International Journal of Mechanical and Electrical Engineering
ISSN: 3005-9615 (Print), ISSN: 3005-7132 (Online) | Volume 4, Number 2, Year 2024
DOI: https://doi.org/10.62051/ijmee.v4n2.01
Journal homepage: https://wepub.org/index.php/IJMEE/index

A Review of Multi-Port DC-DC Converter Research

Caiyi He *

Department of Chongqing Normal University, Chongqing, China
* Corresponding author email: cosinnn@outlook.com

ABSTRACT

In modern power electronics and energy management systems, multi-port DC-DC converters are of excellent research significance as they can meet the demands of multiple energy inputs and multiple load outputs in complex systems. With the increasing complexity of energy systems, traditional single-port and bi-directional DC-DC converters make it challenging to meet these demands, so it has become necessary to develop multi-port DC-DC converters for efficient and flexible energy management. The direction of this research mainly reviews the research background and current status of multi-port DC-DC converters, discusses their applications in renewable energy systems, hybrid vehicles, and microgrids, and proposes future research directions.

KEYWORDS

Multi-Port DC-DC Converter; Isolation Characteristics; Bidirectional Power Flow; Topologies.

1. INTRODUCTION

As modern power electronics advance rapidly, multi-port DC-DC converters have garnered significant attention because of their broad applications in renewable energy systems, electric vehicles, and microgrids. These converters can flexibly distribute energy among multiple input and output ports to improve system efficiency and reliability. Since the three-port concept was first introduced by F. Caricchi et al. [1] in 1993, the design of multi-port DC-DC converters has been mainly based on the extension of a single topology, such as a full-bridge or half-bridge converter. As the demand increased, researchers gradually developed more complex topologies to accommodate a wide range of power and load requirements. These topologies include multiple-input multiple-output (MIMO) converters, cascaded converters, and integrated converters. In the early 2000s, research on multi-port converters focused on improving power density and efficiency, especially for performance optimization under high-frequency operation. In recent years, driven by the advancement of digital control technology and the emergence of advanced semiconductor materials, multi-port converters' control strategy and efficiency have been further improved, especially with soft-switching technology, which effectively reduces switching losses.

2. MULTI-PORT DC-DC CONVERTER

Multi-port DC-DC converters are designed to facilitate energy conversion and management between different voltage levels through multiple input and/or output ports. Their versatility is evident compared to traditional single-port or dual-port DC-DC converters, which are limited to one input and output. The multi-port DC-DC converters boast a more intricate topology and a broader range of potential application scenarios, making them a fascinating area of study and innovation.

Content from this work may be used under the terms of CC BY-NC 4.0 licence (https://creativecommons.org/licenses/by-nc/4.0/).
Published by Warwick Evans Publishing.

Multi-port DC-DC converter topologies vary and can be categorized according to the power flow direction of each port, which can be classified as unidirectional, the coupling method, the isolation characteristics, or the number of ports [2]. According to the classification of the coupling method, each port can be divided into the following three types: Electrically coupled type and energy coupling through the direct connection of the circuit, which is usually used for low-power applications. This type of converter is simple in design and has a low cost but may be affected by electromagnetic interference. The magnetic coupling type, which is used through the transformer or inductor to achieve the energy coupling between the ports, is suited for applications requiring high frequency and high power. The hybrid coupling type combines the methods of electric and magnetic coupling to achieve a more flexible system design and optimize the overall performance.

According to the isolation characteristics, the system is divided into the following three categories: Non-isolated, the ports are directly interconnected without electrical isolation, making this configuration typically suitable for low-cost applications. Partially isolated, the ports in the system are isolated, while other ports are not optimized according to the application's specific needs. Fully isolated, the ports are isolated through the electrical isolation of the transformer to guarantee the safety and integrity of the signal. This paper focuses on categorizing multi-port DC-DC converters according to their isolation characteristics and then discusses the common types under each classification.

2.1. Non-isolated Multi-Port DC-DC Converter

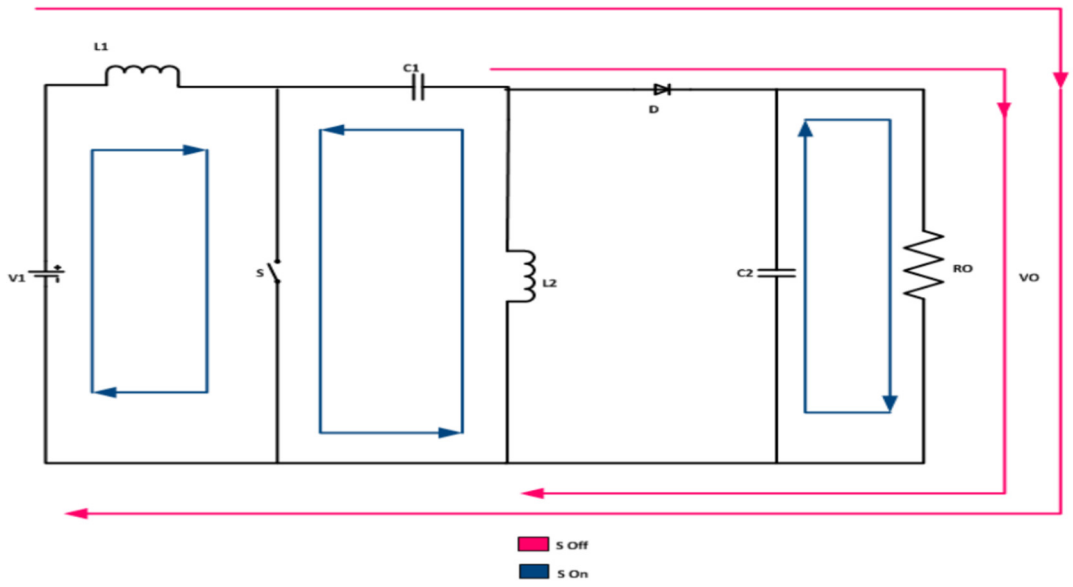


Fig 1. Schematic of a basic SEPIC converter.

Non-isolated multi-port DC-DC converters are typically developed by extending traditional single-port DC-DC converters, incorporating additional components to enable the connection of multiple ports. A typical electrical ground is shared between the ports, and the potentials of the input and output ports are relative to the same reference ground potential, resulting in no electrical isolation of the entire system [3]. The simplicity of this design structure and the flexibility of its application simplify the complexity of the circuits and usually contribute to the efficiency of the energy transfer, but at the same time require special attention to issues such as electromagnetic interference and safety management during design. Common topologies for this type of converter include: multi-input Buck converters, which are suitable for applications that require the voltage of multiple input power supplies to be stepped down to a single or multiple lower output voltages; multi-input Boost

converters, which are used to step up the voltage of multiple input power supplies to match a common high-voltage output bus, and are often used for the integration of renewable energy sources, including solar and wind; and combined Buck-Boost converters, which can either boost or buck, are used for applications with uncertain input and output voltage ranges; SEPIC converters (Fig.1) generally have a non-inverting output and use a series capacitor to transfer energy from the input to the output, compared to Buck-Boost and Cuk converters, and thus can respond to short-circuit outputs more smoothly; coupled-capacitor converters, which are used to boost or buck multiple input sources to match a common high-voltage output bus, are commonly used in the integration of renewable energy sources; and response to short-circuited outputs; coupled inductor topologies, where energy transfer between ports is achieved through coupled inductors, improving efficiency and reducing component count.

2.1.1. Multi-Port Single Ended Primary Inductor Converter

Multi-Port Single Ended Primary Inductor Converter, SEPIC is a flexible and highly efficient DC-DC converter architecture capable of handling multiple input and output ports simultaneously. The basic operating principle of this converter is to utilize inductors to store and release energy during switching operations to achieve voltage conversion.

Literature [4] focuses on two multiport SEPIC converter topologies for photovoltaic applications: SIMO and MIMO configurations, aiming to improve the integration and efficiency of multiple power sources, especially solar energy. The first utilizes a three-port unidirectional model that connects two outputs to a single voltage source, while the second is a four-port SEPIC with unidirectional properties, where the two sources connected to the converter are photovoltaic cells. With fewer topological components and higher power density than conventional multi-input power control converters (MIPCs), these converters effectively reduce system complexity and improve power utilization. The article [5] investigates a dual-input single-output DC-DC converter based on a SEPIC configuration (Fig.2). This converter integrates two energy sources. It can function in various modes, each marked by high efficiency and a minimal component count. The literature gives two basic modes of operation. The first is discharge mode, when the load power demand is high, and both input sources operate simultaneously to meet the load demand. Now, S_a and S_c switches are energized while S_b is turned off. Charging mode is activated when the load demand is low or when a second energy source needs to be charged. Switches S_a and S_b are on, and S_c is off. The converter is suitable for various application scenarios, such as DC microgrids, hybrid vehicles, etc., providing a reliable and cost-effective energy integration solution.

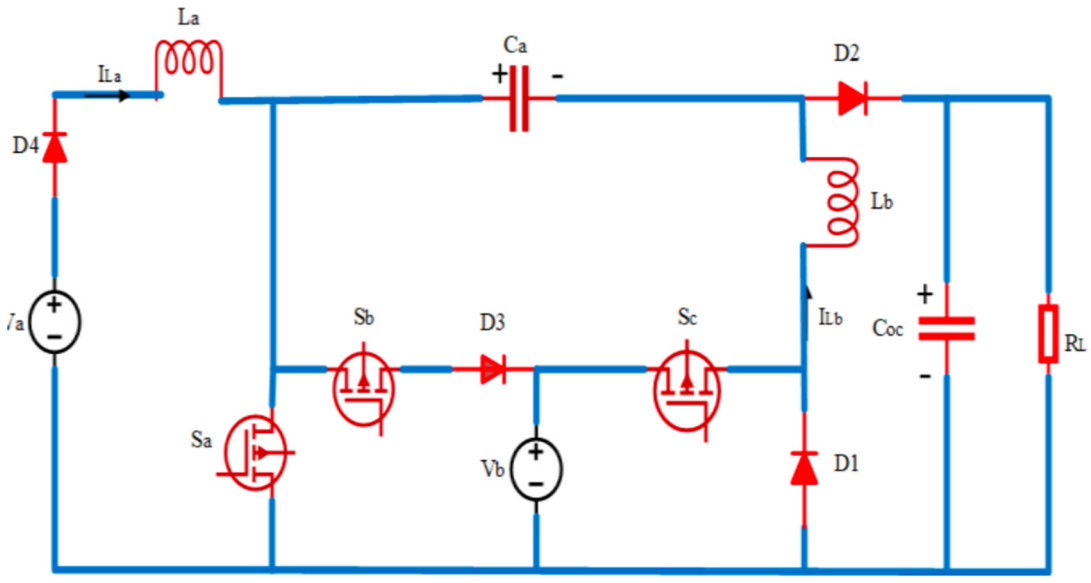


Fig 2. Configuration of SEPIC based dual input DC-DC converter.

However, the converters mentioned in the above two literatures are unidirectional, the power can only flow from the source to the load and not in both directions, which limits the use of the converters in application scenarios that require energy recovery or storage. In contrast, the literature's three-port bi-directional SEPIC converter structure [6] is designedso that its input ports can be connected to a solar PV system and a battery. The converter is designed to achieve a bidirectional power flow, allowing the battery to be both charged from the main supply and fed with regenerative energy from the load side.

2.1.2. Multi-Port Buck-Boost Converter

Conventional non-isolated multi-port Buck-Boost converters typically have multiple input and output ports to connect different power sources and loads. Each port is connected to a central DC busbar through a set of switches and inductors, and the switches of each port are controlled by independent control signals to achieve the boost or buck function and adapt to different voltage and power requirements. Compared to the previously mentioned SEPIC converter, this Buck-Boost is suitable for systems that require the integration of multiple power sources or loads with higher flexibility and power density but require more complex control and design.

Literature [7] proposes a novel multi-port converter structured as a combined version of Buck and Buck-Boost converter containing two unidirectional ports (Port-1 and Port-3) and one bidirectional port (Port-2).The three ports connect the photovoltaic (PV) panel, the battery, and the load. This converter addresses the limitations of conventional Buck-Boost converters, can adapt to different voltage input conditions and load requirements, multiple modes of operation, realizes the integration of PV, battery, and load, has a high ratio of lift-voltage conversion, improves the energy efficiency of the system, and is suitable for investment in the industrial or household industry.

2.1.3. Multi-phase Interleaved Buck Converter

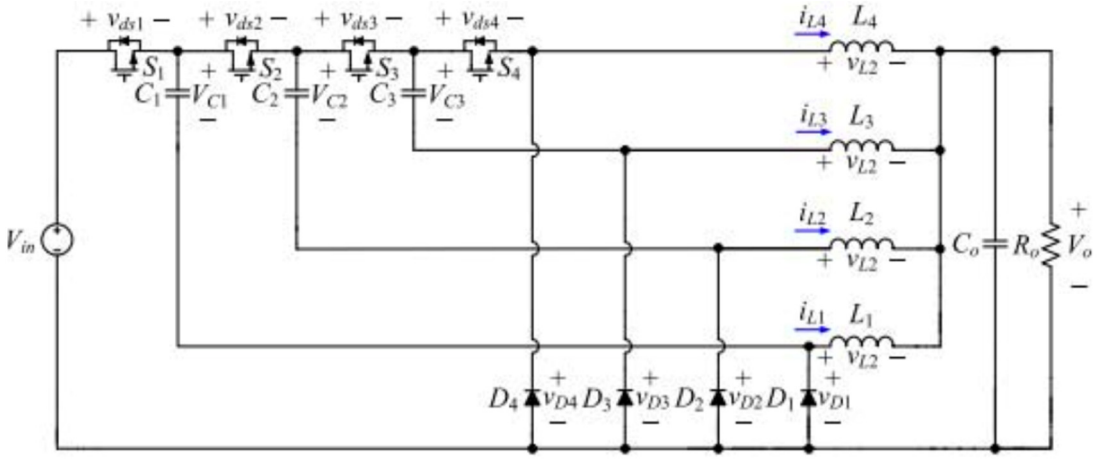


Fig 3. Proposed Four Interleaved buck converter.

Multi-phase Interleaved Buck Converter comprises multiple phases of Buck converters that are connected in parallel. Each phase has independent switches and inductors, and the switching signals of each phase are staggered from each other, but they have the exact feedback mechanism. Multi-phase interleaved parallel connection is not a simple parallel connection, but the drive signals of each phase have the same frequency [8]. With this interleaved operation, the input and output current pulsations are effectively reduced, and the need for filters is reduced, which is particularly suitable in high current and high-power applications.

The improved four-phase interleaved Buck converter (Fig.3) studied in the literature [9] enhances the overall efficiency and performance of the system. This is achieved through an optimized switch series

design and the application of coupling capacitors. Operating at high frequencies with an operating duty cycle of less than 0.25, the converter outperforms the conventional interleaved Buck converter. It excels in terms of reduced voltage stress, a key factor in ensuring the safety of the system, improved buck capability, and reduced current ripple for a variety of high-efficiency power conversion applications.

In contrast to this MIBC, literature [10] investigates a six-phase interleaved parallel Buck topology with inner-loop current-sharing control that emphasizes inter-phase current equalization and filtering design. This design's main focus is to reduce the output current ripple, which is reduced by the phase interleaving technique, making it suitable for applications requiring low ripple and high accuracy output.

2.2. Partially Isolated Multi-Port DC-DC Converter

Partially isolated multi-port DC-DC converters combine the features of partial electrical isolation and multi-port configurations for applications requiring simultaneous connection of multiple power sources and loads. These converters support bidirectional power conversion, efficiently distributing and regulating power among different ports. Although their design and control strategy are more complex and require precise power flow management, their cost is typically lower than that of non-isolated and fully isolated converters. However, they also require a more complex control strategy and are suitable for electric vehicles and distributed energy systems applications.

2.2.1. Three-Port Buck-Boost-Flyback Converter

A conventional, typical partially isolated three-port Buck-Boost-Flyback converter (BBFIC) combines the features of Buck, Boost, and Flyback topologies to provide multi-port (input, output, and isolated) voltage conversion and energy management. Flyback transformers achieve partial electrical isolation between inputs and outputs, increasing safety and reducing electromagnetic interference. Combined Buck and Boost functions enable efficient operation over various input voltages.

The BBFIC proposed in the literature [11] is not merely a theoretical concept but a practical solution for specific applications. It integrates two Buck-Boost converters and a Flyback converter (Fig.4), uses only one active switch, and fully recovers the leakage inductance energy in the coupled inductors without additional active clamp or buffer circuits. This design simplifies the circuit structure but achieves ultra-high voltage gain, making it particularly suitable for applications including photovoltaic and fuel cell systems where efficient voltage conversion is required.

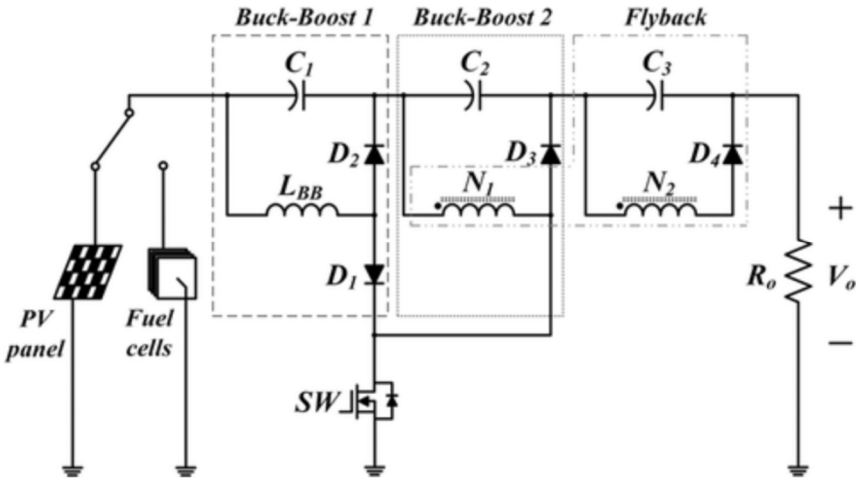


Fig 4. Power stage of the proposed BBFIC.

2.2.2. Dual Active Bridge with Buck/Boost

Compared to BBFICs, which are suitable for high voltage gain applications, the general type of dual ciliated bridge Buck/Boost combi converter is more advantageous in applications with soft switching, low circuit losses, and the need for bi-directional energy flow [12-13]. This is mainly due to the fact that it has Buck-Boost and dual-ordered-bridge topologies: two H-bridge structures are used, one for Buck conversion and one for Boost conversion, and it allows for flexible voltage step-up and down, which enables efficient bidirectional energy flow. In general, integrating dual-edge bridges is a development trend for partially isolated three-port DC-DC converters. Literature [14] gives a circuit diagram of such a converter (Fig.5), which provides a detailed analysis of its fundamental operating principle, operation mechanism, and characteristics:

Bidirectional Buck-Boost Circuit: The ports are connected through two Buck-Boost circuits connected in staggered parallel. Each circuit consists of two switching tubes (S_1, S_2 and S_3, S_4) and a DC inductor (L_1 and L_2), which have the same value (L_1=L_2).The circuit's ability to adjust the state of the switches S_1-S_4 empowers you to regulate the energy boosting or bucking between the ports, giving you full control over the system's operation.

Dual active bridge structure: Switches S_1-S_4 constitute the primary full bridge, while switches S_5-S_8 constitute the secondary full bridge. The two full bridges are connected through transformer T and phase-shifted inductor L_r to form a dual active bridge structure.The on-time discrepancy between the primary-side and secondary-side full bridges is controlled precisely through phase shifting, a critical factor in achieving efficient energy transfer.

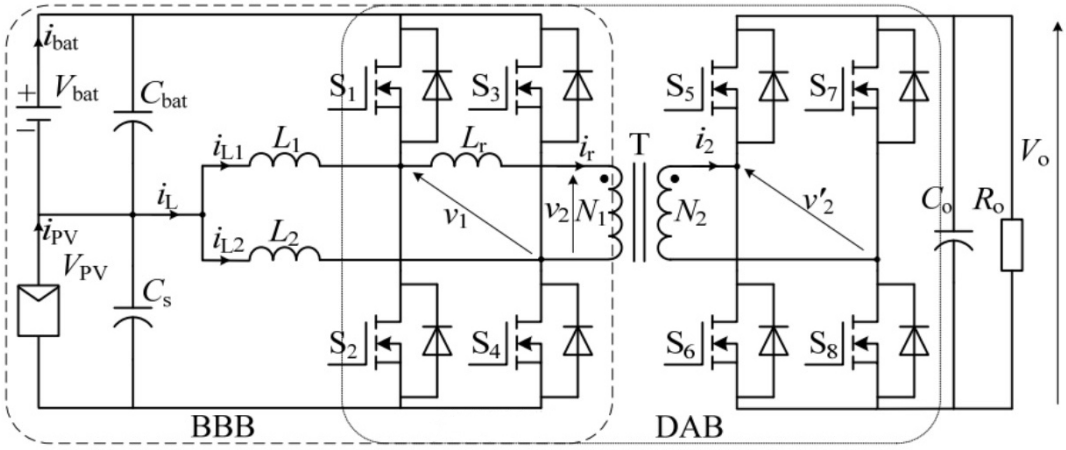


Fig 5. BBB Integrated Three-Port Converter.

2.3. Fully Isolated Multi-Port DC-DC Converter

Fully isolated DC-DC converters provide the highest level of safety and noise rejection by providing complete electrical isolation between all ports for applications with high power and safety requirements, such as medical equipment and power systems. However, compared to the other two types of converters, this converter has a broader range of applications but is more complex and costly to design.

2.3.1. Full-Bridge Converter

Full-bridge three-port converter, a versatile solution, realizes efficient energy conversion and flexible power management through a full-bridge inverter structure and three-port design. Its basic features include a high-frequency transformer that ensures electrical isolation, support for bi-directional power flow, and the ability to connect multiple power sources and loads simultaneously. Advantages include high efficiency, stable power output, high safety, and suitability for high power demand applications.

Literature [15] proposes a three-port converter using a typical interleaved boost full-bridge converter, incorporating pulse width modulation and phase shift control. The converter controls the power switches with phase-shifted PWM signals to independently regulate the input and output voltages. Its design enables the MOSFETs on the primary side to realize zero-voltage switching without adding additional circuitry, and the diode on the secondary side operates under zero-current switching conditions, which effectively reduces reverse-recovery losses. The primary advantages of this converter include high power density, cost-effectiveness, good dynamic response, and adequate power flow control in multiple operating modes, which makes it particularly suitable for application in multi-source hybrid renewable energy systems. However, this converter has high design and control strategy complexity, switching loss issues, and limited applicability. These factors may limit its advantages in specific application scenarios.

2.3.2. Four-Port Dual Active Bridge

Four-Port Dual Active Bridge (FPDAB), compared to the previously mentioned dual active bridge, is mainly designed to connect many different types of energy sources directly, in addition to the differences in isolation characteristics. Literature [16] investigates this converter to connect solar photovoltaic, biomass, or biogas and battery energy storage systems to integrate renewable energy sources. The working mechanism of this converter leverages a high-frequency transformer that regulates the phase shift angle to control power flow, enabling flexible power management across multiple modes. Additionally, it maximizes solar energy utilization through Maximum Power Point Tracking (MPPT). Therefore, a more complex controller design is required to maintain a stable voltage and ensure a fast response during load changes. On the other hand, the four-port isolated DC-DC converter studied in the literature [17] utilizes three dual active bridge converters integrated to form a structure that combines a full bridge on the primary side into a typical three-phase two-level inverter. The basic design also utilizes high-frequency transformers for isolation and energy transfer. However, its advantage lies in its high level of integration, which can reduce conduction losses by up to 23% without adding additional hardware through an optimized modulation strategy.

2.3.3. LLC Resonant Multi-Port Converter

Fully isolated LLC multiport converters feature high efficiency, high power density, and good EMC. Their soft switching through resonant technology reduces switching losses and EMI. In addition, the LLC topology has good regulation performance over a wide output voltage range, making it suitable for multiport energy transfer applications. However, this type of converter requires high device parameter matching under high-frequency operating conditions.

The converter in literature [18] is based on the LLC resonant topology to realize the soft switching operation of the switching devices under zero-voltage (ZVS) or zero-current (ZCS) conditions, which reduces the switching losses and improves the conversion efficiency. Through the use of separate resonant cavities and transformer isolation, each port can be independently controlled to be compatible with sources and loads of various voltage levels. The main advantage is the reduction of switching losses through soft-switching technology. This enables the converter to maintain high efficiency over the entire power range and excellent voltage regulation performance, enabling stable operation under light to heavy load conditions. However, the converter has the common drawbacks of general LLC converters, which involve precise tuning of multiple resonant cavities and precision design of transformers and require high matching of component parameters during high-frequency operation. The main application of this converter is in distributed energy systems to effectively integrate and manage multiple energy sources (e.g. photovoltaic and energy storage batteries) to ensure efficient operation and stability of the system.

Literature [19] utilizes an LLC resonant topology and a multi-winding IF transformer to achieve electrical isolation and efficient power transfer between multiple ports. The design of the converter includes a built-in LLC resonant cavity and a bidirectional boost/buck stage, which enables it to operate at a fixed switching frequency and duty cycle without relying on complex control strategies,

ensuring that soft-switching conditions are maintained, thus reducing switching losses and improving efficiency. The main application objective is to provide flexible and efficient power management for multiple power sources and loads in distributed energy systems and microgrids.

2.3.4. Modular Multilevel Converter

A fully isolated Modular Multi-level Converter (MMC) combines multiple power electronic modules connected in series and parallel, combined with a multi-winding high-frequency transformer to achieve electrical isolation of different voltage levels and power transfer between multiple ports. Its topology usually consists of multiple H-bridge or full-bridge sub-modules connected via multi-winding transformers and resonant cavities to form multi-level outputs, thus realizing high power density and efficiency. The composition of the converter includes an isolation transformer, multiple power switching modules, resonant cavities, and a control system, which ensures power balancing and voltage regulation between the ports through a precise control strategy [20]. Its main advantage lies in the high scalability and flexibility brought by the modular design, which can adapt to different voltage and power requirements. At the same time, The multi-level output minimizes switching loss and enhances system efficiency.

Literature [21] gives two medium cases based on the modular multi-level converter and cascaded H-bridge topologies, aiming at efficient multi-port power conversion in medium voltage direct current systems. The design of Case 1 consists of one MMC input port and two cascaded H-bridge output ports (Fig.6), controlled by phase-shifted pulse-width modulation (CPS-PWM) and realizes the transmission of multi-level stepped waveforms through a transformer. Its main advantages are a relatively simple structure, convenient control, and the ability to achieve low harmonic distortion and switching loss, which makes it suitable for medium-power application scenarios. However, since it only supports two output ports, its flexibility is limited when facing more output ports or higher power requirements. Case 2 is structurally extended to include one MMC input port and four cascaded H-bridge output ports with a quasi-square wave modulation strategy. This modulation method combines the advantages of square-wave and sine-wave modulation, resulting in an enhanced power transfer capability while reducing the difficulty of designing the transformer's insulation on the AC side. In contrast, Case 1 is more suitable for medium power applications with less complex system requirements, where simplicity and higher efficiency are the main advantages. Case 2, on the other hand, is optimized for complex application scenarios that require higher power and multi-port support, increasing system flexibility and power transfer capability.

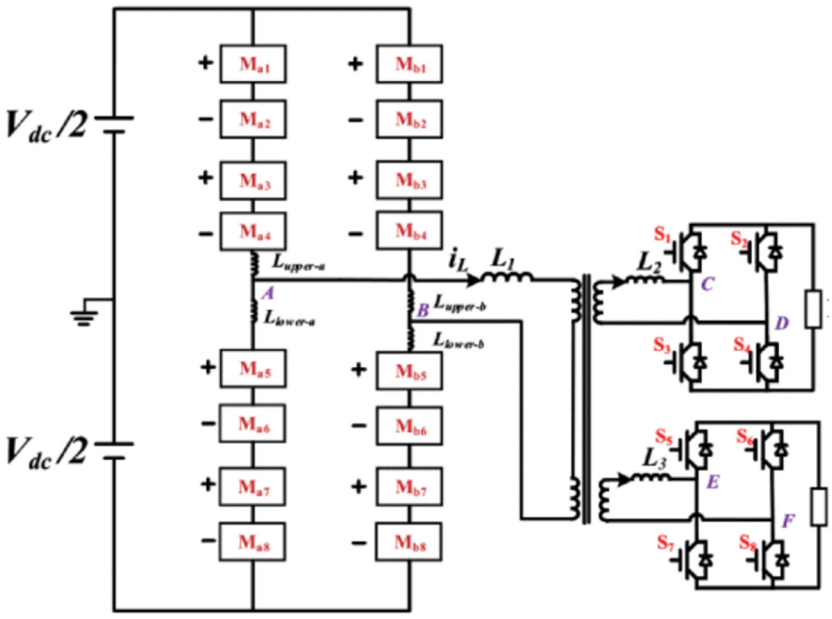


Fig 6. Proposed topology mentioned in case 1.

The basic principle of the dual-branch modular-based multilevel converter (MMC) structure proposed in the literature [22] is to generate multiple output ports by introducing dual-branching arms in the MMC structure to enable power conversion and isolation between DC ports of different voltage levels. This converter aims to replace the conventional MMC structure in high-voltage DC transmission (HVDC) systems by reducing sub-modules to reduce cost and size and simplify the capacitive voltage balancing strategy. This type of converter offers higher scalability and system simplification advantages over the previous two schemes, reducing system cost and complexity by reducing the number of sub-modules and reliance on multi-winding transformers while maintaining efficient energy conversion across multiple ports.

3. CONCLUSION

Multi-port DC-DC converters play a crucial role in modern power electronics and energy management systems, especially in coping with the increasingly complex demands of multiple energy inputs and multiple load outputs. This paper reviews the research background and current status of multi-port DC-DC converters, emphasizing their significant advantages in improving system efficiency, flexibility, and reliability.

Although these converters show great potential, they still face challenges such as complex control strategies and high hardware costs. Accurate control algorithms and higher hardware costs are still required for multi-port power balancing and voltage regulation, and future research should focus on optimizing these control strategies further to enhance the converters' dynamic response and steady-state performance. Similarly, the integration and power density of the converter will be further improved, promoting its popularization and development in a broader range of applications. With the development of the power grid and continuous access to new energy sources, the multi-port converter will be gradually optimized and upgraded to adapt to the needs of different power sources and loads. At the same time, system stability and reliability issues will receive more attention, especially when dealing with many uncertainties in microgrids. In addition, the efficiency and cost of multi-port converters will be critical directions for future research, aiming to improve energy conversion efficiency and reduce system costs. In addition, exploring new topologies and materials to reduce losses and improve system efficiency will continue to be an important direction in the technological advancement of multi-port DC-DC converters.

These trends indicate that multi-port converters will be increasingly important in future energy systems. These efforts will not only help achieve more efficient and reliable energy management. However, they will also promote the key applications of multi-port DC-DC converters in future energy systems and help modernize and smarten them.

REFERENCES

[1] Caricclu F, Crescimbini F, Napoli A D. Testing of a New DC/DC Converter Topology for Integrated Wind-photovoltaic Generating Systems[C]. Proceeding of European Power Electronics and Applications Conference, 1993:83-88.

[2] Ruan Jie. Research on Multiple Ports DC-DC Converters[D].Nanjing University of Aeronautics and Astronautics, 2011.

[3] He Yuanxi. The research on Non-Isolated Three-Port DC-DC Converter [D]. Harbin Institute University, 2013.

[4] Anuradha, C., C. Sakthivel, T. Venkatesan, and N. Chellammal. 2018. "Analysis of Non-Isolated Multi-Port Single Ended Primary Inductor Converter for Standalone Applications" Energies 11, no. 3: 539. https://doi. org/ 10. 3390/en11030539.

[5] S. A. Yasin, J. Kumar, Y. Kumar, S. Athikkal and J. Peter, "Analysis of a Dual Input DC-DC Converter Topology Based on SEPIC Configuration," 2019 International Conference on Power Electronics Applications and Technology in Present Energy Scenario (PETPES), Mangalore, India, 2019, pp. 1-6, doi: 10.1109/PETPES47060.2019.9003780.

[6] Anuradha, C., N. Chellammal, Md Saquib Maqsood, and S. Vijayalakshmi. 2019. "Design and Analysis of Non-Isolated Three-Port SEPIC Converter for Integrating Renewable Energy Sources" Energies 12, no. 2: 221. https:// doi. org/10.3390/en12020221.

[7] B. Chandrasekar et al., "Non-Isolated High-Gain Triple Port DC–DC Buck-Boost Converter With Positive Output Voltage for Photovoltaic Applications," in IEEE Access, vol. 8, pp. 113649-113666, 2020, doi: 10.1109/ ACCESS. 2020.3003192.

[8] Qu Liangpan. Analysis and Design of Multiphase Interleaved Parallel BUCK DC-DC Converter [D]. Chengdu University of Technology, 2019.DOI:10.26986/d.cnki.gcdlc.2019.000083.

[9] M. Ishwarya and R. Dhanalakshmi, "Investigations on multiphase modified interleaved buck converters for high step down voltage," 2017 International Conference on Innovative Mechanisms for Industry Applications (ICIMIA), Bengaluru, India, 2017, pp. 491-496, doi: 10.1109/ICIMIA.2017.7975663.

[10] Gao Qing. RESEARCH ON MULTIPHASE INTERLEAVING BUCK CONVERTERS WITH LOW RIPPLE [D]. Harbin Institute of Technology, 2017.

[11] Shen, C.-L. and Chiu, P.-C. (2016), Buck-boost-flyback integrated converter with single switch to achieve high voltage gain for PV or fuel-cell applications. IET Power Electronics, 9: 1228-1237. https://doi.org/10.1049/iet-pel.2015.0482.

[12] Li W H, Xiao J G, Zhao Y, et al. PWM Plus Phase Angle Shift (PPAS) Control Scheme for Combined Multiport DC/DC Converters[J]. IEEE Transactions on Power Electronics, 2012, 27(3): 1479-1489.

[13] Wang Z, Li H. An Integrated Three-Port Bidirectional DC-DC Converter for PV Application on a DC Distribution System[J]. IEEE Transactions on Power Electronics, 2013, 28(10): 4612-4624.

[14] Huo Qingying. RESEARCH OF A BUCK-BOOST AND DUAL ACTIVE BRIDGE INTEGRATED THREE-PORT DC-DC CONVERTER [D]. Yanshan University, 2015.

[15] M. C. Mira, Z. Zhang, A. Knott and M. A. E. Andersen, "Analysis, Design, Modeling, and Control of an Interleaved-Boost Full-Bridge Three-Port Converter for Hybrid Renewable Energy Systems," in IEEE Transactions on Power Electronics, vol. 32, no. 2, pp. 1138-1155, Feb. 2017, doi: 10.1109/TPEL.2016.2549015.

[16] R. Ranjan, P. N. Singh and S. B. Karanki, "A Dual-Active-Bridge Based Four-Port Bidirectional DC-DC Converter for Renewable Energy Integration," 2023 11th National Power Electronics Conference (NPEC), Guwahati, India, 2023, pp. 1-6, doi: 10.1109/NPEC57805.2023.10384891.

[17] J. Böhler, F. Krismer, T. Sen and J. W. Kolar, "Optimized Modulation of a Four-Port Isolated DC–DC Converter Formed by Integration of Three Dual Active Bridge Converter Stages," 2018 IEEE International Telecommunications Energy Conference (INTELEC), Turino, Italy, 2018, pp. 1-8, doi: 10.1109/ INTLEC. 2018. 8612312.

[18] K. Tomas-Manez, Z. Zhang and Z. Ouyang, "Multi-port isolated LLC resonant converter for distributed energy generation with energy storage," 2017 IEEE Energy Conversion Congress and Exposition (ECCE), Cincinnati, OH, USA, 2017, pp. 2219-2226, doi: 10.1109/ECCE.2017.8096434.

[19] Y. -K. Tran and D. Dujic, "A multiport isolated DC-DC converter," 2016 IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach, CA, USA, 2016, pp. 156-162, doi: 10.1109/APEC.2016.7467867.

[20] K. Sharifabadi, L. Harnefors, H.-P. Nee, S. Norrga and R. Teodorescu, Design Control and Application of Modular Multilevel Converters for HVDC Transmission Systems, Hoboken, NJ, USA:John Wiley Sons, 2016.

[21] G. Sha et al., "Research on Multi-Port DC-DC Converter Based on Modular Multilevel Converter and Cascaded H Bridges for MVDC Applications," in IEEE Access, vol. 9, pp. 95006-95022, 2021, doi: 10.1109/ ACCESS. 2021. 3072161.

[22] Y. Xu, K. Wang, L. Jin, Y. Deng, Y. Lu and Y. Yang, "Isolated Multi-port DC-DC Converter-Based on Bifurcate MMC Structure," 2019 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Macao, China, 2019, pp. 1-6, doi: 10.1109/APPEEC45492.2019.8994701.

[23] Yu Tianyi. Research on Topology and Power Balance Control of Multi-port Cascaded Multilevel Converters for Distributed Energy Accessing[D].Wuhan University,2019.DOI:10.27379/d.cnki.gwhdu.2019.001672.