INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
A. El Ghaly, Vol.16, No.2, June, 2026

Investigating Bidirectional DC-DC Converters: Topologies, Control Algorithms, and Diverse Applications

Abdallah El Ghaly*‡

*ECE Department, Faculty of Engineering, Beirut Arab University, Beirut, Lebanon.

(a.ghali@bau.edu.lb)

‡ Corresponding Author; Abdallah El Ghaly, Beirut 11-5020, Tel: +96170657837,

a.ghali@bau.edu.lb

Received: 06.03.2024 Accepted: 01.05.2024

Abstract- Given the increasing worries surrounding the impact of fuels, nations are now shifting towards sustainable energy production options through the utilization of renewable energy sources. In tandem with advancements in electric vehicle technology, the automotive production market is moving towards the electrification of transportation, contributing to cleaner cities. The integration of renewable sources, batteries, and electric vehicles into the grid leads to the utilization of bidirectional DC-DC converters to secure a two-way power flow. These converters come in various topologies and employ different control techniques based on their application domains. In this review paper, a thorough analysis is conducted concerning the advantages, limitations, and applications of various topologies of DC-DC bidirectional converters. The bidirectional DC-DC converters' main classifications are the isolated and non-isolated types. Within these categories, various topologies are compared. In addition, this review discusses novel topologies and emphasizes their contributions to the existing ones. Finally, an investigation is made into different control strategies utilized in the DC-DC bidirectional converters. This review aims to assist researchers by examining different configurations of DC-DC bidirectional converters. This will serve as a basis for comparing new designs or selecting the most suitable converter for a particular application.

Keywords DC-DC converters, renewable energy, electric vehicles, vehicle-to-grid, emerging technologies.

1. Introduction

Recently, bidirectional DC-DC converters (BDC) have been getting attention in power electronics research [1-5]. As opposed to conventional unidirectional DC-DC converters, a BDC permits bidirectional power flow. The unidirectional converters are simple in construction and implementation, however, the integration of electric vehicles (EVs) into the grid and having them as possible energy storage elements raises the need for a two-way power flow [6], [7]. The power can be transferred from grid-to-vehicle (G2V) in a forward load flow to charge the EV's battery, but in case this battery is meant to be used as a source, a vehicle-to-grid (V2G) operation mode is required. Stand-alone applications also utilize bidirectional power transfer when applying vehicle-to-load (V2L) or vehicle-to-home (V2H) [8], [9].

A BDC is a power electronic device, essential for regulating and optimizing electrical power in several contemporary applications, it is created to effectively convert and transmit electrical power between two DC voltage sources in two directions while controlling the power flow [10]. For instance, the power flow could be forward power flow for charging the EV batteries and reverse power flow for utilizing the battery in V2G mode. Besides EV applications, the BDC is also utilized in renewable energy sources (RES), battery storage systems, uninterrupted power supplies, and aircraft [11], [12]. Most of the currently available BDCs adhere to the simple circuit design illustrated in Fig. 1 which demonstrates the forward and reverse power flow [13].

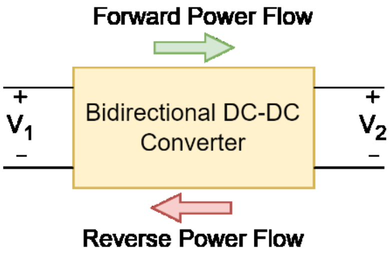


Fig. 1. Bidirectional DC-DC converter power flow.

Implementing bidirectional power flow offers effective solutions to a range of challenges encountered in the grid system. It enhances the stability of the grid by adapting to variations in energy supply and demand including load changes and faults, increases reliability by enabling independent operation of distributed energy sources such as microgrids during grid outages, and enhances power system efficiency by directing power to areas with the highest demand. This will reduce transmission losses and optimize energy unitization, resulting in a more efficient and reliable grid. The growing importance of RES and EVs has led to bidirectional power flow playing a crucial role in shaping cleaner and more sustainable energy usage [14], [15].

BDCs are utilized extensively in EV charge stations, energy storage batteries, and solar panels, among other power systems. An example of the integration of BDC in the power system is depicted in Fig.2. In the context of the V2G principle, these converters play an essential role in charging EVs from the grid and feeding back stored energy from EV to the grid as needed utilizing the two-way power flow property of the BDC. This will lead to grid stability enhancement, minimizing consumption during peak hours tariffs, and having a continuous power supply during blackouts. To stabilize output fluctuations in integrated RES, an energy storage system with a battery and BDC is necessary. The BDC can provide electricity from these sources to charge the EVs; under certain conditions, the power from the EVs will be drawn back to the grid as a reverse power flow. Additionally, when the grid lacks sufficient power, energy can be obtained from these sources through a BDC converter [16]. BDC's essential attributes for charging stations include low cost, high efficiency, and high reliability [13].

Consequently, BDC has emerged as a substantial subject of research in power electronics. It is usually used to minimize the size of the converter by replacing two unidirectional converters with a single BDC which enhances the system's performance and efficiency. BDCs can exist in either isolated or non-isolated forms. Isolated BDC uses transformers in its topology to transfer power while also providing galvanic isolation, whereas non-isolated topologies transfer power without the use of transformers. Isolated converters exhibit higher voltage gain than non-isolated counterparts. However, converter topologies that are not isolated take up less physical space and have a reduced weight. When weight is an essential consideration, non-isolated converters may be utilized [17].

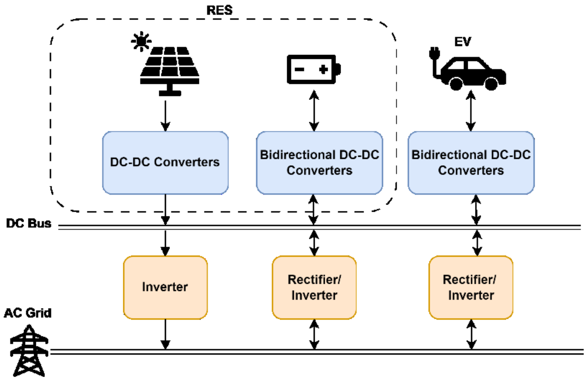


Fig. 2. BDC’s in power systems.

As the significance of BDCs continues to rise, this paper will comprehensively examine various topologies of BDCs. This will include both established designs and novel configurations found in the literature. Additionally, the paper will explore contemporary trends in control strategies employed in the BDC, offering insights into the latest advancements in this dynamic field.

The rest of the paper is organized as follows: Section 2 provides a classification of basic topologies for bidirectional DC-DC converters. Section 3 compares the novel topologies designed for BDC. In Section 4, an overview.

2. Classifications of BDC Basic Topologies

BDC is primarily categorized into two main types: the isolated BDC and the non-isolated BDC. The isolated BDC employs a high-frequency transformer with a high step voltage gain, ensuring galvanic isolation between two distinct voltage levels. It operates by initially transforming the DC voltage into high-frequency AC voltage and subsequently converting the AC voltage back into DC, effectively functioning as a controlled inverter and rectifier set in a back-to-back configuration.

On the other hand, the non-isolated BDC lacks galvanic isolation between voltage levels but offers a reduced weight due to the absence of an isolating transformer. The non-isolated BDC operates primarily in either buck or boost modes, contingent upon the power flow direction between the two distinct DC voltage levels. Among these non-isolated types, the main topologies include the buck-boost, cascaded, CUK, SEPIC, and ZETA BDCs.

For the isolated BDC, the main topologies consist of the flyback, CUK, dual half bridge, dual active bridge, LCLC resonant, and LCL-T resonant BDCs. These topologies are visually represented in Fig 3.

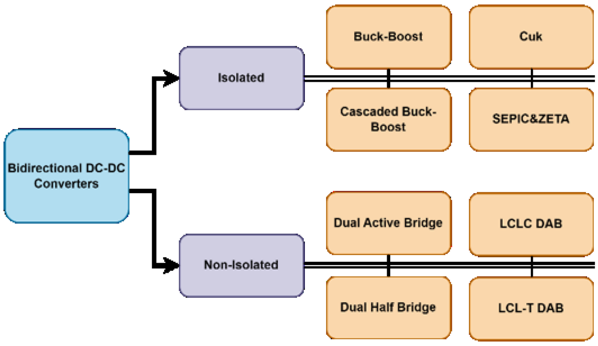


Fig. 3. BDC topologies.

2.1. Non-isolated BDC Topologies

The initial non-isolated BDC topology is a modification of the traditional buck and boost unidirectional converters, allowing bidirectional load flow, as illustrated in Fig. 4. For example, when S1 is activated and S2 is inactive, the converter functions in a buck topology, directing power from the high voltage (V_H) side to the low voltage side (V_L). Conversely, when S2 is activated while S1 is inactive, the converter operates as a boost, facilitating power flow from V_L to V_H [18].

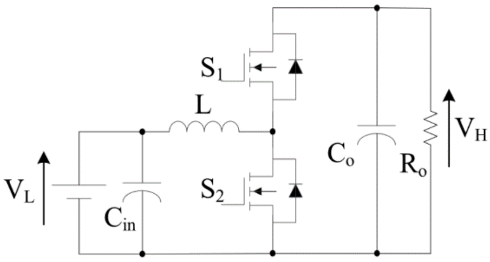


Fig. 4. Buck-boost non-isolated BDC.

In case two or more buck-boost converters are used in cascaded form [19], this will result in another non-isolated BDC topology. The main advantage of this topology is the higher voltage gains with lower current stress for the same switching frequency where it was initially invented to be used in EV applications. However as reflected in Fig.5, the main drawback of this converter is the increase in the number of switches, which leads to a much-complicated control system as well as increased turn-on losses brought on by the reverse recovery issue with transistor body diodes; a specific period passes after a diode shifts from the forward-biased state to the reverse-biased state when it is employed as a switch.

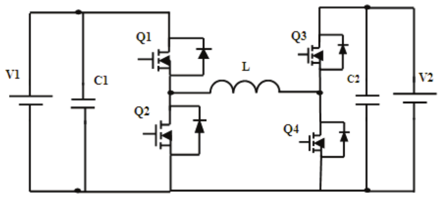
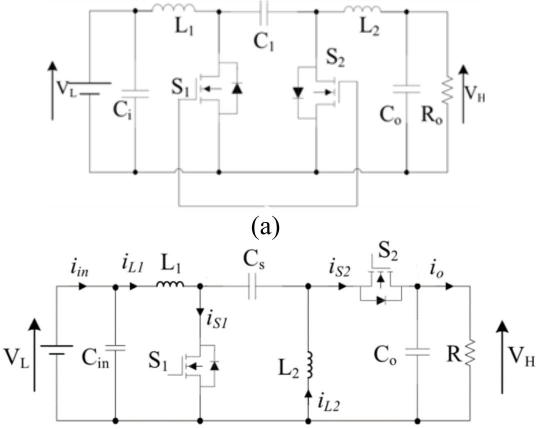


Fig. 5. Cascaded buck-boost non-isolated BDC.

Another topology of the non-isolated BDC is the Cuk non-isolated converter as depicted in Fig.6 (a), this type includes two inductors and two capacitors in addition to the switching elements. The continuity of both input and output currents is the main feature of this converter in the bidirectional load flows, in addition to the minimized ripples due to the inductors. For that, great gain and efficiency may be attained with a small duty cycle and a large load variation range. It finds application in power supplies, battery charging systems, renewable energy converters, and voltage regulation in electronic devices, enabling efficient and precise voltage conversion with minimal losses. However, its control and stability can be more challenging compared to traditional converters due to the complexity of its dual inductor design.

A change in the elements arrangement of the Cuk non-isolated converter results in another type of BDC which is the single-ended primary inductor converter SEPIC&ZETA converter as in Fig.6 (b). This modified Cuk converter acts as a BDC. In forward power flow operation, the converter operates as a SEPIC converter, while in negative power flow mode, it operates as a ZETA converter [20].



(a)

(b)

Fig. 6. (a): Cuk non-isolated, (b) SEPIC&ZETA non-isolated.

Another topology is the hybrid boost converter. The hybrid boost converter combines features of buck and boost converters, enabling efficient voltage regulation across varying input levels. It efficiently steps up or steps down voltage as needed, making it versatile for applications requiring both voltage increase and decrease. It's commonly used in electric vehicles, renewable energy systems, and various power conversion applications [21].

2.2. Isolated BDC Topologies

The isolated BDC is characterized by a galvanic isolation that secures electrical isolation between the primary and the secondary. The primary motivations behind implementing isolation in these converters are protection, noise mitigation, and voltage regulation. In diverse applications, isolation plays a pivotal role in safeguarding vulnerable electronic components, mitigating the occurrence of ground loops, and augmenting overall safety measures.

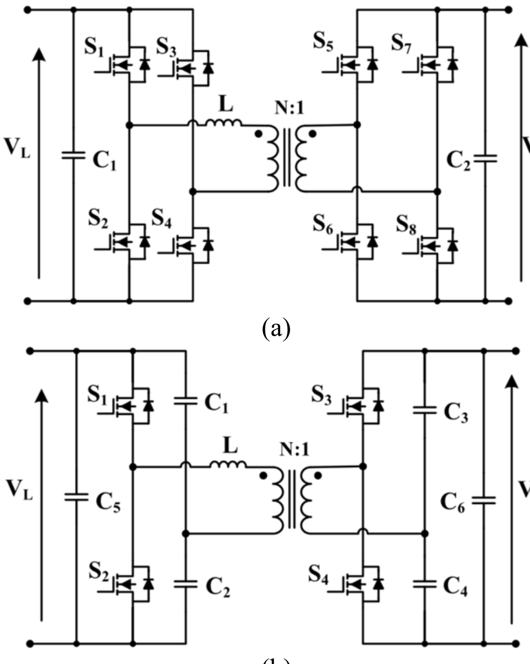
By establishing a complete absence of direct electrical linkage between the input and output sides, galvanic isolation effectively prevents the transmission of detrimental factors such as noise, voltage spikes, and variations in ground potential. These factors possess the potential to inflict harm on the system. Furthermore, isolation aids in diminishing electromagnetic interference and alleviating noise-related concerns that could otherwise compromise the integrity of sensitive components.

Additionally, the provision of isolation ensures a steady output voltage even in the face of input fluctuations, thereby guaranteeing consistent and reliable system performance. In applications involving electric cars, renewable energy sources, and airplanes, the utilization of isolated bidirectional converters emerges as an attractive option. Presented below is a comprehensive list and classification of these topologies.

One widely adopted practice involves utilizing back-to-back bidirectional configurations that are separated by a high-frequency transformer. These back-to-back converters could be half or full-bridge converters. The fundamental structure of the Dual Active Bridge (DAB) converter, which represents the basic topology, is depicted in Fig. 7 (a). The number of switches in bidirectional converters directly affects the power transmission capacity [22]. However, these eight power switches with galvanic isolation transformer, make it well-suited for high-power applications. The use of silicon carbide or gallium nitride power switches can address power losses resulting from switching [23], [24].

This topology represents the most prevalent isolated bidirectional topology and is especially suitable for high-power applications. It is worth highlighting the advantages of this converter, ranging from its dynamic response to the ability to limit phase-shift changes. Control methods such as average current mode control or peak current mode control are well-suited for this topology. Each converter within the configuration generates an AC waveform with a maximum amplitude equivalent to or semi-equivalent to the DC terminal voltage [25]. As a result, the voltage stress on each switch is limited to the bus voltage levels. Moreover, the current stresses on the switches appear to be balanced. Another advantage is that this converter does not require any active or passive components during soft switching. Nonetheless, there are several drawbacks associated with this design. These include high ripple current requiring effective filtering, the need for sophisticated control to prevent DC saturation at both ends, loss of soft switching capability under light loading conditions, the requirement for precise phase shift timers, and increased size due to multiple components, resulting in higher costs and gate losses [26], [27].

In applications where lower power is required and the number of power switches can be reduced to four, this will result in Dual Half Bridge (DHB) topology as shown in Fig 7 (b) which illustrates an isolated bidirectional converter utilizing voltage-fed half-bridge topologies. Using only one transformer, the suggested converter achieves the needed bidirectional flow of electricity for battery charging and discharging. It, also, makes use of MOSFETs' bidirectional power transmission ability, in addition to other benefits of the proposed topology that consist of lower part count due to the use of identical components in the power flow direction, minimal stress on the switches, galvanic isolation, low ripple in the unit charging current, rapid switchover on collapse and recurrence of dc mains, and the requirement of a small number of active switches. Common applications for such design are battery charging and fuel cell systems [24].

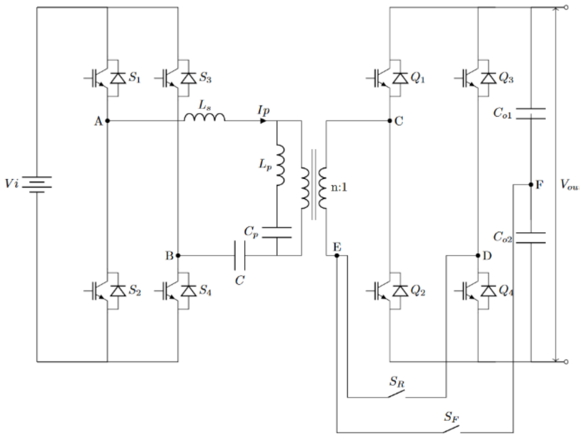


(a)

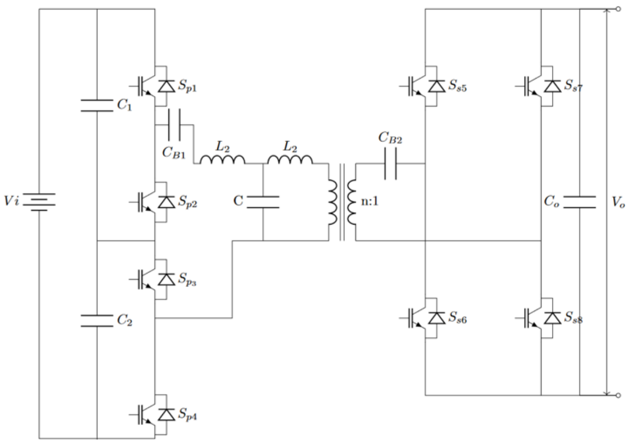
(b)

Fig. 7. (a): Dual active bridge (b) Dual half bridge.

Many isolated topologies are derived from the DAB configuration, for instance, by adding an inductance and capacitance resonant tank to the primary side of the high-frequency transformer an LCLC-DAB topology is developed and reflected in Fig. 8 (a). This topology achieves a high gain with the increase of effective inductance correlated with switching frequency increase [8].



(a)



(b)

Fig. 8. (a) LCLC DAB (b) LCL-T DAB.

With different configurations of inductance and capacitance at the primary side, another topology could be derived which is the LCL-T, where inductance capacitance and inductance are used at the primary side as depicted in Fig.8 (b). The LCL-T network is a three-element immittance-based network that employs phase-shift three-level modulation with a fixed frequency [28]. This modulation technique enables the achievement of zero-voltage switching for transistors while simultaneously regulating the output current during constant voltage and constant power modes [29]. All these basic isolated and non-isolated topologies are compared in Table 1.

3. Novel BDC Topologies

This section introduces novel topologies derived from the commonly used topologies discussed in the previous section. Researchers have aimed to enhance the performance of these basic topologies, including their efficiency, current stress, current and voltage ripples, voltage gain, and other relevant factors. The objective is to address the limitations of the existing basic topologies and improve their overall performance.

Shaabani et al. [30] introduced a novel high-step-up Buck-Boost Converter based on a non-isolated topology. The key innovation lies in the significant increase in voltage gain, attributed to the integration of switched capacitors and inductor cells. Notably, this topology features a single-switch design, simplifying control operations such as Pulse Width Modulation (PWM). In another study, researchers [16] proposed a multiport DC-DC converter tailored for the integration of hybrid Renewable Energy Sources (RES) into DC microgrids. This innovative topology minimizes costs by utilizing the fewest number of devices compared to existing BDC multiport in the literature.

Addressing the challenges of regenerative braking in Electric Vehicles (EV), a novel BDC was presented by authors in [31]. This converter operates in three modes - boost, buck, and buck-boost effectively overcoming issues where the generated voltage might be insufficient to charge the battery with conventional BDCs. Another high-gain non-isolated converter based on the boost topology was proposed by other researchers [32]. This was achieved through the integration of voltage multiplier cells into the topology.

Table 1. Basic topologies comparaison

Topology	Isolation	No. of Switches	Voltage Stress on Switches	Main Characteristics	Application
Buck-boost	Non-isolated	2	High	Simple construction	Uninterrupted power supply & PV
Cascaded Buck-boost	Non-isolated	4	Medium	High voltage gain	EV and Smart Grids
Cuk non-isolated	Non-isolated	2	Medium	Continues input and output currents	power supplies, battery charging, RES
SEPIC&ZETA	Non-isolated	2	Medium	Reduced current ripples	Power system distribution
Hybrid Boost Converter	Non-isolated	2	Medium	Improved efficiency and voltage regulation	EV, RES
Dual Active Bridge	Isolated	8	High	Suitable for high-power applications	High power and Automotive
Dual Half Bridge	Isolated	4	High	Suitable for lower power applications than DAB	Batteries and Automotive
LCLC DAB	Isolated	8	High	Wide range of Switching frequency	RES, EV
LCL-T DAB	Isolated	8	High	High Efficiency	EV charging

In the context of standalone photovoltaic and battery RES systems, a new topology was introduced by researchers [11]. By incorporating a resonant branch into a buck-boost BDC and implementing appropriate control, this topology resulted in increased efficiency for photovoltaic generation. To minimize switching operations and subsequently reduce losses, a six-pack buck-boost converter was proposed by researchers [19]. A soft-switching bidirectional topology designed for solar LED streetlights was developed by another group [33]. This innovative solution aims to enhance the efficiency of self-contained PV-battery street light LEDs.

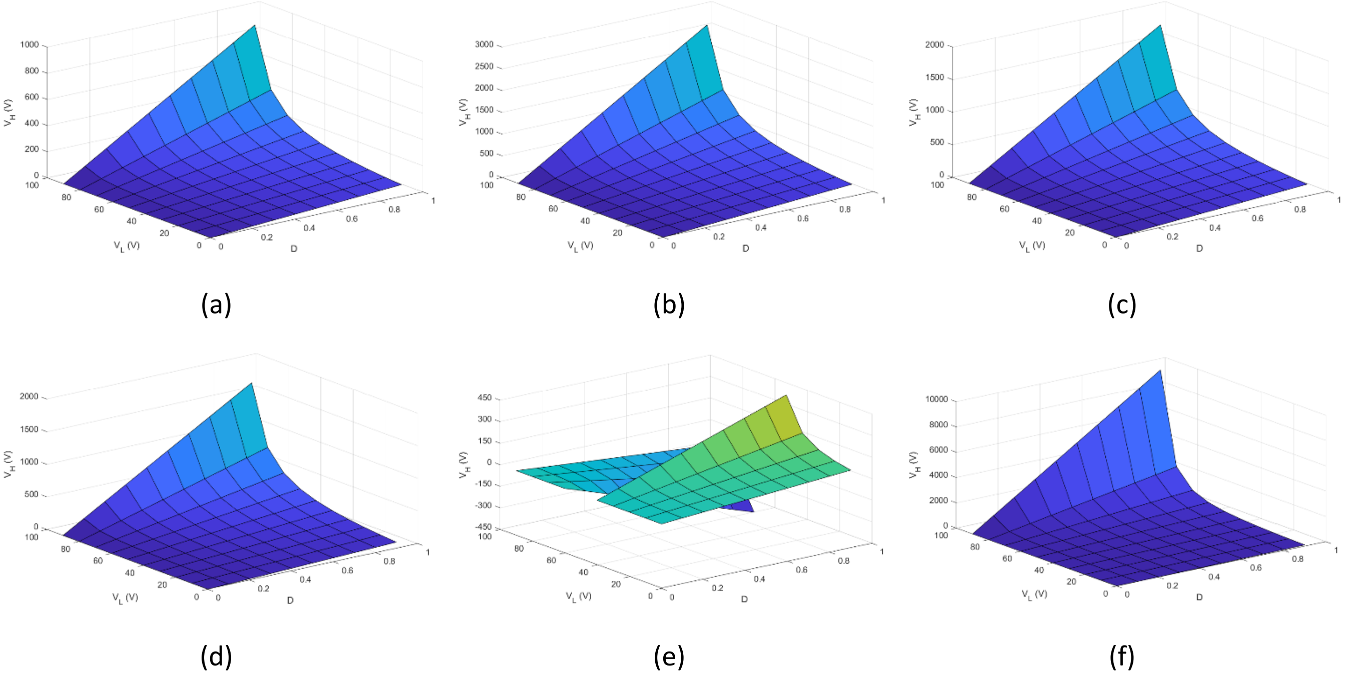
For rural DC microgrid applications, a novel modular multilevel DC-DC converter was introduced by authors in [34]. Based on a modified buck-boost topology, this converter offers advantages such as easy stacking for high voltage gain without the need for voltage-boosting techniques. This enhances the modularity of the system and simplifies its control method. As for EV applications with hybrid energy sources, researchers [35] proposed a switched-capacitor and quasi-Z-source hybrid form for a novel BDC. Notably, this topology exhibits a wide voltage gain range compared to traditional quasi-Z sources.

The literature demonstrates a clear emphasis among researchers on enhancing the performance of the BDC through various means. These include improving efficiency, increasing voltage gain, expanding the gain range, minimizing ripples, and reducing costs. It is worth noting that the determination of gain differs across different topologies, with some relying on control algorithms while others depend solely on the duty cycle. The most used predetermined gain values for different topologies are summarized in Table 2, where G represents the gain factor, D represents the duty cycle, V_H denotes the high-level voltage, and V_L represents the low-level voltage.

Figure 9 visually represents the curves of the different topologies (a) Ideal Boost, (b) Interleaved, (c) Three level, (d) Quazi-Z, (e) H-Bridge, (f) Cascaded, providing valuable insights into their performance characteristics such as high-level voltage versus low-level voltage and duty cycle. In contrast, Fig. 10 offers a comparative graph that enables researchers to evaluate and compare the performance of the topologies, facilitating informed decision-making and identification based on boost voltage gain.

Table 2. Various topologies gain

Reference	Topology	Boost Gain G=V_H/V_L
[36]	Ideal Boost	$G=\frac{1}{1-D}$
[37]	Interleaved	$G=\frac{3}{1-D}$
[38]	Three Level	$G=\frac{2}{1-D}$
[39]	Quasi-Z	$G=\frac{1+D}{1-d}$
[40]	H-Bridge	$G=\frac{1}{1-2D}$
[41]	Cascaded	$G=\frac{1+D-D^2}{(1-d)^2}$



(a) (b) (c)

(d) (e) (f)

Fig. 9. High voltage variation versus low voltage level and duty cycle (a) Ideal Boost, (b) Interleaved, (c) Three level, (d) Quazi-Z, (e) H-Bridge, (f) Cascaded.

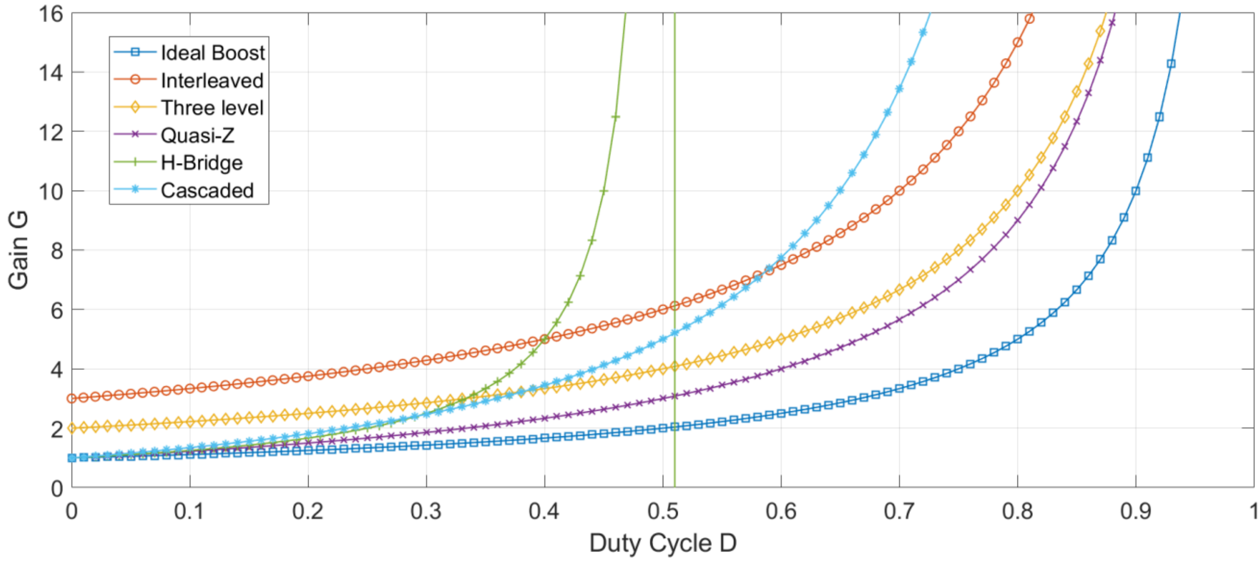


Fig. 10. Voltage gain of various BDC.

Conversion efficiency, crucial in bidirectional DC-DC converters, measures output power against input power. Yet, due to parasitic parameters and frequent switching, losses like conduction and switching occur, lowering output power and elevating converter temperature. This inefficiency not only wastes energy but demands larger cooling systems. Hence, enhancing conversion efficiency is vital. This study evaluates typical bidirectional DC-DC converters versus input voltage in per unit with a step of 0.2 pu. Efficiency curves in Fig.11 reveal efficiency increases as input voltage increases, due to lowering losses from decreased input current.

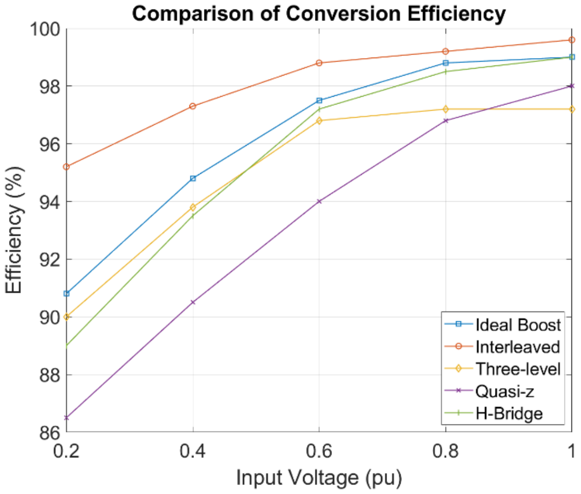


Fig. 11. Conversion efficiency of various BDC.

4. Control Strategies of BDC

This section delves into the control strategies employed in different topologies of the BDC. These strategies encompass both conventional approaches and innovative methods. The PID controller is commonly employed as the initial choice due to its straightforward implementation process, compatibility with other control systems, and applicability across a wide range of topologies and control challenges. Controlling the power flow in both directions is a prevalent issue in non-isolated BDC [13].

As BDC topologies exhibit non-linear configurations, the dynamic equation of the converter changes. Linearizing the control algorithm by employing linearization techniques is one approach to address this issue. However, due to its dependence on assumptions and predictions, this technique may not accurately represent the model. Consequently, non-linear control methods are preferred to operate BDCs, offering a fast, dynamic, and reliable system capable of adapting to external disturbances [42]. Sliding mode control (SMC) is a non-linear control approach known for its remarkable precision, resilience, and simplicity in tuning and application [43]. In [44], the authors developed a high-order sliding mode control to enhance robustness in an interleaved BDC configuration.

A popular control method for DABs is switching with an identifiable phase shift of 0.5 duty ratio to the transformer's primary and secondary sides. This control is called single phase shift (SPS) which aims to control the direction and magnitude of the power flow, decrease the voltage, and control the needed power for the battery through the variation of voltage. It leads to dynamic response but has poor backflow control of power [45]

Fuzzy logic controllers (FLC) are effective for complex, non-linear systems that experience disturbances and parameter fluctuations, requiring a robust response. They are commonly used in BDCs due to their adaptability and ability to operate without prior knowledge of system characteristics, resulting in reduced power wastage from the utility grid. FLCs can be categorized as Fuzzy PI control and Fuzzy PSOPI control, and they consist of fuzzification, knowledge base, decision-making, rule base, and defuzzification components. Achieving optimal performance with FLC requires advanced knowledge in the field [46], [47].

Artificial Neural Network (ANN) is crucial in DC-DC converter control especially in hybrid EVs as it enables superior forecasted control compared to fuzzy control. The system exhibits faster response with ANN-based PID control. However, fuzzy logic can replicate expert knowledge and be combined with common wisdom. Neural network approaches like RFFN and RBFN are used in control algorithms such as ANFIS and FNN. For bidirectional buck-boost converters (BBBC) with fluctuating load characteristics, conventional PID control is insufficient [41], [42]. Large memory, processing time, and the required training are considered drawbacks for this control. To achieve better control, the model predictive control algorithm, combined with ANN training, offers improved efficiency and effectiveness [48], [49], [50].

Table 3. Control strategies comparison

Reference	Control Algorithm	Advantages	Disadvantages	Applications
[13]	PID Controller	- Straightforward implementation process - Compatibility with other control systems - Applicability across a wide range of topologies and control challenges	- Limited accuracy in non-linear configurations -May require tuning adjustments	Non-isolated BDC
[43]	Sliding Mode Control	- Remarkable precision and resilience - Simple tuning and application	- Limited backflow control of power	Interleaved BDC
[40]	Fuzzy Logic Controller	- Effective for complex, non-linear systems - Adaptability and operation without prior knowledge of system characteristics	- Requires advanced knowledge in the field	BDCs
[41]	Artificial Neural Network (ANN)	- Superior forecasted control - Faster response with ANN-based PID control	- Large memory and processing time requirements - Training complexity	Hybrid EVs
[48], [49], [50]	Model Predictive Control (MPC) with ANN	- Improved efficiency and effectiveness - Better control over fluctuating load characteristics	- High processing time and training requirements	Bidirectional Buck-Boost Converters (BBBC)
[51]	Digital Control	- Improved transient response, reduced switching losses, enhanced efficiency, and stability	- Difficulty in implementation - High processing power requirements	Flyback BDC
[52]	Deep Learning Control	- Enhanced performance - Higher efficiency and reduced overshoot during transients	- Requires training and data availability	BDC in V2G applications
[53], [54]	Novel Approaches	- Address specific challenges and enhance performance	- Application-specific, may not be universally applicable	Various applications in BDCs

Digital control is usually used in flyback BDC to improve the transient response, reduce switching losses, enhance efficiency, and improve stability. The limitations of this control are the difficulty in implementation and the high processing power requirements [51].

In recent studies on control strategies for BDC, several novel approaches have been proposed to enhance performance and address specific challenges. Authors in [53] introduce a control strategy that incorporates virtual inertia to eliminate changes in the DC-link voltage, thereby improving grid operation reliability and stability. [54] focuses on minimizing voltage stress on the switches by implementing a voltage doubler concept in BDC control, which was experimentally verified on a 2kW system operating at 100kHz.

Deep learning control for BDC in V2G applications is explored in [52], where a deep neural network control is employed to enhance performance, resulting in higher efficiency and reduced overshoot during transients. The utilization of a DAB BDC is proposed in [55], combining an SPS control and variable frequency control to achieve a loss-less primary bridge and peak efficiency of approximately 99% across a range of power outputs.

To address converter harmonics, power factor correction, and voltage regulation in AC supply, [14] proposes a genetic algorithm-based tuning PID controller for power flow management. [12] introduces a novel PWM algorithm aimed at eliminating interference from electromagnetics, to improve power quality specifically for Electric Vehicle (EV) applications.

In terms of modulation schemes for DAB BDCs, [56] presents a novel triple-phase shift control strategy derived from the single-phase shift and double-phase shift approaches. This novel control scheme minimizes current stress while maintaining the required voltage conversion ratio. These recent studies demonstrate the ongoing efforts to develop advanced control strategies for BDCs, addressing various performance parameters and application-specific requirements. A comparison between these various control strategies are summarized in Table 3.

5. Conclusion

This paper presents a comprehensive investigation of bidirectional DC-DC converters, covering their topology structures, control algorithms, and applications. These converters enable two-way power flow and find applications in renewable energy sources, power converters, battery chargers, and electric vehicles under vehicle-to-grid operation. The paper classifies bidirectional DC-DC converters into isolated and non-isolated structures, with various topologies available in each category. Isolated topologies, including Dual Active Bridge, half active bridge, LCLC DAB, and LCL-T DAB, provide galvanic isolation but are associated with increased size and weight due to the isolating transformer. Non-isolated topologies, such as buck-boost, cascaded buck-boost, Cuk, and SEPIC&ZETA, are designed for compact applications. The paper compares these topologies based on their characteristics, number of switches, and application suitability.

In addition to conventional topologies, the paper explores novel topologies proposed in the literature to enhance the performance of bidirectional DC-DC converters in terms of efficiency, gain range, voltage gain, ripple values, and other indicators. The investigation particularly focuses on the voltage gain in boost mode, comparing various topologies through graphical illustrations. Furthermore, the paper discusses the control techniques employed for bidirectional DC-DC converters, covering both conventional and innovative approaches. Researchers in the field continuously strive to achieve optimal performance and address gaps in existing literature through novel control proposals. The review aims to assist researchers in selecting appropriate topology designs and controls for specific applications by providing a graphical comparison of different topologies.

Acknowledgements

The author declares that no external funding or support was received for this work.

Author Contributions

A.E.G. was responsible for the conceptualization, validation, resources, data curation, software development, methodology, formal analysis, investigation, original draft preparation, review and editing, and visualization. The Author has read and agreed to the published version of the manuscript.

Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

[1] V. F. Pires, D. Foito, A. Cordeiro, and A. J. Pires, “A bidirectional DC-DC converter to interlink unipolar and bipolar DC microgrids,” 2021 9th International Conference on Smart Grid (icSmartGrid), pp. 37–42, June 2021. doi: 10.1109/icSmartGrid52357.2021.9551209.

[2] O. E. Oyewole and K. H. Ahmed, “Comparative analysis of decoupling control methods for multiport-isolated bidirectional DC-DC converter with hydrogen storage system integration,” 2023 11th International Conference on Smart Grid (icSmartGrid), pp. 1–8, June 2023. doi: 10.1109/icSmartGrid58556.2023.10170888.

[3] V. F. Pires, A. Cordeiro, D. Foito, and J. F. Silva, “Control of bidirectional quadratic DC-DC converters for storage support of DC power grids,” 2018 7th International Conference on Renewable Energy Research and Applications (ICRERA), pp. 227–232, Oct. 2018. doi: 10.1109/ICRERA.2018.8566946.

[4] S. Ikeda, K. Kajiwara, K. Tsuji, and F. Kurokawa, “Efficiency improvement of isolated bidirectional boost full bridge DC-DC converter,” 2018 7th International Conference on Renewable Energy Research and Applications (ICRERA), pp. 673–676, Oct. 2018. doi: 10.1109/ICRERA.2018.8566997.

[5] A. Sahbani, K. Cherif, and K. B. Saad, “Multiphase interleaved bidirectional DC-DC converter for electric vehicles and smart grid applications,” International Journal of Smart Grid-ijSmartGrid, vol. 4, no. 2, June 2020.

[6] J. Yuan, L. Dorn-Gomba, A. D. Callegaro, J. Reimers, and A. Emadi, “A review of bidirectional on-board chargers for electric vehicles,” IEEE Access, vol. 9, pp. 51501–51518, 2021. doi: 10.1109/ACCESS.2021.3069448.

[7] S. Semsar, T. Soong, and P. W. Lehn, “On-board single-phase integrated electric vehicle charger with V2G functionality,” IEEE Transactions on Power Electronics, vol. 35, no. 11, pp. 12072–12084, Nov. 2020. doi: 10.1109/TPEL.2020.2982326.

[8] A. F. P. A., R. Ramchand, and H. S. Nair, “A survey of bi-directional DC-DC converters for transportation electrification and microgrid applications,” 2023 International Conference on Power, Instrumentation, Control and Computing (PICC), pp. 1–6, Apr. 2023. doi: 10.1109/PICC57976.2023.10142639.

[9] G. I. Hasyim, S. Wijanarko, J. Furqani, A. Rizqiawan, and P. A. Dahono, “A current control method for bidirectional multiphase DC-DC boost-buck converter,” International Journal of Electrical and Computer

Engineering, vol. 12, no. 3, pp. 2363–2377, June 2022. doi: 10.11591/ijece.v12i3.pp2363-2377.

[10] M. Eull and M. Preindl, “Bidirectional three-level DC-DC converters: Sum-difference modeling and control,” 2017 IEEE Transportation Electrification Conference and Expo (ITEC), pp. 573–578, June 2017. doi: 10.1109/ITEC.2017.7993334.

[11] K.-H. Chao and C.-H. Huang, “Bidirectional DC-DC soft-switching converter for stand-alone photovoltaic power generation systems,” IET Power Electronics, vol. 7, no. 6, pp. 1557–1565, 2014. doi: 10.1049/iet-pel.2013.0335.

[12] Z. Zhang and K.-T. Chau, “Pulse-width-modulation-based electromagnetic interference mitigation of bidirectional grid-connected converters for electric vehicles,” IEEE Transactions on Smart Grid, vol. 8, no. 6, pp. 2803–2812, Nov. 2017. doi: 10.1109/TSG.2016.2541163.

[13] S. A. Gorji, H. G. Sahebi, M. Ektesabi, and A. B. Rad, “Topologies and control schemes of bidirectional DC-DC power converters: An overview,” IEEE Access, vol. 7, pp. 117997–118019, 2019. doi: 10.1109/ACCESS.2019.2937239.

[14] K. Bharathi and M. Sasikumar, “Power flow control based on bidirectional converter for hybrid power generation system using microcontroller,” Microprocessors and Microsystems, vol. 82, p. 103950, Apr. 2021. doi: 10.1016/j.micpro.2021.103950.

[15] P. K. Maroti, S. Padmanaban, M. S. Bhaskar, V. K. Ramachandaramurthy, and F. Blaabjerg, “The state-of-the-art of power electronics converters configurations in electric vehicle technologies,” Power Electronic Devices and Components, vol. 1, p. 100001, Mar. 2022. doi: 10.1016/j.pedc.2021.100001.

[16] J. Zeng, X. Du, and Z. Yang, “A multiport bidirectional DC-DC converter for hybrid renewable energy system integration,” IEEE Transactions on Power Electronics, vol. 36, no. 11, pp. 12281–12291, Nov. 2021. doi: 10.1109/TPEL.2021.3082427.

[17] L. Gevorkov, J. L. Domínguez-García, and À. Filbà Martínez, “Modern trends in multiport converters: Isolated, non-isolated, and partially isolated,” 2022 IEEE 63rd International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), pp. 1–6, Oct. 2022. doi: 10.1109/RTUCON56726.2022.9978910.

[18] G. Vacheva, V. Dimitrov, and N. Hinov, “Modelling and control of bidirectional buck-boost converter for electric vehicles applications,” 2019 16th Conference on Electrical Machines, Drives and Power Systems (ELMA), pp. 1–4, June 2019. doi: 10.1109/ELMA.2019.8771496.

[19] Y. Kim and S. Choi, “Bidirectional six-pack SiC boost-buck converter using droop control in DC nano-grid,” Sensors, vol. 23, no. 21, 2023. doi: 10.3390/s23218777.

[20] J. Wang, B. Wang, L. Zhang, J. Wang, N. I. Shchurov, and B. V. Malozyomov, “Review of bidirectional DC-DC converter topologies for hybrid energy storage system of new energy vehicles,” Green Energy and Intelligent Transportation, vol. 1, no. 2, p. 100010, Sept. 2022. doi: 10.1016/j.geits.2022.100010.

[21] S. Jeyasudha and B. Geethalakshmi, “Performance analysis of reduced switch boost multilevel hybrid converter,” 2018 4th International Conference on Electrical Energy Systems (ICEES), pp. 14–19, Feb. 2018. doi: 10.1109/ICEES.2018.8442395.

[22] Y.-K. Tai and K.-I. Hwu, “A control design technology of isolated bidirectional LLC resonant converter for energy storage system in DC microgrid applications,” Energies, vol. 16, no. 19, 2023. doi: 10.3390/en16196877.

[23] V. V, R. A. C, and V. S. Reddy, “Bidirectional DC-DC converter circuits and smart control algorithms: A review,” SSRN, Oct. 2022. [Online]. Available: https://papers.ssrn.com/abstract=4255850

[24] P. He and A. Khaligh, “Comprehensive analyses and comparison of 1 kW isolated DC-DC converters for bidirectional EV charging systems,” IEEE Transactions on Transportation Electrification, vol. 3, no. 1, pp. 147–156, Mar. 2017. doi: 10.1109/TTE.2016.2630927.

[25] K. López-Rodríguez, W. Gil-González, and A. Escobar-Mejía, “Design and implementation of a PI-PBC to manage bidirectional power flow in the DAB of an SST,” Results in Engineering, vol. 14, p. 100437, June 2022. doi: 10.1016/j.rineng.2022.100437.

[26] B. Zhao, Q. Song, W. Liu, and Y. Sun, “Overview of dual-active-bridge isolated bidirectional DC-DC converter for high-frequency-link power-conversion system,” IEEE Transactions on Power Electronics, vol. 29, no. 8, pp. 4091–4106, Aug. 2014. doi: 10.1109/TPEL.2013.2289913.

[27] Y. Harrye, A. Abdalla, and H. A. Mahasneh, “The generalization of bidirectional dual active bridge DC/DC converter modulation schemes: State-of-the-art analysis under triple phase shift control,” Energies, vol. 16, no. 22, 2023. doi: 10.3390/en16227577.

[28] H. Al Attar, M. A. Hamida, M. Ghanes, and M. Taleb, “Review on modeling and control strategies of DC-DC LLC converters for bidirectional electric vehicle charger applications,” Energies, vol. 16, no. 9, 2023. doi: 10.3390/en16093946.

[29] S. Mukherjee, J. M. Ruiz, and P. Barbosa, “A high power density wide range DC-DC converter for universal electric vehicle charging,” IEEE Transactions on Power Electronics, vol. 38, no. 2, pp. 1998–2012, Feb. 2023. doi: 10.1109/TPEL.2022.3217092.

[30] M. Shaabani, A. Mirzaei, M. Rezvanyvardom, F. Khosravi, and S. A. Gorji, “A hybrid switched-inductor/switched-capacitor DC-DC converter with high voltage gain using a single switch for photovoltaic

application," Energies, vol. 16, no. 14, 2023. doi: 10.3390/en16145524.

[31] N. Dias, A. J. Naik, and V. N. Shet, "A novel tri-mode bidirectional DC-DC converter for enhancing regenerative braking efficiency and speed control in electric vehicles," World Electric Vehicle Journal, vol. 15, no. 1, 2024. doi: 10.3390/wevj15010012.

[32] S. A. Gorji, H. Gholizadeh, and D. Sera, "A new non-isolated high-gain single-switch DC-DC converter with continuous input current," IECON 2023 - 49th Annual Conference of the IEEE Industrial Electronics Society, pp. 1–5, Oct. 2023. doi: 10.1109/IECON51785.2023.10312183.

[33] S. Danyali, M. Shirkhani, J. Tavoosi, A. G. Razi, M. M. Salah, and A. Shaker, "Developing an integrated soft-switching bidirectional DC/DC converter for solar-powered LED street lighting," Sustainability, vol. 15, no. 20, 2023. doi: 10.3390/su152015022.

[34] R. D. N. Aditama, N. Ramadhani, T. Ardriani, J. Furqani, A. Rizqiawan, and P. A. Dahono, "New modular multilevel DC-DC converter derived from modified buck-boost DC-DC converter," Energies, vol. 16, no. 19, 2023. doi: 10.3390/en16196950.

[35] Y. Zhang, Q. Liu, Y. Gao, J. Li, and M. Sumner, "Hybrid switched-capacitor/switched-quasi-Z-source bidirectional DC-DC converter with a wide voltage gain range for hybrid energy sources EVs," IEEE Transactions on Industrial Electronics, vol. 66, no. 4, pp. 2680–2690, Apr. 2019. doi: 10.1109/TIE.2018.2850020.

[36] M. Nikbakht, K. Abbaszadeh, S. Abbasian, H. Allahyari, and S. A. Gorji, "An ultra-step-up quadratic boost DC-DC converter based on coupled inductors and quasi-resonance operation," IEEE Journal of Emerging and Selected Topics in Industrial Electronics, vol. 4, no. 4, pp. 1096–1109, Oct. 2023. doi: 10.1109/JESTIE.2023.3302706.

[37] F. Wang, Y. Wang, F. Zhang, and C. Teng, "A novel high-conversion-ratio bidirectional three-phase DC-DC converter," The Journal of Engineering, vol. 2019, no. 16, pp. 2764–2771, 2019. doi: 10.1049/joe.2018.8782.

[38] Y. Zhang, Y. Gao, J. Li, and M. Sumner, "Interleaved switched-capacitor bidirectional DC-DC converter with wide voltage-gain range for energy storage systems," IEEE Transactions on Power Electronics, vol. 33, no. 5, pp. 3852–3869, May 2018. doi: 10.1109/TPEL.2017.2719402.

[39] Y. Zhang, Q. Liu, J. Li, and M. Sumner, "A common ground switched-quasi-Z-source bidirectional DC-DC converter with wide-voltage-gain range for EVs with hybrid energy sources," IEEE Transactions on Industrial Electronics, vol. 65, no. 6, pp. 5188–5200, June 2018. doi: 10.1109/TIE.2017.2756603.

[40] H. Bi, P. Wang, and Z. Wang, "Common grounded H-type bidirectional DC-DC converter with a wide voltage conversion ratio for a hybrid energy storage system," Energies, vol. 11, no. 2, Feb. 2018. doi: 10.3390/en11020349.

[41] Z. Wang, P. Wang, H. Bi, and M. Qiu, "A bidirectional DC/DC converter with wide-voltage gain range and low-voltage stress for hybrid-energy storage systems in electric vehicles," Journal of Power Electronics, vol. 20, no. 1, pp. 76–86, Jan. 2020. doi: 10.1007/s43236-019-00017-2.

[42] C. Zhou, Y. Wang, X. Zhang, and S. Qu, "Comparative research of digital-PID and sliding mode control strategy for DC/DC converter," Proceedings of 2014 International Conference on Modelling, Identification & Control, pp. 1–5, Dec. 2014. doi: 10.1109/ICMIC.2014.7020717.

[43] A. Etxeberria, I. Vechiu, H. Camblong, and J.-M. Vinassa, "Comparison of sliding mode and PI control of a hybrid energy storage system in a microgrid application," Energy Procedia, vol. 12, pp. 966–974, 2011. doi: 10.1016/j.egypro.2011.10.127.

[44] Y. Jia, D. Wang, G. Sun, Y. Ni, K. Song, and Y. Li, "High-order sliding-mode control strategy for improving robustness of three-phase interleaved bidirectional converter," Sustainability, vol. 15, no. 12, 2023. doi: 10.3390/su15129720.

[45] M. H. Ashfaq, J. A. Selvaraj, and N. A. Rahim, "Control strategies for bidirectional DC-DC converters: An overview," IOP Conference Series: Materials Science and Engineering, vol. 1127, no. 1, p. 012031, Mar. 2021. doi: 10.1088/1757-899X/1127/1/012031.

[46] F. Tlili and F. Bacha, "Fuzzy logic direct power control of a bidirectional three-phase AC/DC converter," 2020 20th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA), pp. 201–206, Dec. 2020. doi: 10.1109/STA50679.2020.9329316.

[47] M. Nagaiah and K. C. Sekhar, "Analysis of fuzzy logic controller based bi-directional DC-DC converter for battery energy management in hybrid solar/wind micro grid system," International Journal of Electrical and Computer Engineering, vol. 10, no. 3, pp. 2271–2284, June 2020. doi: 10.11591/ijece.v10i3.pp2271-2284.

[48] R. S. R. Sankar, K. Deepika K., M. Alsharef, and B. Alamri, "A smart ANN-based converter for efficient bidirectional power flow in hybrid electric vehicles," Electronics, vol. 11, no. 21, 2022. doi: 10.3390/electronics11213564.

[49] M. Y. Bote-Vazquez, J. Ramirez-Hernandez, L. Hernandez-Gonzalez, E. D. Delgado-Piña, and O. U. Juarez-Sandoval, "Artificial neural network-based voltage control in a DC-DC converter using a predictive model," 2022 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC), pp. 1–6, Nov. 2022. doi: 10.1109/ROPEC55836.2022.10018649.

[50] G. Rojas-Dueñas, J. Roger Riba, and M. Moreno-Eguilaz, "Modeling of a DC-DC bidirectional converter used in mild hybrid electric vehicles from measurements,"

Measurement, vol. 183, p. 109838, Oct. 2021. doi: 10.1016/j.measurement.2021.109838.

[51] P. Thummala, D. Maksimovic, Z. Zhang, and M. A. E. Andersen, “Digital control of a high-voltage (2.5 kV) bidirectional DC-DC flyback converter for driving a capacitive incremental actuator,” IEEE Transactions on Power Electronics, vol. 31, no. 12, pp. 8500–8516, Dec. 2016. doi: 10.1109/TPEL.2016.2520497.

[52] M. K. Banda, S. Madichetty, and S. K. Nandavaram Banda, “Implementation of deep learning-based bi-directional DC-DC converter for V2V and V2G applications—An experimental investigation,” Energies, vol. 16, no. 22, 2023. doi: 10.3390/en16227614.

[53] A. Bakeer, A. Chub, A. Abid, S. A. Zaid, T. A. H. Alghamdi, and H. S. Salama, “Enhancing grid-forming converters control in hybrid AC/DC microgrids using bidirectional virtual inertia support,” Processes, vol. 12, no. 1, 2024. doi: 10.3390/pr12010139.

[54] W. F. Lopes, M. L. da S. Martins, A. Converti, H. V. Siqueira, and C. H. Illa Font, “Experimental evaluation of a 2 kW/100 kHz DC-DC bidirectional converter based on a Cuk converter using a voltage-doubler concept,” Energies, vol. 17, no. 2, 2024. doi: 10.3390/en17020362.

[55] V. Esteve, J. L. Bellido, J. Jordán, and E. J. Dede, “Improving the efficiency of an isolated bidirectional dual active bridge DC-DC converter using variable frequency,” Electronics, vol. 13, no. 2, 2024. doi: 10.3390/electronics13020294.

[56] J. Huang, Y. Wang, Z. Li, and W. Lei, “Unified triple-phase-shift control to minimize current stress and achieve full soft-switching of isolated bidirectional DC-DC converter,” IEEE Transactions on Industrial Electronics, vol. 63, no. 7, pp. 4169–4179, Jul. 2016. doi: 10.1109/TIE.2016.2543182.