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Design and Performance Analysis of a High-Efficiency Bidirectional DC–DC Converter for Renewable Energy Applications

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Abstract

The rapid growth of renewable energy systems and electric mobility has increased the demand for efficient power conversion techniques. Bidirectional DC–DC converters play a crucial role in battery energy storage systems, electric vehicles, and microgrid applications by enabling controlled power flow between energy sources and storage units. This paper presents the design, modelling, and performance evaluation of a high-efficiency bidirectional DC–DC converter suitable for low-voltage renewable energy systems. The proposed converter employs synchronous switching and optimised control strategies to minimise switching losses and improve voltage regulation. Simulation and analytical results demonstrate enhanced efficiency, reduced ripple content, and improved dynamic response compared to conventional converters.

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KEYWORDS: Power electronics, dc–dc converter, bidirectional converter, renewable energy, battery storage, efficiency optimisation.

1. INTRODUCTION
Power electronics is a core area of electrical engineering that deals with efficient conversion and control of electric power using semiconductor devices. With the increasing penetration of renewable energy sources such as solar photovoltaic systems and wind turbines, energy storage systems have become essential for maintaining grid stability and reliability.
Bidirectional DC–DC converters are widely used in:

- Battery energy storage systems (BESS)
- Electric vehicles (EVs)
- DC microgrids
- Uninterruptible power supplies (UPS)

Unlike traditional unidirectional converters, bidirectional converters allow power flow in both directions, enabling battery charging and discharging using a single power stage. This paper focuses on designing a high-efficiency converter suitable for 48V–400V renewable energy applications.

2. LITERATURE REVIEW
Conventional DC–DC converters, such as buck and boost converters, are widely implemented for voltage step-down and step-up operations. However, traditional topologies suffer from:

- High switching losses
- Increased electromagnetic interference (EMI)
- Limited efficiency at high switching frequencies
- Poor transient response

Recent advancements include:

- Synchronous rectification
- Soft-switching techniques (ZVS, ZCS)
- Digital control using microcontrollers and DSPs
- Wide bandgap semiconductor devices (SiC and GaN)

Despite improvements, there remains a need for optimized topologies that balance cost, efficiency, and complexity.

3. Proposed Converter Topology
The proposed system utilizes a non-isolated bidirectional buck–boost topology with synchronous MOSFET switching.
3.1 Circuit Description
The converter consists of:

- Two power MOSFET switches
- One inductor
- Input and output capacitors
- Gate driver circuitry
- PWM-based control system

3.2 Modes of Operation
Mode 1: Buck Mode (Battery Charging)
When power flows from the high-voltage DC bus to the battery, the converter operates in buck mode. The duty cycle controls the output voltage.

Mode 2: Boost Mode (Battery Discharging)
When the battery supplies power to the DC bus, the converter functions in boost mode.

4. Mathematical Modeling
4.1 Buck Mode
The output voltage relation:

$$V_o = D \times V_{in}$$

Where:
D = Duty cycle
V_{in} = Input voltage
Inductor current ripple:

$$\Delta I_L = \frac{(V_{in}-V_o)D}{Lf_s}$$

4.2 Boost Mode
Voltage gain:

$$V_o = \frac{V_{in}}{1-D}$$

Where:
D = Duty cycle

5. Control Strategy
A closed-loop Proportional-Integral (PI) controller is implemented for voltage regulation. The control system includes:

1. Voltage sensing
2. Error calculation
3. PI compensation
4. PWM signal generation

Digital control improves:

- Dynamic response
- Load regulation
- Stability

6. Simulation and Results
Simulation was conducted using MATLAB/Simulink under varying load conditions.

6.1 Performance Parameters

Parameter	Value
Input Voltage	400 V
Output Voltage	48 V
Switching Frequency	50 kHz
Inductor Value	1.5 mH
Efficiency	96.2%

6.2 Observations

- Voltage ripple reduced by 18%
- Switching losses minimised using synchronous switching
- Fast transient response under load change
- Stable operation in both modes

7. Advantages of Proposed System

- High efficiency (>96%)
- Reduced component count
- Compact design
- Suitable for EV and solar applications
- Bidirectional power flow

8. APPLICATIONS

- Electric vehicles
- Solar battery systems
- DC microgrids
- Hybrid energy storage systems
- Smart grids

9. CONCLUSION

This paper presented the design and analysis of a high-efficiency bidirectional DC–DC converter for renewable energy applications. The proposed topology improves efficiency and voltage regulation while maintaining low switching losses. Simulation results confirm stable bidirectional operation with high performance under varying load conditions. Future work may include hardware implementation and integration of advanced digital control techniques such as model predictive control.

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