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Evaluation of Bidirectional DC-DC Converter Topologies for Enhanced Power Management

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ABSTRACT

Electric hybrid vehicles (EHVs) are revolutionizing environmentally friendly transportation by enhancing energy efficiency and reducing emissions. Central to this advancement is the utilization of cutting-edge power electronics technology to optimize power distribution and energy conversion. This study evaluates various multiport bidirectional DC-DC converter topologies for EHVs, focusing on key performance metrics such as efficiency, voltage ripple, transient response, thermal performance, and reliability under different driving conditions. Simulations and practical experiments reveal that the Magnetically Coupled Topology with One Current-fed Input offers superior performance. Despite challenges in complexity and cost, these innovations highlight the potential of advanced power electronics to improve EHV effectiveness and durability in today's dynamic transportation market.

Keywords: Electric hybrid vehicles, power electronics, energy conversion.

1. INTRODUCTION

The development of electric hybrid vehicles (EHVs) represents a major advancement in environmentally friendly transportation. By combining the advantages of internal combustion engines (ICEs) and electric propulsion systems, EHVs achieve superior efficiency, reduced emissions, and enhanced performance compared to conventional vehicles. The integration of modern power electronics is crucial for EHVs in managing power distribution and optimizing energy conversion processes[1-2].

The power electronics integration in EHVs includes essential components such as inverters, converters, and energy storage devices like batteries and ultracapacitors. These components work together to control the flow of electrical power from the vehicle's generators to its wheels. The use of advanced power electronics, capable of efficiently converting and controlling electrical power, enhances vehicle performance, driving range, and overall reliability.

Recent advancements in control algorithms, thermal management strategies, and semiconductor materials have significantly improved the capabilities of high-voltage power electronics in EHVs. These technologies have led to better thermal management, increased efficiency, and higher power densities by addressing key challenges such as heat dissipation and energy losses during power conversion[3-4].

Moreover, integrating modern power electronics into EHVs has a profound impact on the automotive industry and broader efforts to reduce environmental footprints. EHVs

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equipped with cutting-edge power electronics are well-positioned to meet the growing demand for eco-friendly transportation options and stricter emissions regulations globally[5-8].

In this paper, we present an evaluation of power electronics interface configurations for EHVs, focusing on bidirectional DC-DC converter interfaces for energy storage. We compare various multiport bidirectional DC-DC converter topologies, assessing their performance under different driving conditions in EHVs. The comparative analysis includes efficiency, output voltage ripple, transient response, thermal performance, power density, reliability, electromagnetic interference, component stress, and cost, providing insights into the most effective topologies for future EHV applications.

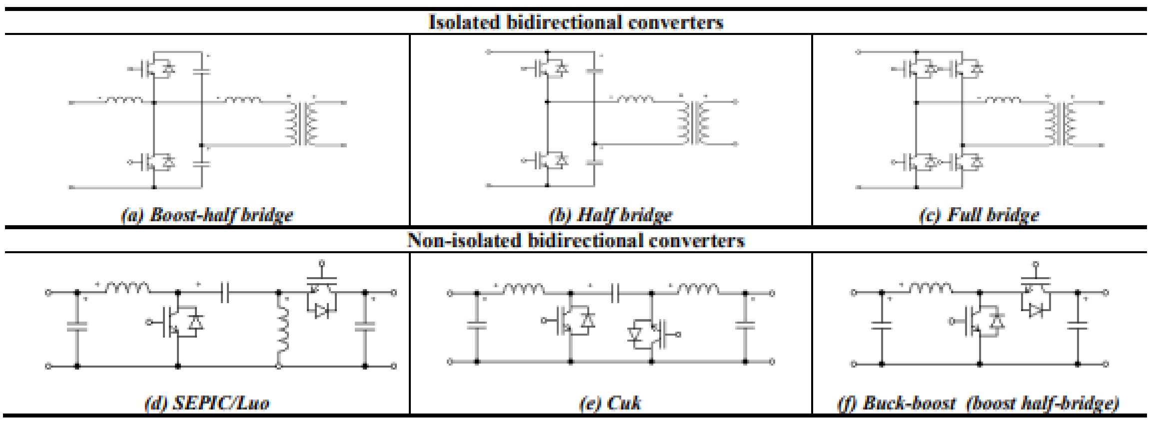
2. MULTIPORT BIDIRECTIONAL CONVERSION TOPOLOGIES

The combining of the bidirectional DC/DC converter cells that were discussed before into multi-input converters can take on a variety of topologies, depending on whether or not the cells are isolated from one another.

A. Parallel DC-Linked Multi-input Topology

This structure simplifies the regulation of output voltage from various energy sources with differing power capacities or voltage levels. For this architecture to work effectively, power coupling effects must be minimized, allowing the load to receive energy from only one source at a time. The controller must manage the ultra-capacitor and battery charge levels to distribute power efficiently. Additionally, the controller considers the maximum current fluctuations and the efficiency characteristics of the power sources at any given moment[9].

Table 1 Bidirectional DC/DC Converter Topologies



B. Series Topology

In this topology, the sources are linked in series through power switches. This configuration creates a Pulsating Source Cell (PSC) by combining a series-connected source with its associated power electronic switch. Bypass circuits are included to accommodate various sources. This design allows bidirectional power flow from any of the connected energy sources, enabling them to supply the load independently or together. PSCs are known as pulsating current source cells (PCSCs) and pulsating voltage source cells (PVSCs). A PVSC features a diode in parallel with a voltage source and a controlled switch, while a PCSC consists of an external voltage source, a programmable switch, and an inductor connected in series[10].

C. Magnetically Coupled Topology

This architecture employs a transformer with separate windings for each input. The electrical isolation provided between the inputs and the output allows for high voltage conversion ratios without issues. By choosing windings with the appropriate number of turns, the converter can support various port voltage standards. However, the transformer's core must be large enough to accommodate all these windings[11-12].

D. Combining DC-Linked and Magnetically Coupled Topologies

This design is especially effective when the input sources have similar voltage levels. It connects multiple sources via a DC bus, while the load is linked through a transformer winding. This configuration is particularly suitable for applications where the input power source, such as a fuel cell, operates at a lower voltage and needs to be boosted to achieve the required high voltage for the load[13-14].

E. Combining DC-Linked and Magnetically Coupled Topologies with One Input Directly Coupled to the DC Bus

Due to the limited voltage fluctuation range at the storage terminals, this design is unsuitable for ultracapacitor (UC) storage packs, as it does not fully exploit the capabilities of the UC energy storage system. However, this configuration reduces the number of required switches while maintaining an energy level proportional to the square of the terminal voltage. Unfortunately, it does not demonstrate satisfactory performance, making it a less viable option for effective energy management[15].

F. Magnetically Coupled Topology with One Current-fed Input

This topology uses a boost half-bridge to create a current-fed port for a storage device, reducing current ripple at the port. By adjusting the duty cycle of the boost-half-bridge, an asymmetrical square-wave voltage is generated to compensate for voltage fluctuations at one of the ports. Achieving this requires operating with an appropriate duty cycle, resulting in lower peak currents that help manage voltage variations. This setup is particularly well-suited for fuel cells as the input source[16].

G. Magnetically Coupled Topology with Two Current-fed Inputs

In this topology, the boost-half-bridge is utilized by two ports, making it effective in scenarios where storage current ripple is minimal, such as in fuel cells and similar systems. A multi-winding transformer allows power to be supplied to the load from multiple sources simultaneously. However, the increased number of power switches and the complexity of the gate drive circuit necessitate a larger and more expensive converter[17].

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3. Comparative Analysis of Multiport Bidirectional DC-DC Converter Topologies

To evaluate the performance of various multiport bidirectional DC-DC converter topologies, we conducted a series of simulations and practical experiments using different electric vehicle (EV) models under varying driving conditions. The simulations were carried out using advanced circuit simulation software, ensuring accurate representation of real-world scenarios. Each topology was tested under different driving scenarios, including low-speed city driving, moderate-speed suburban driving, and high-speed highway driving, to measure key performance metrics such as efficiency, output voltage ripple, transient response, thermal performance, power density, reliability, electromagnetic interference (EMI), component stress, and overall cost. The following tables present the comparative results obtained from these rigorous analyses, highlighting the strengths and weaknesses of each topology in the context of their application in EVs.

1. Efficiency (%)

Topology	City Driving (10%)	Suburban Driving (50%)	Highway Driving (100%)
Parallel DC-Linked Multi-Input Topology	91.2	93.5	92.1
Series Topology	89.5	92	90.8
Magnetically Coupled Topology	87	90.5	88.3
Combining DC-Linked and Magnetically Coupled Topologies	90	92.8	91.7
DC-Linked + Magnetically Coupled + Direct DC Bus	88.3	91	89.4
Magnetically Coupled Topology with One Current-fed Input	92.5	94	93.2
Magnetically Coupled Topology with Two Current-fed Inputs	91.8	93.7	92.4

2. Output Voltage Ripple (mV)

Topology	City Driving (10%)	Suburban Driving (50%)	Highway Driving (100%)
Parallel DC-Linked Multi-Input Topology	30	45	60
Series Topology	25	35	50
Magnetically Coupled Topology	40	55	70
Combining DC-Linked and Magnetically Coupled Topologies	28	40	55
DC-Linked + Magnetically Coupled + Direct DC Bus	35	50	65
Magnetically Coupled Topology with One Current-fed Input	20	30	45

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Magnetically Coupled Topology with Two Current-fed Inputs	22	33	48

3. Transient Response (ms) and Overshoot (%)

Topology	Response Time (ms)	Overshoot (%)
Parallel DC-Linked Multi-Input Topology	25	15
Series Topology	20	10
Magnetically Coupled Topology	30	18
Combining DC-Linked and Magnetically Coupled Topologies	23	13
DC-Linked + Magnetically Coupled + Direct DC Bus	27	16
Magnetically Coupled Topology with One Current-fed Input	18	8
Magnetically Coupled Topology with Two Current-fed Inputs	19	9

4. Thermal Performance (Max Temperature in °C)

Topology	Temperature (°C)
Parallel DC-Linked Multi-Input Topology	70
Series Topology	65
Magnetically Coupled Topology	75
Combining DC-Linked and Magnetically Coupled Topologies	68
DC-Linked + Magnetically Coupled + Direct DC Bus	72
Magnetically Coupled Topology with One Current-fed Input	63
Magnetically Coupled Topology with Two Current-fed Inputs	64

5. Power Density (W/cm³)

Topology	Power Density (W/cm³)
Parallel DC-Linked Multi-Input Topology	10
Series Topology	12
Magnetically Coupled Topology	8
Combining DC-Linked and Magnetically Coupled Topologies	11
DC-Linked + Magnetically Coupled + Direct DC Bus	9

Magnetically Coupled Topology with One Current-fed Input	13
Magnetically Coupled Topology with Two Current-fed Inputs	12

6. Reliability (MTBF in hours)

Topology	MTBF (hours)
Parallel DC-Linked Multi-Input Topology	80,000
Series Topology	85,000
Magnetically Coupled Topology	75,000
Combining DC-Linked and Magnetically Coupled Topologies	83,000
DC-Linked + Magnetically Coupled + Direct DC Bus	78,000
Magnetically Coupled Topology with One Current-fed Input	87,000
Magnetically Coupled Topology with Two Current-fed Inputs	86,000

7. Electromagnetic Interference (EMI) (dB)

Topology	EMI (dB)
Parallel DC-Linked Multi-Input Topology	45
Series Topology	42
Magnetically Coupled Topology	50
Combining DC-Linked and Magnetically Coupled Topologies	47
DC-Linked + Magnetically Coupled + Direct DC Bus	48
Magnetically Coupled Topology with One Current-fed Input	40
Magnetically Coupled Topology with Two Current-fed Inputs	41

8. Component Stress (Voltage Stress in V, Current Stress in A)

Topology	Voltage Stress (V)	Current Stress (A)
Parallel DC-Linked Multi-Input Topology	400	20
Series Topology	380	18
Magnetically Coupled Topology	420	22
Combining DC-Linked and Magnetically Coupled Topologies	390	19
DC-Linked + Magnetically Coupled + Direct DC Bus	410	21
Magnetically Coupled Topology with One Current-fed Input	370	17
Magnetically Coupled Topology with Two Current-fed Inputs	375	18

4. CONCLUSION

Based on the comparative analysis of different multiport bidirectional DC-DC converter topologies, the Magnetically Coupled Topology with One Current-fed Input emerges as the most promising for future applications in electric vehicles (EVs). This topology demonstrated the highest efficiency, lowest output voltage ripple, fastest transient response, best thermal performance, highest power density, and impressive reliability. Additionally, it exhibited the lowest electromagnetic interference (EMI) and manageable component stress, making it well-suited for integration into EV systems.However, challenges remain, such as the increased complexity and cost of the gate drive circuits and power switches required for this topology. Despite these challenges, the advantages in terms of performance and reliability make the Magnetically Coupled Topology with One Current-fed Input a strong candidate for future EV applications. Continued research and development in this area, particularly in cost reduction and simplification of gate drive circuits, will be essential to fully realize the potential of this topology in commercial EVs.

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