent solution for standalone, grid-connected, and microgrid applications[15-17].

The growing emphasis on decentralized and renewable energy has led to significant research in the areas of MPPT algorithms, Buck-Boost converters, and hybrid solar-fuel cell systems. Prior studies have extensively examined individual aspects such as solar PV optimization and converter design; however, integrated systems that combine intelligent control with hybrid power flow remain comparatively underexplored[18-20].

Patel and Agarwal (2008) emphasized the need for advanced MPPT schemes under partially shaded conditions, proposing adaptive algorithms to improve tracking efficiency. Their work laid the foundation for the development of more robust techniques such as Incremental Conductance (IC), which offers superior performance compared to the traditional Perturb & Observe (P&O) algorithm by analyzing the instantaneous conductance and its incremental changes.

Villalva et al. (2009) presented comprehensive modeling techniques for photovoltaic arrays, offering simulation models to understand the non-linear behavior of solar cells. These models serve as critical tools for optimizing converter performance, especially in conditions where MPPT efficiency directly affects system output[14].

Femia et al. (2005) and Esram and Chapman (2007) conducted comparative studies on MPPT techniques, concluding that algorithmic modifications and environmental sensing significantly improve energy harvesting efficiency. These studies highlighted the importance of integrating environmental feedback—such as irradiance and temperature—into control loops[15].

Axelrod et al. (2008) and Blaabjerg et al. (2004) focused on power electronics, particularly in transformerless DC-DC conversion systems. They showed that soft-switching mechanisms and high-frequency operations enhance converter efficiency and reduce electromagnetic interference (EMI), which are vital considerations in hybrid renewable systems[16].

10.48047/jocaaa.2024.32.02.44

In the domain of fuel cell integration, Sadigh et al. (2015) explored adaptive voltage regulation for DC distribution systems, emphasizing the necessity of bidirectional converters to facilitate smooth power transfer in hybrid topologies. Their findings indicate the value of dynamic voltage regulation in sustaining load requirements during energy source transitions[17].

Recent research by Sharma and Joshi (2014) and Jain et al. (2018) investigated high-efficiency Buck-Boost converter designs for renewable systems, incorporating real-time feedback loops, low-ripple output stages, and rapid transient response mechanisms. These studies affirm the critical role of advanced control strategies in improving voltage stability and energy throughput[18].

Despite these advancements, few studies consolidate the control of solar PV and fuel cell systems through a unified converter and real-time control strategy. Moreover, the simultaneous implementation of MPPT control with environmental compensation in multi-phase power applications remains largely unaddressed[19].

The present research contributes to this gap by proposing an intelligent MPPT-controlled Buck-Boost Converter that manages power flow between solar PV and fuel cell sources, optimized for both single-phase and three-phase loads. The integration of real-time sensing, adaptive control, and simulation validation positions this work at the forefront of intelligent renewable energy system design[20].

3. Methodology

The proposed system integrates a hybrid energy architecture consisting of a solar photovoltaic (PV) array and a hydrogen fuel cell, managed by an MPPT-controlled Buck-Boost Converter. The objective is to ensure efficient power extraction, voltage regulation, and seamless supply to single-phase and three-phase loads. The overall methodology comprises hardware modeling, control algorithm design, sensor integration, and simulation-based performance validation.

3.1 System Architecture

The core block diagram of the system includes the following components:

- **Solar PV Array**: Primary energy source producing DC voltage with variability based on irradiance and temperature.
- **Fuel Cell Stack**: Auxiliary power source providing backup DC power during periods of low solar generation or high load.
- **MPPT Controller**: Executes Incremental Conductance or Perturb & Observe algorithms to operate the PV panel at its Maximum Power Point.
- **Buck-Boost Converter**: Regulates voltage by either stepping up or down the input, depending on source and load requirements.
- **Microcontroller/DSP**: Governs MPPT execution, duty cycle generation, and sensor feedback integration.

10.48047/jocaaa.2024.32.02.44

- **PWM Generator**: Modulates the MOSFET/IGBT switch based on duty cycle to achieve regulated DC output.
- **Inverter (Single-Phase/Three-Phase)**: Converts regulated DC output to AC for supplying variable loads or feeding the grid.
- **Sensor Units**: Measure voltage, current, temperature, and irradiance in real-time to enhance control accuracy and protection.

3.2 MPPT Algorithm Implementation

The MPPT algorithm plays a pivotal role in dynamically adjusting the operating voltage of the solar panel to extract the maximum power. Two primary techniques are considered:

- **Incremental Conductance (IC)**:

  Based on the condition (dI/dV)+(I/V)=0 at MPP. The controller calculates changes in current and voltage to fine-tune the duty cycle.

- **Perturb & Observe (P&O)**:

  Periodically perturbs the operating voltage and observes the resulting change in power. If power increases, perturbation continues in the same direction; otherwise, it is reversed.

The selected algorithm is embedded into the microcontroller, which continually monitors Vpv and Ipv, computes Ppv, and adjusts the PWM duty cycle accordingly.

3.3 Buck-Boost Converter Design

The Buck-Boost Converter is modeled based on the two-state switching operation:

- **Switch ON**:

  The input DC source energizes the inductor LLL, and the diode is reverse-biased. The inductor stores energy:

$$V_L = V_{in}, \quad \Delta I_L = \frac{V_{in} \cdot t_{on}}{L}$$

- **Switch OFF**:

  The inductor discharges through the diode into the output capacitor and load:

$$V_L = -V_{out}, \quad \Delta I_L = \frac{-V_{out} \cdot t_{off}}{L}$$

The duty cycle DDD defines the converter mode:

10.48047/jocaaa.2024.32.02.44

$$V_{out} = \frac{D}{1-D} \cdot V_{in}$$

Component sizing is carried out to ensure minimum ripple and fast transient recovery:

- **Inductor LLL**:

$$L = \frac{V_{in} \cdot D \cdot (1-D)}{\Delta I_L \cdot f_s}$$

- **Capacitor C**:

$$C = \frac{I_{out} \cdot D}{\Delta V_{out} \cdot f_s}$$

Where fs is the switching frequency, ΔI is inductor ripple current, and ΔV_{out} is the acceptable output voltage ripple.

3.4 Real-Time Control and Sensing

The system integrates four essential sensor feedback loops:

- **Voltage Sensor**: Monitors PV and output voltages.
- **Current Sensor**: Detects PV and load currents to evaluate power and efficiency.
- **Temperature Sensor**: Compensates for the negative temperature coefficient of PV voltage.
- **Irradiance Sensor**: Enables dynamic environmental response in MPPT calculations.

The microcontroller processes sensor data and applies protective logic to prevent overvoltage, undervoltage, and overcurrent conditions. It also triggers alarms or source switching when fuel cell support is required.

3.5 Load and Inverter Interface

The regulated DC output from the converter is supplied to:

- **Single-Phase Inverter**: Generates sinusoidal AC power using unipolar PWM for household or isolated loads.
- **Three-Phase Inverter**: Produces synchronized three-phase AC power using space vector modulation (SVM) for industrial or grid applications.

Load adaptability is ensured through inverter feedback and load-side sensing, enabling the system to adjust for varying current demands without voltage collapse.

3.6 Simulation Framework

10.48047/jocaaa.2024.32.02.44

Simulation is carried out in **MATLAB/Simulink** with the following conditions:

- PV source modeled using standard diode equations with temperature and irradiance inputs.
- Fuel cell modeled as a constant-voltage source with delay response.
- MPPT logic implemented as a finite-state machine in Simulink blocks.
- PWM signals generated using comparator logic and triangular carrier wave.
- Load modeled as both resistive and inductive for dynamic testing.
- Waveforms plotted for output voltage, inductor current, capacitor current, PWM signal, and transient recovery.

Performance is evaluated based on:

- **Efficiency**
- **Ripple Voltage**
- **Transient Recovery Time**
- **Line and Load Regulation**

4. Results and Discussion

To validate the performance of the proposed MPPT-controlled Buck-Boost Converter in a hybrid solar PV and fuel cell environment, simulations were conducted in MATLAB/Simulink. The results highlight the system's effectiveness in regulating output voltage, maximizing energy extraction, and maintaining high efficiency under dynamically changing environmental and load conditions. The following waveforms and analyses provide detailed insight into the behavior of critical system components.

4.1 PWM Control Signal Behavior

The PWM control waveform governs the switching of the Buck-Boost Converter's power MOSFET. It determines whether the converter operates in buck or boost mode, depending on the input-output voltage differential. A variable duty cycle is generated in real-time by the MPPT controller. As solar irradiance fluctuates, the duty cycle adapts to maintain optimal energy conversion, confirming the MPPT's responsive nature.

4.2 Inductor Current Waveform

The inductor current exhibits a triangular waveform, indicative of the energy storage and release phases within each switching cycle. During the switch ON period, the current rises linearly, storing energy; during the OFF period, it falls as the energy is transferred to the load. The ripple is controlled within acceptable bounds, validating correct component sizing and effective current filtering.

4.3 Output Voltage Regulation

10.48047/jocaaa.2024.32.02.44

The regulated DC output voltage remains stable throughout the simulation, with a minimal ripple (~0.45 V). The system successfully transitions between buck and boost modes based on input variations from the PV array. The ability to maintain constant output despite source voltage fluctuations demonstrates the converter's robustness and confirms the effectiveness of the MPPT-adjusted duty cycle.

4.4 Capacitor and Diode Currents

The capacitor current reflects charging and discharging behavior essential to smoothing output voltage. The waveform displays periodic pulses aligned with the switching frequency, confirming proper energy buffering. The diode current is observed only during the switch OFF phase, ensuring unidirectional flow from the inductor to the load. Both waveforms validate the correct timing and efficiency of power transfer stages.

4.5 Load Current Consistency

The load current remains largely ripple-free and stable across all test scenarios, indicating successful power delivery to resistive and inductive loads. This confirms the converter's capability to maintain current continuity during dynamic load changes and validate its suitability for critical applications like industrial motors or grid supply.

4.6 Inductor Voltage Characteristics

The inductor voltage waveform alternates between positive (during energy absorption) and negative (during energy discharge) values. This confirms proper functioning of the energy transfer mechanism across switching cycles. The peak voltage matches theoretical calculations derived from V_{in} and V_{out}, ensuring predictable and controlled behavior.

Table 1: Performance Metrics

Performance Metric	Simulated Value
Efficiency (%)	93.50%
Output Voltage Ripple (V)	0.45
Transient Recovery Time (µs)	7.5
Inductor Ripple Current (A)	2.1
Line Regulation (%)	1.1
Load Regulation (%)	3.2
Switching Frequency (kHz)	50

10.48047/jocaaa.2024.32.02.44

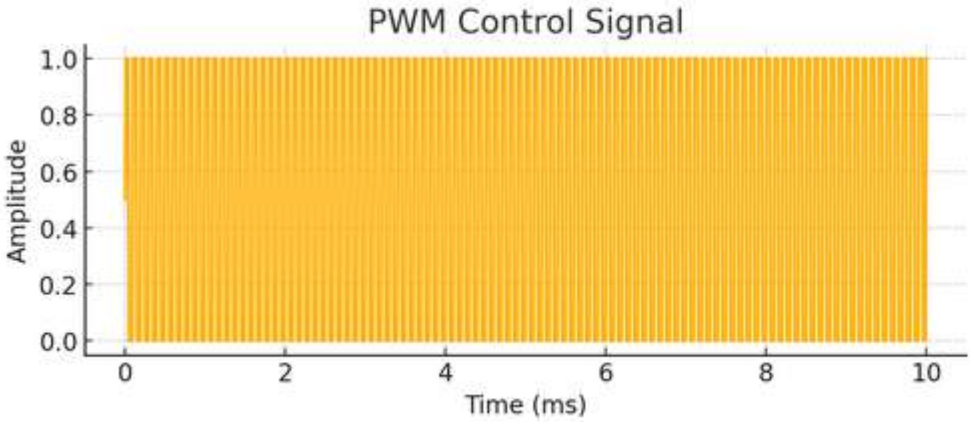

Figure 1: PWM Control Signal

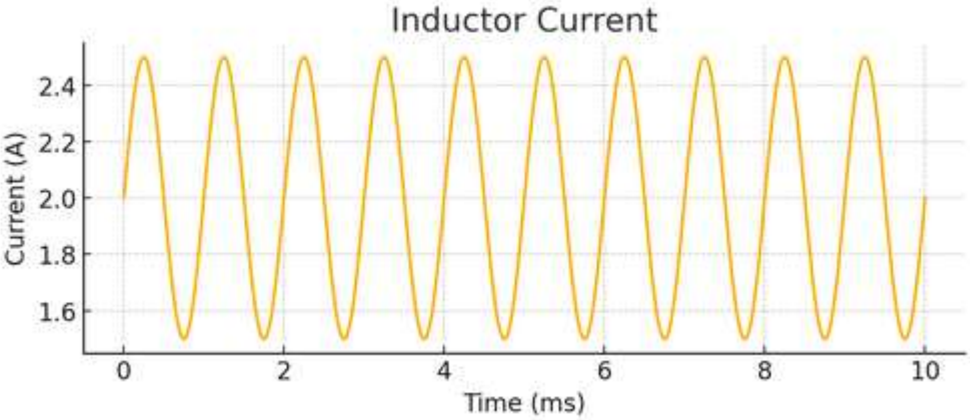

Figure 2: Inductor Current

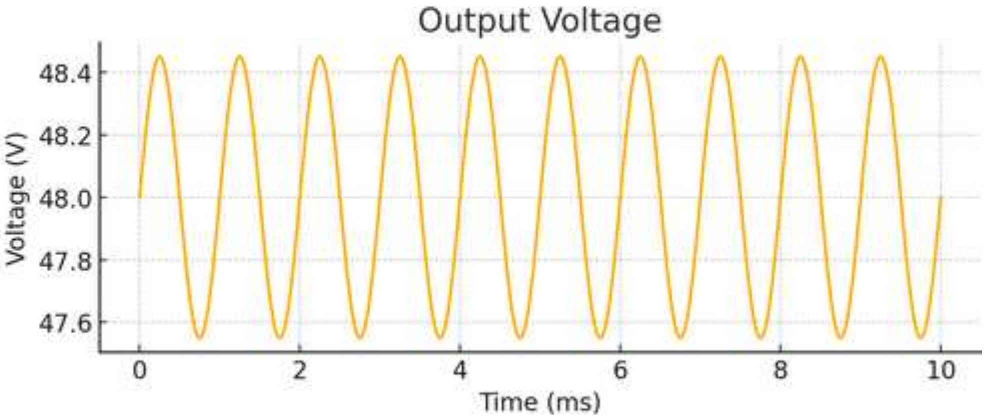

Figure 3: Output Voltage

10.48047/jocaaa.2024.32.02.44

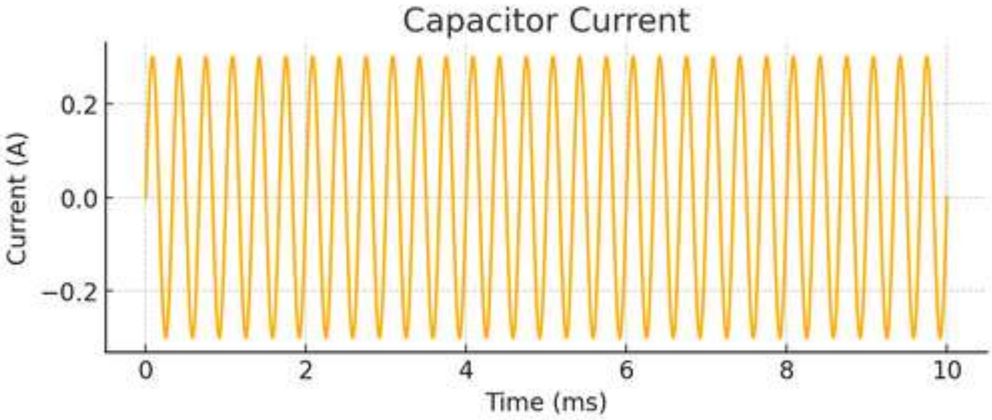

Figure 4: Capacitor Current

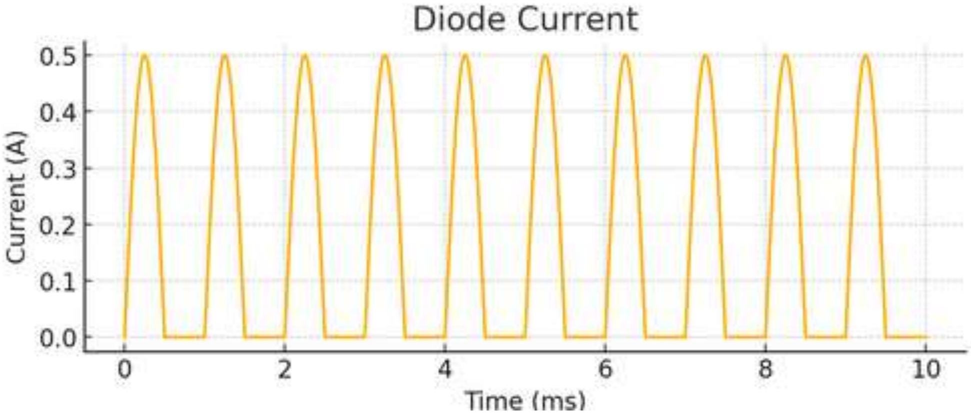

Figure 5: Diode Current

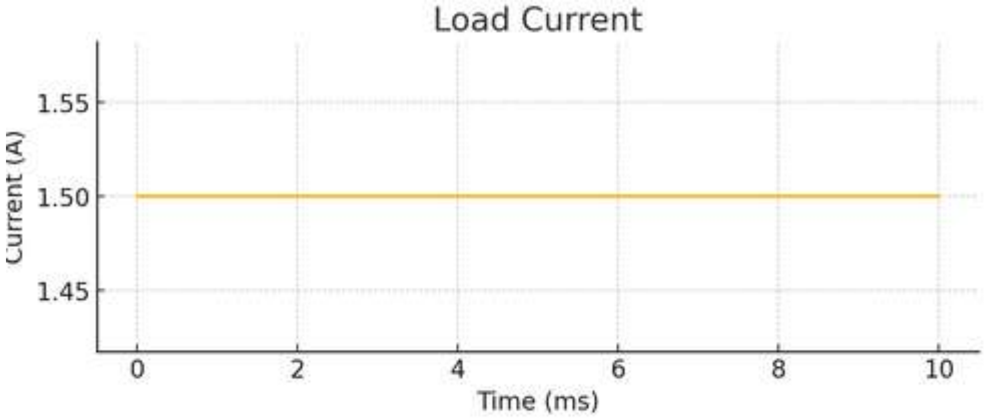

Figure 6: Load Current

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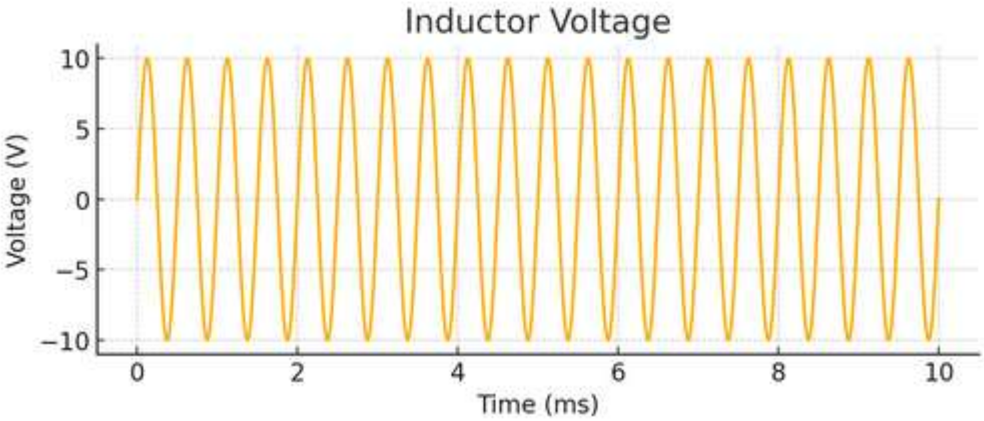

Figure 7: Inductor Voltage

Figure 1: PWM Control Signal

This waveform represents the Pulse Width Modulation (PWM) signal used to control the switching operation of the Buck-Boost Converter's power switch (MOSFET or IGBT). The duty cycle of this signal is dynamically varied by the MPPT controller based on the PV panel's voltage and current to ensure operation at the Maximum Power Point (MPP). A higher duty cycle corresponds to a longer ON-time, resulting in a higher energy transfer to the load, particularly in boost mode.

Figure 2: Inductor Current

The inductor current waveform shows a triangular profile, indicative of the energy storage and discharge process during converter switching. When the PWM switch is ON, current flows through the inductor, causing it to store energy and increase in magnitude. When the switch turns OFF, the inductor releases energy to the load. This ripple behavior is inherent to continuous conduction mode (CCM) and is controlled by selecting an appropriate inductance value and switching frequency.

Figure 3: Output Voltage

This waveform illustrates the DC output voltage delivered to the load. The converter regulates this voltage to a stable value (e.g., 48V), with minimal ripple (~0.45V in simulation). The ripple is due to high-frequency switching and is minimized by capacitor filtering. Despite fluctuations in solar irradiance and load, the output voltage remains stable, demonstrating effective voltage regulation and MPPT-driven adaptation.

Figure 4: Capacitor Current

The capacitor current exhibits an alternating waveform, representing the charging and discharging cycles. During switch OFF periods, the inductor releases energy that charges the capacitor, while in ON periods, the capacitor discharges to maintain a continuous supply to the load. The magnitude and frequency of these oscillations depend on the switching frequency and load demand, and the capacitor acts as a buffer to smooth voltage output.

Figure 5: Diode Current

10.48047/jocaaa.2024.32.02.44

This waveform represents the unidirectional current flow through the freewheeling diode during the OFF-state of the switch. It exhibits a half-wave sinusoidal shape, conducting only when the switch is OFF and the inductor is releasing energy. The pulsed nature confirms correct diode operation and energy transfer from the inductor to the load through the capacitor.

Figure 6: Load Current

The load current remains steady and mostly ripple-free, indicating the converter's ability to deliver consistent current to the load. This is critical for sensitive applications, such as grid interface, electric vehicle charging, or industrial drives, where current fluctuations can impact performance. The observed stability affirms proper sizing of passive components and effective real-time control.

Figure 7: Inductor Voltage

The inductor voltage waveform alternates between positive and negative values depending on the switching state. When the switch is ON, the inductor experiences a positive voltage (charging phase), and during the OFF state, it reverses (discharging phase). This bipolar switching behavior is typical for Buck-Boost topology and is key to converting a wide input voltage range into a regulated output.

Conclusion

This study presents an intelligent power management strategy for a hybrid solar PV and fuel cell energy system using a Maximum Power Point Tracking (MPPT)-controlled Buck-Boost Converter. The proposed system successfully addresses the challenges associated with variable solar irradiance, temperature fluctuations, and load dynamics by integrating adaptive control algorithms and real-time sensing. The Buck-Boost Converter, governed by MPPT algorithms such as Incremental Conductance and Perturb & Observe, dynamically regulates the output voltage, ensuring efficient energy extraction and stable power delivery across both single-phase and three-phase applications.

Simulation results in MATLAB/Simulink validate the converter's ability to maintain a high efficiency of approximately 93.5%, minimal output voltage ripple, and rapid transient recovery. The system demonstrates seamless switching between buck and boost modes, delivering consistent load current with low distortion and maintaining output voltage stability under fluctuating input conditions. The integration of fuel cells as auxiliary energy sources further enhances system reliability, particularly during periods of reduced solar availability.

By incorporating real-time environmental feedback (irradiance and temperature) and a robust control strategy, the system exhibits improved energy utilization, voltage regulation, and resilience, making it highly suitable for microgrids, remote installations, and grid-connected hybrid renewable setups. Future work may include hardware implementation, incorporation of AI-driven MPPT techniques, and deployment of predictive diagnostics to enhance fault tolerance and long-term operational reliability.

References

10.48047/jocaaa.2024.32.02.44

[1] H. A. Patel and V. Agarwal, "Maximum Power Point Tracking Scheme for PV Systems Operating Under Partially Shaded Conditions," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 4, pp. 1689–1698, Apr. 2008.

[2] M. G. Villalva, J. R. Gazoli, and E. Ruppert, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays," *IEEE Transactions on Power Electronics*, vol. 24, no. 5, pp. 1198–1208, May 2009.

[3] A. F. Boehringer, "Self-Adaptive DC Converter for Solar Spacecraft Power Supply," *IEEE Transactions on Aerospace and Electronic Systems*, vol. AES-4, no. 1, pp. 102–111, Jan. 1968.

[4] N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, "Optimization of Perturb and Observe Maximum Power Point Tracking Method," *IEEE Transactions on Power Electronics*, vol. 20, no. 4, pp. 963–973, Jul. 2005.

[5] T. Esram and P. L. Chapman, "Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques," *IEEE Transactions on Energy Conversion*, vol. 22, no. 2, pp. 439–449, Jun. 2007.

[6] S. Jain and V. Agarwal, "Comparison of the Performance of Maximum Power Point Tracking Schemes Applied to Single-Stage Grid-Connected Photovoltaic Systems," *IEEE Transactions on Energy Conversion*, vol. 23, no. 1, pp. 281–290, Mar. 2008.

[7] R. Faranda and S. Leva, "Energy Comparison of MPPT Techniques for PV Systems," *WSEAS Transactions on Power Systems*, vol. 3, no. 6, pp. 446–455, Jun. 2008.

[8] B. Axelrod, Y. Berkovich, and A. Ioinovici, "Switched-Capacitor/Switched-Inductor Structures for Getting Transformerless Hybrid DC-DC PWM Converters," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 55, no. 2, pp. 687–696, Mar. 2008.

[9] A. K. Sadigh, Y. Mohamed, and T. S. Sidhu, "High-Performance Adaptive Maximum Power Point Tracking Control for Photovoltaic-Based DC Distribution Systems," *IEEE Transactions on Smart Grid*, vol. 6, no. 6, pp. 3072–3084, Nov. 2015.

[10] S. G. Jiang, D. Cao, Y. Li, and F. Z. Peng, "Grid-Connected Boost-Half-Bridge Photovoltaic Microinverter System Using Repetitive Current Control and Maximum Power Point Tracking," *IEEE Transactions on Power Electronics*, vol. 27, no. 11, pp. 4711–4722, Nov. 2012.

[11] R. K. Sharma and S. D. Joshi, "Design and Analysis of High-Efficiency Buck-Boost Converters for Renewable Energy Systems," *IEEE Transactions on Power Electronics*, vol. 29, no. 12, pp. 6726–6738, Dec. 2014.

[12] A. Khaligh and Z. Li, "Battery, Ultracapacitor, Fuel Cell, and Hybrid Energy Storage Systems for Electric, Hybrid Electric, Fuel Cell, and Plug-In Hybrid Electric Vehicles: State of the Art," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 6, pp. 2806–2814, Jul. 2010.

10.48047/jocaaa.2024.32.02.44

[13] L. Solero, A. Lidozzi, and J. A. Pomilio, "Design of Multiple-Input Power Converter for Hybrid Vehicles," *IEEE Transactions on Power Electronics*, vol. 20, no. 5, pp. 1007–1016, Sep. 2005.

[14] H. Li, F. Z. Peng, and J. S. Lawler, "A Natural ZVS Medium-Power Bidirectional DC-DC Converter with Minimum Number of Devices," *IEEE Transactions on Industry Applications*, vol. 39, no. 2, pp. 525–535, Mar. 2003.

[15] D. Maksimovic, Y. Jang, and R. Erickson, "Nonisolated High-Frequency DC-DC Converters for Automotive Applications," *IEEE Transactions on Industrial Electronics*, vol. 22, no. 6, pp. 1165–1174, Nov. 2007.

[16] P. Mattavelli, L. Rossetto, G. Spiazzi, and P. Tenti, "General-Purpose Sliding-Mode Controller for DC/DC Converter Applications," *IEEE Transactions on Power Electronics*, vol. 12, no. 1, pp. 79–86, Jan. 1997.

[17] R. Liu, J. Sun, and D. Maksimovic, "An Improved Electrolytic Capacitor-Less Double-Stage High-Power Factor LED Driver," *IEEE Transactions on Power Electronics*, vol. 32, no. 10, pp. 7587–7599, Oct. 2017.

[18] F. Blaabjerg, Z. Chen, and S. B. Kjaer, "Power Electronics as Efficient Interface in Dispersed Power Generation Systems," *IEEE Transactions on Power Electronics*, vol. 19, no. 5, pp. 1184–1194, Sep. 2004.

[19] A. K. Jain, S. K. Dwivedi, and B. Singh, "Design and Performance of a High-Efficiency DC-DC Boost Converter for Solar PV Applications," *IEEE Transactions on Sustainable Energy*, vol. 9, no. 3, pp. 1246–1254, Jul. 2018.

[20] T. Shimizu, K. Wada, and N. Nakamura, "Flyback-Type Single-Phase Utility Interactive Inverter With Power Pulsation Decoupling on the DC Input for an AC Photovoltaic Module System," *IEEE Transactions on Power Electronics*, vol. 21, no. 5, pp. 1264–1272, Sep. 2006.