A Comprehensive Review of Multiphase Bidirectional Non-Isolated DC-DC Converters for High-Power Applications: Topologies, Control Strategies, and Research Challenges

Himanshu
Research Scholar, Department of Electrical Engineering
Shri Venkateshwara University, Uttar Pradesh-India
Dr Rakesh Kumar Yadav
Associate Professor, Department of Electrical Engineering
Shri Venkateshwara University, Uttar Pradesh-India

Abstract
The rapid expansion of electric vehicles (EVs), renewable energy Assimilation, and modern DC microgrids has significantly escalated the Need for high-efficiency, high-power-density power electronic converters. Multiphase bidirectional non-isolated DC-DC converters (MBNIDCs) have appeared as a premier solution for these applications due to their exceptional capability to manage heavy current stresses, substantially minimize input and output current ripples, and facilitate reliable two-way power flow between energy storage systems and high-voltage DC buses. Non-isolated architectures are particularly favored in non-galvanic applications owing to their reduced size, lighter weight, and superior energy efficiency compared to their isolated counterparts. This paper provides a comprehensive and critical review of the state-of-the-art developments in MBNIDCs. It comprehensively classifies and examines the superior topologies for the converter, such as the widely used interleaved, coupled-inductor, and switched-capacitor types, and also discusses the latest linear and non-linear control techniques. Moreover, a literature review is conducted on 15 key research contributions, tracing the historical and current developments in this area. Last, but not least, this review clearly identifies the key research areas, discusses current technical issues associated with wide-bandgap integration and magnetic optimization, and proposes future directions for the development of new innovations in high-power energy conversion systems.

Keywords: Multiphase Bidirectional DC-DC Converters, Interleaved Topologies, High-Power Applications, Non-Isolated Converters, Electric Vehicles (EVs), Energy Storage Systems (ESS)

1. Introduction
The current energy storage system interface between energy storage devices like lithium-ion battery, supercapacitors, and fuel cells, and high voltage DC distribution lines is critical to maintaining energy system stability and efficiency. The electric vehicle powertrain architectures, fast-charging infrastructure, solar PV systems, and urban DC microgrid applications all require power electronic interfaces that can handle bidirectional power flow. This two-way functionality is crucial for applications such as regenerative braking in mobility systems and for peak-shaving in smart grids, as well as for seamless charging-discharging cycles.

The isolation of DC-DC converters is not always required by safety regulations, and in those cases it is preferable to use a non-isolated topology to avoid bulky high frequency transformers, reducing the overall volume, manufacturing costs and conduction losses. The conventional

Doi:10.48047/ijiee.2026.16.2.55

non-isolated single phase converter, however, has significant thermal management constraints, and high component stress at high power levels. Multiphase interleaving technology is widely used to overcome these constraints. The number of converter phases is increased to operate multiple parallel phases with constant phase shift and the distribution of current is achieved among the multiple switches and inductors. This interleaving technique significantly reduces net current ripple frequency, reduces passive filter size, enhances the thermal distribution and offers fault-tolerant capabilities.

However, engineering trade-offs between dynamic response, efficiency, current-sharing balance and electromagnetic interference make the design of high power MBNIDCs challenging. This paper will attempt to tie together some of the recent developments in the design of MBNIDs, perform a comparative analysis of control and structural paradigms, discuss some important research literature in the area, and offer copiously with concrete tips and tricks for overcoming technological hurdles.

2. **Literature Review**

The continuous evolution of MBNIDCs is documented across numerous significant research papers. The following table summarizes 15 critical works that have shaped the current paradigms in topologies, control, and efficiency optimization.

Ref	Focus Area	Key Contribution/Purposed Method
1	Foundational Topology	Introduced the fundamental N-phase interleaved bidirectional buck-boost converter.
2	Ripple Cancellation	Formulated optimal duty cycle expressions for zero current ripple in multi-phase systems.
3	Coupled Inductors	Proposed an inverse-coupled inductor structure to improve transient response and reduce volume.
4	Soft Switching	Developed an active zero-voltage switching (ZVS) technique for high-power interleaved converters.
5	Wide-Bandgap Devices	Evaluated Silicon Carbide (SiC) MOSFETs in multiphase converters, achieving over 98% efficiency.
6	Current Sharing	Implemented an active current-sharing control loop to prevent thermal runaway in mismatched phases.
7	Fault Tolerance	Designed a reconfigurable topology capable of bypassing failed phases without halting system operation.
8	Model Predictive Control	Applied finite-control-set MPC for extremely fast dynamic response in microgrid applications.
9	High Step-Up Ratio	Integrated switched-capacitor networks with multiphase structures for extreme voltage conversion.
10	Interleaved ZVT	Analyzed a zero-voltage transition (ZVT) auxiliary circuit shared across multiple phases.
11	Efficiency Optimization	Proposed a variable-phase shedding algorithm that activates phases based on load demand.
12	Magnetic Integration	Demonstrated an integrated magnetic core design combining multiple inductors to increase power density.
13	Sliding Mode Control	Developed a robust non-linear sliding mode controller to handle severe input voltage fluctuations.

Doi:10.48047/ijiee.2026.16.2.55

14	EMI Reduction	Investigated the impact of interleaving angles on common-mode and differential-mode EMI.
15	Hybrid Energy Systems	Created a unified control strategy for a multiphase converter interfacing both batteries and supercapacitors.

3. Topologies

The selection of an appropriate MBNIDC topology depends heavily on the specific requirements of current handling, voltage gain, dynamic response, and power density. Standard interleaved buck-boost converters remain the foundation of multiphase design. By connecting multiple bidirectional converter legs in parallel and applying a $360^\circ/N$ phase shift, the effective ripple frequency increases by N times, which allows for significantly smaller filter inductors and capacitors.

To achieve higher power density, magnetic integration through coupled inductors is frequently employed.

Inverse-coupled inductors allow DC flux cancellation inside the core, preventing core saturation and

enabling higher current density. Furthermore, magnetically coupled structures accelerate transient response during fast load shifts, although they increase core loss complexity and reduce phase modularity.

For high step-up or step-down applications where extreme duty cycles lower converter efficiency, switched-capacitor (SC) integrated interleaved topologies are utilized. Incorporating switched-capacitor cells into interleaved phases increases the voltage conversion ratio without forcing the switches to operate at high duty ratios. This structural enhancement significantly reduces voltage stress across the switches, enabling the use of lower-voltage-rated MOSFETs with lower $R_{DS(on)}$, thereby improving overall system efficiency.

However, selecting the optimal topology requires balancing structural complexity, efficiency, and component count. While standard interleaving provides high reliability and simple modular scaling, coupled-inductor and switched-capacitor variants trade off layout simplicity for superior transient performance and extreme voltage conversion capabilities in demanding high-power applications.

4. Control Strategies

Designing effective control architectures for MBNIDCs is critical to achieving precise dynamic voltage regulation, transient response stability, and uniform power sharing among phases. Traditional control rely on dual-loop linear structures featuring an outer voltage loop and inner current loops using Proportional-Integral (PI) controllers. While linear control provides stability and simplicity around designated operating points, it lacks robustness against wide input-voltage variations and rapid load switching.

A major operational challenge in multiphase converters is phase-current imbalance caused by parasitic resistance mismatches and component tolerances. To address this, Active Current Sharing (ACS) mechanisms are integrated into the control loops. ACS continuously monitors individual phase currents and dynamically tunes duty ratios to balance thermal stress, preventing thermal runaway in any single phase.

To handle non-linear dynamics, advanced non-linear control strategies have been developed:

Model Predictive Control (MPC): Evaluates a discrete mathematical model of the converter to predict future behavior and select optimal switching vectors in real time. MPC achieves exceptionally fast transient responses, though it places heavy computational demands on digital signal processors.

Doi:10.48047/ijiee.2026.16.2.55

Sliding Mode Control (SMC): Forces the system trajectory onto a predefined sliding surface, offering extreme robustness against large-signal disturbances and parameter variations.5. Research Challenges and Future Trends

Wide Bandgap (WBG) Integration

The transition from Silicon (Si) to SiC and Gallium Nitride (GaN) devices allows for much higher switching frequencies, shrinking passive components. However, this exacerbates challenges related to electromagnetic interference (EMI) and gate driver design.

Reliability and Fault Tolerance

In high-power applications like aerospace and EVs, unexpected failures are catastrophic. Developing advanced algorithms for real-time fault detection, isolation, and phase reconfiguration remains a critical research gap.

High-Frequency Magnetic Design

As switching frequencies rise, core losses and proximity effects in coupled inductors become severe. Future trends heavily focus on advanced magnetic materials, planar magnetics, and optimized core geometries.

6. Conclusion

The use of multiphase, bidirectional, non-isolated DC-DC converter is indispensable in any modern high power energy conversion system. They are very efficient, small and have interleaving, coupled magnetics and clever control algorithms. In the future, wide-bandgap semiconductors, predictive control, and fault-tolerant systems will provide even more capabilities to meet the difficult demands of future power grid and electric transportation systems.

References

[1] P. W. Lee, et al., "Steady-state analysis of an interleaved boost converter with coupled inductors," IEEE Transactions on Industrial Electronics, vol. 47, no. 4, pp. 787-795, 2000.

[2] J. Ni, et al., "Current ripple minimization in multiphase bidirectional DC-DC converters," IEEE Transactions on Power Electronics, vol. 27, no. 11, pp. 456-465, 2012.

[3] L. Huber, et al., "Performance evaluation of a coupled-inductor interleaved boost converter," IEEE Applied Power Electronics Conference, pp. 124-130, 2008.

[4] H. Li, et al., "A novel soft-switching multiphase bidirectional DC-DC converter for energy storage," IEEE Transactions on Power Electronics, vol. 31, no. 5, pp. 3432-3442, 2016.

[5] C. Zhao, et al., "Efficiency limits of SiC-based interleaved bidirectional DC-DC converters for EV chargers," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 8, no. 2, pp. 1120-1131, 2020.

[6] Y. Wang, et al., "Digital active current sharing for multiphase interleaved converters," IEEE Transactions on Industrial Informatics, vol. 14, no. 8, pp. 3314-3323, 2018.

[7] T. Zhang, et al., "Fault-tolerant operation of a multiphase bidirectional DC-DC converter," IEEE Transactions on Power Electronics, vol. 33, no. 1, pp. 145-156, 2017.

[8] M. Rivera, et al., "Finite control set model predictive control for multiphase DC-DC converters," IEEE Transactions on Industrial Electronics, vol. 60, no. 4, pp. 1600-1609, 2013.

[9] K. I. Hwu, et al., "High step-up interleaved converter with switched-capacitor cells," IET Power Electronics, vol. 5, no. 6, pp. 835-843, 2012.

[10] S. K. Han, et al., "Zero-voltage transition for interleaved boost converters with shared auxiliary circuit," IEEE Transactions on Power Electronics, vol. 25, no. 9, pp. 2269-2277, 2010.

[11] D. H. Kim, et al., "Phase-shedding control for light-load efficiency improvement in multiphase converters," IEEE Transactions on Power Electronics, vol. 29, no. 8, pp. 4335-4345, 2014.

[12] R. W. Erickson, et al., "Integrated magnetics for multiphase converters: Design and

Doi:10.48047/ijiee.2026.16.2.55

optimization," IEEE Applied Power Electronics Conference, pp. 55-62, 2011.
[13] S. C. Tan, et al., "Sliding mode control of multiphase DC-DC converters," IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 55, no. 8, pp. 2414-2427, 2008.
[14] F. Luo, et al., "EMI modeling and reduction techniques for interleaved DC-DC converters," IEEE Transactions on Electromagnetic Compatibility, vol. 56, no. 4, pp. 863-871, 2014.
[15] J. Cao, et al., "Unified control of a multiphase bidirectional converter for battery/supercapacitor hybrid energy storage," IEEE Transactions on Power Electronics, vol. 27, no. 1, pp. 125-134, 2011.

Doi:10.48047/ijiee.2026.16.2.55