Modular Multi-Port Converters for Hybrid Electric Vehicles (HEVs)

Rahul S. Yadav[1], Anika Ghosh[1], Vikram P. Sharma[2]
Associate Professor, Assistant Professor
Department of Power Electronics
Sarojini Naidu Technical College, India
Email ID: *- Rahulyadav3s@yahoo.com, anikaghosh29@gmail.com, sharmavikrampr@rediffmail.com*

ABSTRACT

This paper reviews the recent advancements in ***modular multi-port power converters*** *focusing specifically on their application in* ***Hybrid Electric Vehicles (HEVs)****. As HEVs increasingly integrate multiple energy sources such as batteries, ultra-capacitors, fuel cells, and renewable inputs, the role of multi-port converters becomes pivotal for efficient energy distribution and bidirectional power flow. This review discusses the* ***architecture, topologies, design challenges, control strategies, and performance metrics*** *of modular multi-port converters used in HEVs. Both isolated and non-isolated converter designs, as well as bidirectional and scalable modular architectures, are examined. The study highlights how these converters can enable simultaneous integration of multiple sources with improved power density, reliability and efficiency while reducing overall system complexity. Finally, future research directions and unresolved challenges are identified to support further advancements in this essential field of transportation electrification.*

KEYWORDS: *- Hybrid Electric Vehicles, Multi-Port Converter, Modular Architecture, DC-DC Converter, Bidirectional Power Flow, Energy Management, Power Electronics*

Page 192-206 © MANTECH PUBLICATIONS 2019. All Rights Reserved

INTRODUCTION

Hybrid Electric Vehicles (HEVs) are an essential technology in the transition toward **sustainable transportation**. They combine energy from multiple sources — traditionally internal combustion engines with electrical storage — to achieve **higher fuel efficiency and lower emissions** compared to conventional vehicles. However, managing these diverse energy sources within a compact and efficient framework poses significant challenges. A key enabling technology is the **multi-port power converter** — a converter that can interface multiple energy sources with the vehicle's power bus, motor drives, and storage systems simultaneously.

Traditional single-input converters are often insufficient for HEVs because they require separate converter units for each source, leading to **increased cost, size, complexity, and reduced reliability**. In contrast, **modular multi-port converters** provide a more integrated solution where power flow is regulated between multiple ports in a controlled, efficient, and scalable manner.

BACKGROUND AND MOTIVATION

1. Hybrid Electric Vehicles and Power Needs

Hybrid Electric Vehicles (HEVs) are designed to improve fuel efficiency, reduce emissions, and enhance driving performance by combining electrical energy sources with conventional propulsion systems. Modern HEVs typically employ a combination of **electrochemical batteries**, **ultra-capacitors**, and in some advanced architectures, **fuel cells**, each serving a distinct role within the vehicle's energy ecosystem. Batteries provide high energy density and support sustained driving, ultra-capacitors offer high power density for transient demands such as acceleration and regenerative braking, while fuel cells can extend driving range through continuous energy generation.

These energy sources inherently operate at **different voltage levels** and exhibit **diverse dynamic behaviors**. For instance, batteries respond relatively slowly to sudden load changes but store large amounts of energy, whereas ultra-capacitors can respond rapidly but store energy for shorter durations. Fuel cells, on the other hand, require controlled operating conditions to ensure efficiency and longevity. Coordinating power flow among these heterogeneous sources therefore poses significant challenges for the vehicle's power electronic interface.

Page 192-206 © MANTECH PUBLICATIONS 2019. All Rights Reserved

Efficient energy utilization in HEVs demands **advanced power conversion schemes** capable of:

- Supplying **variable voltage and current** to electric traction motors under different driving conditions,
- Enabling **bidirectional power flow**, particularly for regenerative braking where kinetic energy is converted back into electrical energy,
- Allowing **simultaneous utilization of multiple energy sources** to optimize efficiency, performance, and component lifetime,
- Maintaining **high conversion efficiency** over wide operating ranges, including partial-load and transient conditions.

Traditional DC–DC converters are generally designed for **single-input single-output (SISO)** applications. While they are effective in conventional systems, they lack the structural and functional flexibility needed to manage multiple energy sources and loads simultaneously. Using multiple independent converters increases system complexity, component count, size, weight, and control overhead, which is undesirable in automotive applications where space, cost, and reliability are critical constraints.

As HEV architectures continue to evolve toward higher levels of electrification and energy integration, there is a growing need for **compact, flexible, and intelligent power conversion solutions**. This requirement has driven research interest toward multi-port power converters, which can unify power management functions into a single, coordinated conversion stage.

2. What Are Multi-Port Converters?

A **multi-port converter (MPC)** is an advanced power electronic interface that connects **more than two electrical ports**, enabling multiple energy sources and/or loads to exchange power through a single converter topology. Unlike conventional converters that handle only one source and one load, multi-port converters facilitate **direct and controlled energy transfer** among batteries, ultra-capacitors, fuel cells, and motor drives.

Each port in a multi-port converter can be configured as an **input, output, or bidirectional interface**, depending on system requirements. This flexibility allows ports to operate

Page 192-206 © MANTECH PUBLICATIONS 2019. All Rights Reserved

independently or cooperatively, making it possible to support complex power flow scenarios such as simultaneous vehicle propulsion and battery charging, or regenerative braking combined with ultra-capacitor energy storage.

Multi-port converters can be broadly classified into:

- **Non-isolated multi-port converters**, which share a common ground reference and are typically more compact and efficient, making them suitable for low- to medium-voltage HEV applications.
- **Isolated multi-port converters**, which incorporate high-frequency transformers to provide galvanic isolation, enhanced safety, and voltage matching across widely different voltage levels.

By integrating multiple conversion functions into a single structure, multi-port converters reduce the number of power stages, minimize passive components, and simplify overall system architecture. This leads to **improved power density, reduced losses, and enhanced reliability**. Moreover, centralized control of multiple ports enables optimal energy management strategies, such as prioritizing high-efficiency sources or minimizing battery stress.

In the context of HEVs, multi-port converters are increasingly viewed as a **key enabling technology** for next-generation energy management systems. Their ability to seamlessly coordinate multiple energy sources aligns well with the growing demand for high efficiency, compactness, and intelligent power flow control in electrified transportation.

MODULAR MULTI-PORT CONVERTER ARCHITECTURES

1. Modular Architecture Explained

Modular architecture in multi-port power converters represents a systematic design approach in which the overall power conversion system is realized through the interconnection of multiple **smaller, functionally identical or partially identical sub-modules**, rather than relying on a single centralized and monolithic converter stage. Each sub-module typically integrates its own power semiconductor switches, gate drivers, passive filtering elements, sensing units, and local

Page 192-206 © MANTECH PUBLICATIONS 2019. All Rights Reserved

control logic. These modules are electrically and logically coordinated to function as a unified multi-port converter capable of managing complex power flow requirements.

In Hybrid Electric Vehicles (HEVs), this modular approach aligns well with the **highly dynamic and unpredictable operating conditions** inherent to automotive applications. Vehicle power demand varies significantly during different driving modes, such as rapid acceleration, steady cruising, regenerative braking, hill climbing, and auxiliary load operation. Modular architectures enable power demand to be dynamically shared among multiple sub-modules, ensuring that no single module is excessively stressed while maintaining high efficiency across both transient and steady-state conditions.

A defining advantage of modular multi-port converters is their **inherent scalability**. As HEV platforms evolve toward higher power ratings or incorporate additional energy storage devices—such as supplementary battery packs or ultra-capacitors—the converter system can be scaled by simply adding or removing converter modules. This eliminates the need for complete redesign when transitioning between different hybrid configurations, including mild hybrids, full hybrids, and plug-in hybrid electric vehicles (PHEVs). Scalability also supports platform-based vehicle development, where a common converter architecture can be reused across multiple vehicle variants with minimal modification.

Reliability and fault tolerance are significantly improved in modular architectures compared to centralized designs. In conventional single-stage converters, the failure of a critical power device can result in total system shutdown. In contrast, modular multi-port converters allow faulty sub-modules to be isolated, bypassed, or derated, enabling continued operation at reduced power levels. This capability is especially valuable in HEVs, where maintaining partial functionality can enhance vehicle safety and prevent sudden loss of propulsion.

Another major benefit is **standardization and design reuse**. Standardized converter modules can be developed, validated, and manufactured in large volumes, reducing development cost, testing time, and production complexity. These reusable building blocks simplify system integration and maintenance while ensuring consistent electrical performance across different vehicle models.

Page 192-206 © MANTECH PUBLICATIONS 2019. All Rights Reserved

Additionally, standardized modules make it easier to interface with diverse energy sources, such as batteries, ultra-capacitors, and fuel cells, without extensive hardware redesign.

From a power handling perspective, modular architectures enable **high total power capability** by paralleling or stacking multiple lower-rated modules. This distributed power processing approach enhances thermal performance by spreading heat generation across several modules rather than concentrating it in a single location. Improved thermal distribution simplifies cooling system design, reduces peak junction temperatures, and ultimately extends the operational lifetime of power electronic components.

Furthermore, modular multi-port converters provide **enhanced flexibility in control and energy management**. Advanced supervisory control algorithms can selectively activate or deactivate individual modules based on real-time load demand, state of charge, and thermal conditions. During light-load operation, unnecessary modules can be turned off to minimize switching losses, while during peak power events, multiple modules can operate simultaneously to meet high power demands. This adaptive operation contributes to improved efficiency, reduced losses, and optimized utilization of energy storage elements.

In summary, modular multi-port converter architectures offer a **robust, scalable, and efficient solution** for modern HEV power systems. Their ability to adapt to varying power requirements, tolerate faults, simplify thermal management, and integrate multiple energy sources makes them a strong candidate for next-generation automotive power electronic interfaces.

TOPOLOGIES OF MULTI-PORT CONVERTERS FOR HEVS

A wide range of **multi-port converter topologies** has been proposed in the literature to meet the diverse power management requirements of Hybrid Electric Vehicles (HEVs). These topologies are designed to efficiently integrate multiple energy sources and loads while minimizing system size, weight, and losses. The selection of a suitable topology depends on factors such as voltage levels, power rating, isolation requirements, efficiency targets, and system cost. Among the most commonly studied configurations are bidirectional multi-port DC–DC converters, tri-port converters, and isolated or non-isolated architectures.

Page 192-206 © MANTECH PUBLICATIONS 2019. All Rights Reserved

1. Bidirectional Multi-Port DC–DC Converters

Bidirectional multi-port DC–DC converters play a critical role in HEVs by enabling **two-way power flow** between energy sources and the vehicle's DC bus. This capability is essential for functions such as regenerative braking, where kinetic energy recovered from the motor is converted back into electrical energy and stored in batteries or ultra-capacitors.

These converters typically integrate **buck and boost operating modes** within a single conversion stage, allowing the system to accommodate varying voltage levels among different energy sources. For example, the converter may operate in boost mode when supplying power from a low-voltage battery to a high-voltage DC link, and in buck mode during battery charging or regenerative energy recovery.

Advanced bidirectional multi-port converters are capable of interfacing **multiple energy storage elements**, such as batteries, ultra-capacitors, and fuel cells, to a common DC bus. In such systems, ultra-capacitors can handle high peak power demands during acceleration and absorb sudden regenerative braking energy, while batteries provide sustained energy over longer driving periods. Fuel cells, when present, can supply steady power and improve overall energy efficiency.

By consolidating multiple power conversion functions into a single bidirectional multi-port converter, the need for separate converters is eliminated. This results in **reduced component count, lower power losses, and simplified control architecture**, all of which are highly desirable for automotive applications. However, the control of bidirectional multi-port converters is more complex, requiring coordinated current and voltage regulation to ensure stable and efficient power sharing among ports.

2. Tri-Port Converters

Tri-port converters represent a widely studied and practical subclass of multi-port converters for HEVs. As the name suggests, these converters interface **three electrical ports**, commonly connecting a primary energy source (such as a battery), a secondary source (such as an ultra-capacitor or generator), and a load or DC link feeding the motor drive or auxiliary systems.

Page 192-206 © MANTECH PUBLICATIONS 2019. All Rights Reserved

The key advantage of tri-port converters lies in their ability to **dynamically manage power flow among three nodes** without relying on multiple independent converter stages. This integrated structure significantly reduces system weight, volume, and cost—critical considerations in automotive design. Furthermore, tri-port converters enable direct energy exchange between sources, such as transferring regenerative braking energy from the motor directly to an ultra-capacitor without intermediate processing stages.

Tri-port topologies are particularly effective in scenarios where **simultaneous charging and discharging operations** are required. For instance, during regenerative braking, energy can be directed to both the battery and ultra-capacitor based on their state of charge and power handling capabilities. During acceleration, the battery and ultra-capacitor can jointly supply the motor, improving vehicle performance and reducing stress on individual components.

Despite their advantages, tri-port converters introduce **increased control complexity**, as multiple power paths must be regulated simultaneously. Careful design of control algorithms is required to prevent unwanted circulating currents and ensure stable operation under rapidly changing load conditions.

3. Non-Isolated vs. Isolated Configurations

Multi-port converter topologies for HEVs can be broadly classified into **non-isolated** and **isolated** configurations, depending on whether galvanic isolation is provided between ports.

Non-isolated multi-port converters share a common electrical ground among all ports. These converters are typically characterized by:

- High power density due to fewer components,
- Lower cost and simpler structure,
- Higher efficiency resulting from the absence of transformer losses.

Because of these advantages, non-isolated configurations are often preferred in low- to medium-voltage HEV systems where safety regulations permit a shared ground reference. However, the lack of galvanic isolation limits their application in systems requiring strict electrical separation between energy sources and loads.

Page 192-206 © MANTECH PUBLICATIONS 2019. All Rights Reserved

In contrast, **isolated multi-port converters** employ high-frequency transformers to provide electrical isolation between ports. This isolation enhances system safety, reduces electromagnetic interference, and allows **flexible voltage matching** across widely different port voltage levels. Isolated configurations are especially useful in HEVs that integrate high-voltage DC buses with low-voltage auxiliary systems or fuel cell stacks.

The primary trade-offs associated with isolated converters include increased circuit complexity, higher cost, and additional losses due to transformer and magnetic components. Nevertheless, ongoing advancements in high-frequency magnetics and wide bandgap semiconductor devices are helping mitigate these drawbacks, making isolated multi-port converters increasingly viable for advanced HEV architectures.

MODULAR MULTI-PORT CONVERTERS IN HEV CONTEXT

1. Power Flow Management

One of the most critical challenges in Hybrid Electric Vehicles (HEVs) is the **effective management of power flow** among multiple energy sources, energy storage devices, and the vehicle load. HEVs typically combine batteries, ultra-capacitors, and in some configurations fuel cells or generators, each possessing distinct voltage levels, power densities, and dynamic characteristics. Coordinating energy exchange among these elements in an efficient and reliable manner is essential for achieving optimal vehicle performance and energy utilization.

Modular multi-port converters address this challenge by providing **multiple controlled power paths through a centralized DC bus**, enabling flexible and intelligent energy routing. Through appropriate control, power can be dynamically shared between the battery and ultra-capacitor based on instantaneous vehicle demand. During high power events such as acceleration, ultra-capacitors can supply rapid bursts of energy, thereby reducing peak current stress on the battery and improving its lifetime. Conversely, during steady cruising, the battery can provide sustained energy at higher efficiency.

A major advantage of multi-port converters is their ability to efficiently handle **regenerative braking energy**. During braking, electrical energy generated by the motor can be routed directly

Page 192-206 © MANTECH PUBLICATIONS 2019. All Rights Reserved

to the most suitable storage element. For example, ultra-capacitors can absorb high-power, short-duration energy spikes, while batteries can store energy over longer time scales. This selective energy routing minimizes losses and maximizes energy recovery efficiency.

Furthermore, modular multi-port converters enhance **system robustness and reliability** by enabling alternative energy paths. In the event of partial failure or degradation of a primary energy source, the converter can redirect power flow to secondary sources without interrupting vehicle operation. This capability is particularly valuable in safety-critical automotive applications, where uninterrupted power delivery is essential.

Overall, modular multi-port converters enable **centralized yet flexible power flow management**, allowing HEVs to adapt to varying driving conditions while optimizing efficiency, energy recovery, and component utilization.

2. Control Strategies

Efficient power flow management in modular multi-port converters relies heavily on the implementation of **advanced control strategies** capable of regulating voltage, current, and power across multiple ports simultaneously. As the number of ports increases, control complexity grows significantly, requiring coordinated and hierarchical control approaches.

Conventional **Pulse Width Modulation (PWM)** techniques are widely used to regulate individual converter ports by adjusting duty cycles to control voltage and current levels. In modular multi-port architectures, PWM-based control is often combined with inner current loops and outer voltage loops to ensure stable and precise power sharing among modules.

For isolated multi-port converters, **phase-shift modulation** is commonly employed, particularly in transformer-based topologies. By varying the phase shift between switching signals of different ports, power flow can be smoothly controlled without significantly altering switching frequency. This approach enables soft-switching operation, reducing switching losses and improving overall efficiency.

Page 192-206 © MANTECH PUBLICATIONS 2019. All Rights Reserved

Adaptive duty cycle control and real-time power balancing strategies further enhance system performance by dynamically adjusting converter operation based on load demand, state of charge, thermal conditions, and driving mode. These adaptive methods are particularly effective in modular systems, where individual sub-modules can be activated, deactivated, or derated to optimize efficiency under partial-load conditions.

To manage the increased complexity, modular multi-port converters often employ **hierarchical control structures**, consisting of a supervisory energy management layer and lower-level converter control loops. The supervisory controller determines power distribution priorities based on vehicle operating conditions, while local controllers execute fast switching and current regulation tasks. This layered approach ensures both fast dynamic response and long-term energy optimization.

In summary, the combination of modular hardware and sophisticated control strategies enables multi-port converters to deliver **high efficiency, fast dynamic response, and robust operation** in HEV applications. Continued advancements in digital control platforms and real-time optimization algorithms are expected to further enhance the effectiveness of modular multi-port converter systems.

PERFORMANCE METRICS AND COMPARISONS

1. Efficiency

Multi-port converters generally have high efficiency because they reduce the number of overall conversion stages. However, converter efficiency can vary with load conditions, control strategy, and topology.

2. Power Density

Modular designs achieve higher power density because smaller modules can be distributed to spread heat and minimize losses. However, modular systems sometimes incur additional losses at interconnection points compared with monolithic converters.

3. Scalability

Modular multi-port converters offer unmatched scalability. Adding another source or load port usually only requires adding another module, without redesigning the whole converter.

Page 192-206 © MANTECH PUBLICATIONS 2019. All Rights Reserved

CHALLENGES IN HEV MULTI-PORT CONVERTERS

Despite their advantages, several challenges remain:

1. Control Complexity

Controlling multiple ports in real-time with widely varying load conditions is a significant challenge requiring complex algorithms, rapid switching, and robust fault handling.

2. Cost and Reliability

While modular systems can reduce long-term maintenance costs, the initial cost may be higher due to more components and additional control hardware.

3. Thermal Management

More components in modular systems mean thermal management becomes critical, necessitating effective heat sinking and cooling strategies.

CASE STUDIES AND EXAMPLES

1. Bidirectional Converter in HEV and FCV

An integrated multi-port bidirectional DC-DC converter has been shown to interface batteries, ultra-capacitors, and fuel cells with the DC link of HEV and Fuel Cell Vehicle (FCV) systems. Its bidirectional capability enables efficient energy transfer across all ports, improving drivability and system efficiency.

2. Enhanced Multi-Port DC-DC Converter Prototype

Recent work has proposed a multi-port topology capable of delivering several output voltages simultaneously without constraint on duty cycles, overcoming cross-regulation problems observed in many multi-output converters. Prototype test results validate the feasibility of this approach.

Comparative Table: Selected Multi-Port Architectures

Topology	Number of Ports	Isolation	Bidirectional	Notes
Integrated Bidirectional DC-DC	3+	No	Yes	Interfaces multiple sources to DC link

Page 192-206 © MANTECH PUBLICATIONS 2019. All Rights Reserved

Topology	Number of Ports	Isolation	Bidirectional	Notes
Tri-Port Converter	3	Varied	Partial	Energy sharing between three nodes
Enhanced Multi-Output DC-DC	3	No	Variable	Overcomes cross-regulation issues

FUTURE DIRECTIONS

Future research in modular multi-port converters for HEVs should concentrate on:

- **Advanced Control Algorithms:** More efficient software to dynamically balance energy flows.
- **Wide Bandgap Semiconductors:** Using GaN or SiC devices for higher operating frequencies and reduced losses.
- **Integration with Grid:** Vehicle-to-Grid (V2G) support for greater flexibility.
- **AI-Based Energy Management:** Smart prediction of load and source availability to optimize power routing.

CONCLUSION

Modular multi-port converters present an essential technology for **next-generation hybrid electric vehicles**. They offer **flexible, efficient, and scalable energy management** solutions that overcome many limitations of traditional converters. By supporting multiple energy sources, bidirectional power flow, and modular scalability, these converters significantly improve vehicle performance and system reliability. Despite challenges in control complexity, cost, and thermal management, ongoing research promises continued refinements, positioning modularmulti-port converters as a core component of future smart and sustainable HEVs.

REFERENCES

1. Levon Gevorkov, José Luis Domínguez-García, Lluis Trilla Romero, & Àlber Filbà Martínez, **"Modern MultiPort Converter Technologies: A Systematic Review,"** *Applied Sciences*, vol. 13, no. 4, 2023, doi:10.3390/app13042579. This article reviews

Page 192-206 © MANTECH PUBLICATIONS 2019. All Rights Reserved

multi-port converter technologies and highlights modular architectures that can interface renewable sources and EV applications.

2. **A Review of Multiple Input DC-DC Converter Topologies Linked with Hybrid Electric Vehicles and Renewable Energy Systems,** *Renewable and Sustainable Energy Reviews*, vol. 135, Jan. 2021. This review analyzes multi-input DC-DC converter topologies that serve HEV power systems.
3. Mahesh, B. Chokkalingam, C. Santhakumar, et al., **"A Multiport DC-to-DC Converter-Driven Inductive Wireless Charging System for EVs with Integrated Photovoltaic and Energy Storage Systems,"** *Scientific Reports*, vol. 15, article 23772, 2025. This paper demonstrates a multiport DC-DC converter application within EV and charging scenarios.
4. **"Analysis and Implementation of Multi-Port Bidirectional Converter for Hybrid Energy Systems,"** *Energy Reports*, vol. 8, Nov. 2022. This research presents a bidirectional converter that supports multiple energy ports — key for HEV hybrid systems.
5. **"Modeling and Control of a New Multi-Port Converter for Hybrid Energy System Integration,"** *Journal of Energy Storage*, vol. 96, Aug. 2024. Introduces a quasi-Z-source isolated multi-port converter topology combining efficiency with reduced component count.
6. Bang Le-Huy Nguyen, Honnyong Cha, Tuyen Vu, & Thai-Thanh Nguyen, **"Integrated Multiport Bidirectional DC-DC Converter for HEV/FCV Applications,"** *arXiv preprint*, 2022. Proposes an extendable multi-port bidirectional converter to interface batteries, ultra-capacitors, and fuel cells in hybrid vehicles.
7. **Krishna P. Yalamanchili & Mehdi Ferdowsi, "Review of Multiple Input DC-DC Converters for Electric and Hybrid Vehicles,"** *Proc. IEEE Vehicle Power and Propulsion Conference*, 2005. A foundational review on multi-input DC-DC converters for EV and HEV applications.
8. **"Design and Analysis of a High Energy Efficient Multi-Port DC-DC Converter Interface for Fuel Cell/Battery Electric Vehicle-to-Home (V2H) System,"** *Journal of Energy Storage*, vol. 45, Jan. 2022. Discusses multi-port interfaces in V2H systems relevant to bidirectional HEV converter design.

Page 192-206 © MANTECH PUBLICATIONS 2019. All Rights Reserved

9. H. Tao & J. L. Duarte, **"Multi-Port Converters for Hybrid Power Sources,"** in *IEEE Power Electronics Specialists Conference (PESC)*, 2008. A widely cited early contribution on multi-port converter design for hybrid systems.
10. Matthew McDonough & Pourya Shamsi, **"Multi-Port Power Electronic Interface — Concept, Modeling, and Design,"** *IEEE Transactions on Power Electronics.* This work presents a core model for multi-port power electronics interfaces relevant for HEVs and renewable integration.

Page 192-206 © MANTECH PUBLICATIONS 2019. All Rights Reserved