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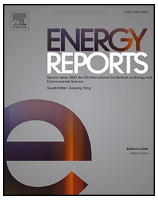

Review article

Recent advances of step-up multi-stage DC-DC converters: A review on classifications, structures and grid applications

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ABSTRACT

In the contemporary landscape of trend industries including sustainable energy sources, high-voltage direct current, and electrified mobility, the need for power conversion units to bridge disparate sections is felt more than ever before. Among these conversion units, the step-up DC-DC converters occupy a pivotal role, elevating the DC voltage levels and facilitating interactions between converters and circuits. However, the multistage DC-DC converters, prevalent in large-scale industries, offer higher voltage gains and power density. This review paper has categorized the multistage DC-DC converters into isolated/non-isolated, voltage-fed/current-fed, unidirectional/bidirectional, hard-switched/soft-switched, and step-up/step-down configurations. It has been followed by a brief review of various voltage boosting techniques, containing an analysis of multi-staging voltage boosting methods and recent advances in converter structures. Then, the multistage DC-DC converters have been classified into several distinct categories: quadratic gain, cascaded, interleaved, modular, multilevel, and hybrid structures. Recent advancements and developments in each of these categories have been meticulously examined, with a focus on their fundamental concepts, advantages, and disadvantages. In particular, the voltage gains, voltage stresses, and current stresses associated with quadratic gain and cascaded DC-DC converters have been analyzed and compared in detail. Furthermore, an in-depth exploration of the structures and configurations of interleaved, modular, and multilevel DC-DC converters has been conducted. This includes a discussion on the combinations of modules, the benefits arising from these integrations, and insights for future developments. The applications of each category of multistage DC-DC converters across various industries—particularly in grid applications—have been thoroughly analyzed. Subsequently, these converters have been evaluated based on several criteria: reliability, component count, control complexity, voltage gain, power level, cost, and weight. The prioritization of these factors has also been systematically presented.

1. Introduction

1.1. Background and motivation

In the contemporary landscape of power networks and automotive innovation, the emergence of Renewable Energy Sources (RESs) and Electric Vehicles (EVs) underscores the necessity for advanced power conversion technologies. High-voltage Direct Current (HVDC) systems have become pivotal for integrating the RESs into power grids, facilitating efficient long-distance energy transmission and enabling the incorporation of solar and wind energy sources (Wang et al., 2020a). These systems enhance grid resilience by managing energy generation fluctuations and promoting a transition to cleaner energy sources. The growing EV market presents both challenges and opportunities in power electronics, necessitating efficient solutions for energy conversion, battery management, and charging infrastructure (Bassa de los Mozos et al., 2019). The Multistage DC-DC Converters (MSDCCs) have attracted attentions for their ability to meet the efficiency and power density demands of the RESs, the HVDC systems and the EVs. The MSDCCs are capable to elevate voltages to high or ultrahigh levels, thereby improving grid performance and energy efficiency.

Despite their advantages—such as superior voltage regulation, high power density, and efficiency across a wide load range—the MSDCCs also face challenges including increased complexity, higher costs, and

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control scheme difficulties. Their units' configuration can be tailored in series, parallel, or series-parallel arrangements to optimize voltage and current outputs, necessitating meticulous selection of each stage for optimal performance. As MSDCCs are composed of several stages, they provide the potential of independent control of each stage in most of the cases. This makes the MSDCCs voltage regulation more precise, appropriate for sensitive loads. Due to dependency of stages to each other and their interaction of some of the MSDCCs, each stage must be selected obsessively, considering the control cooperation, stability, reliability, voltage gain, etc.

2. Literature review

Numerous voltage boosting techniques have been explored by researchers to achieve high and ultrahigh voltage gains in DC-DC converters. These methods typically involve the integration of passive and/or active components within the circuit, mostly result in a nonlinear gain relationship. High step-up DC-DC converters generally utilize multiple arrays of capacitors and/or inductors to elevate voltage levels, relying on energy storage and timed release. Among these techniques, Switched Capacitor (SC) configurations are particularly prominent (Forouzesh et al., 2017). In SC systems, capacitors are charged by the input DC source, with output voltage amplified through the connection arrangements changes (Palumbo and Pappalardo, 2010). Notable SC circuits include Ladder (Xie and Smedley, 2021), Dickson (Li et al., 2019a), and Makowski or Fibonacci (Sundararaman et al., 2020) designs. Voltage Multiplier Cells (VMCs), characterized by their simplicity, primarily consist of capacitors, diodes, and occasionally inductors; however, they are predominantly utilized in low-power applications (Forouzesh et al., 2017; Alcazar et al., 2012). Another category, the Voltage Lifting (VL) methods, focuses on charging/energizing capacitors and inductors (Navamani et al., 2021). Researchers frequently combine these techniques with traditional step-up converters in cascaded and quadratic gain topologies. F.L. Luo has proposed various voltage lifted converters including self-lift, re-lift, triple-lift, quadruple-lift, and super-lift converters (Navamani et al., 2021). Additionally, the Switched Inductor (SL) cells have emerged, with derivatives such as basic SL, elementary-lift SL, self-lift SL, and double self-lift SL cells gaining recognition (Axelrod et al., 2008). Coupled inductors are favored among the DC-DC converters designers due to their inherent merits on voltage gain and current characteristics (Lu et al., 2015; Huang and Lehman, 2016). By integrating the SC configurations with coupled inductors, researchers can achieve even greater voltage gains (Hsieh et al., 2011; Tang et al., 2014a). Furthermore, employing tapped inductors—switched-tapped, diode-tapped, or rail-tapped—affords enhanced flexibility in voltage gain regulation (Vazquez et al., 2007; Cheng, 2006).

Numerous voltage boosting techniques have been explored over recent decades, leading to complexities in selecting the appropriate method for designing a high step-up DC-DC converter. The choice utterly depends on various factors, including rated power, desired voltage gains, reliability, load sensitivity, cost, etc. Review papers serve as valuable resources for designers, elucidating the advantages and disadvantages of different converter topologies, techniques, and control schemes to facilitate informed decision-making. For instance, M. Forouzesh et al. provide a thorough review including the SCs, the VMCs, magnetic coupling, and more, evaluating their topologies and applications (Forouzesh et al., 2017). This work also presents comparative data on voltage gains and component counts across various configurations while clearly expressing the operational mechanisms and developmental hierarchies of each technique.

The review investigation in (Hossain and Rahim, 2018) explores advanced DC-DC converter topologies, beginning with classical isolated and non-isolated converters and their combinations. Afterward, they took a glimpse on resonant converters just confining on introducing some of most famous and fascinating topologies and their cons and pros. More attention has been given to multilevel (Lüth et al., 2013) and interleaved (Ni et al., 2011) structures. It has mentioned that interleaving techniques is utilized to suppress the input current ripple and support higher current levels, as a consequence. Interleaving does not affect the voltage gain, solitarily. Also, some instances of modular and cascaded multilevel DC-DC converters (MLDCC) have been introduced in (Hafez, 2015; Dey et al., 2017). Moreover, different control techniques such as Asymmetric Pulse Width Modulation (APWM), Phase-Shift (PS) control, Extended PS (EPS), Single-PS (SPS), Dual-PS (DPS), Triple-PS (TPS), Closed-Loop Control (CLC), Open-Loop Control (OLC), Current Synchronized Control (CSC), Space Vector Modulation (SVM), etc., have been addressed at a glance. Eroglu et al. provide an extensive analysis of bidirectional MLDCCs for the EVs Battery Storage Systems (BSSs) (Eroğlu et al., 2021). They categorize the MLDCCs into cascaded submodule multilevel, diode-clamped multilevel, flying-capacitor multilevel, and Modular-Multilevel Converters (MMC). The review details commonly used rechargeable battery technologies in EVs and thoroughly examines the circuit architecture and module topologies of both single and two-stage MMCs, following a similar approach for the other MLDCC types.

Isolated High Step-up DC-DC (IHSDC) converters utilize transformers, offering advantages such as lower Electromagnetic Interference (EMI), non-common ground configurations, and shock protection, unlike the non-isolated ones. These converters are particularly suitable for sensitive applications, including medical devices, prompting extensive research in this area. In (Revathi and Prabhakar, 2016), the Non-Isolated High Step-up DC-DC (NHSDC) converters topologies for the Photovoltaic (PV) application have been introduced. The conventional grid connected and grid-tied PV systems have also been introduced. The main point that has been widely concerned by the authors is considered the diodes' reverse recovery time during the design procedure, especially for high duty cycles close to unity. They have concluded to achieve high voltage gains in a high power DC-DC converter, it is recommended to combine multiple voltage boosting techniques. While these techniques are briefly analyzed, detailed discussions on specific topologies are often lacking. H. Tarzamni et al. have provided a fair comparative review of most well-known NHSDC converters since 2010–2023 (Tarzamni et al., 2023). They have redesigned all of the aforementioned converters with same operating conditions and compared them from various criteria such as components count, voltage gain, cost, weight, size, gain/cost, gain/weight, gain/size, etc. Furthermore, the NHSDCs have been categorized to fourteen groups to evaluate three last mentioned criteria. These categories are Current-Fed (CF) (Babaei et al., 2017), Voltage-Fed (VF) (Tseng et al., 2015), common ground (Dwari and Parsa, 2010), floating ground (Zhao et al., 2021), single-stage (Eskandarpour Azizkandi et al., 2020), multistage (Lahooti Eshkevari et al., 2021), interleaved, multilevel, SC, SL, switched capacitor and inductor, with snubber or clamp (Shaneh et al., 2019), unidirectional (Choi et al., 2016), and bidirectional (Ashique and Salam, 2018). They have deduced using coupled inductors can significantly enhance voltage gain and is applicable to high-power converters.

A comprehensive review of DC-DC converter architectures compatible with Maximum Power Point Tracking (MPPT) for RESs is presented in (Raghavendra et al., 2019). The study compares isolated and non-isolated topologies as well as modulation strategies; however, it does not adequately address MSDCCs. B. Sri Revathi et al. explore solar PV systems, focusing on configurations ranging from low to high power and gain layouts (Revathi and Prabhakar, 2016). Additionally, a focused investigation on buck-boost converters is conducted in (Mumtaz et al., 2021), which exclusively examines this converter type. M. Z. Hossain et al. provide a thorough overview of advancements in DC-DC converter technologies, emphasizing various topologies and control strategies while discussing practical design considerations and applications within renewable energy systems (Hossain and Rahim, 2018). They also identify future research directions and challenges, stressing the necessity for innovative solutions to enhance the functionality and reliability of DC-DC converters across diverse applications. A. Kolli et al. present an extensive overview of different DC-DC converter topologies specifically tailored for fuel cell systems, detailing their respective advantages and limitations (Kolli et al., 2015). They underscore the significance of multi-stack architectures in improving the flexibility, reliability, and efficiency of fuel cell-based power sources. One notable application of MSDCCs is in HVDC systems, where Paez et al. investigate the DC-DC converters utilized within the HVDC industry (Paez et al., 2018). However, their research is confined to a specific application and does not encompass all MSDCCs. To minimize converter volume and reduce the number of semiconductors, the adoption of multi-input DC-DC converters is recommended, particularly for connecting distributed generation units. In this context, available literature and structures are reviewed in (Khosrogorji et al., 2016), comparing their effects on battery life, switching schemes, source utilization, and overall topologies. Given that switches are critical components susceptible to failure that can lead to converter shutdown or malfunction, early fault diagnosis is essential. G. K. Kumar et al. have examined fault diagnosis algorithms and fault-tolerant strategies for various DC-DC converters (Kumar and Elangovan, 2020). However, various MSDCCs topologies have not been explored in a comprehensive way, as conducted in this paper.

3. Reading map

This review paper intends to provide a comprehensive exploration of the MSDCCs, comparing their classification, topologies, and applications. By analyzing the latest advances and research trends in the corresponding field, this review paper seeks to shed light on the pivotal role of the MSDCCs in different industries. The DC-DC converters categorization from configuration point of view and voltage boosting techniques are addressed in Section II, briefly. Section III initially classifies the most well-known MSDCCs. Subsequently, this section addresses various introduced topologies of each class such as quadratic gain, cascaded, interleaved, modular, multilevel, and hybrid MSDCCs. They would be compared from technical point of view. In Section IV, different applications of the MSDCCs have been studied in more details, distinguishing the suitable MSDCCs' topology class for each of them. Finally, conclusions and future research recommendations are given in Section V.

4. Classification of the DC-DC converters and voltage boosting techniques

The DC-DC converters can be categorized from various perspectives, with no single category being inherently superior. In fact, the intended application defines the converter selection and design rules that would make some of the DC-DC converters suitable, brightening the available choices and tools for manufacturer. Notably, a converter may belong to multiple categories, benefiting from the advantages of each. Voltage conversion ratio, voltage/current stress on power semiconductors, voltage conversion range, output current/voltage ripple, input current ripple, protection requirements, complexity, reliability, power quality, power density, manufacturing procedure, and cost are the most frequent criteria for desired DC-DC converter selection. Some of the worthiest classifications of these converters are depicted in Fig. 1 and discussed in the following.

4.1. Isolated/non-isolated

Isolated DC-DC converters provide electrical isolation between the input and output of the circuit, typically achieved by high-frequency transformers, as illustrated in Fig. 2. This isolation enhances safety, reduces noise, and enables high voltage capabilities (Blaabjerg et al., 2021). Among the most commercially prevalent types are flyback, forward, push-pull, Half-Bridge (HB), and Full-Bridge (FB) converters. Flyback converters are favored for their simplicity and versatility, making them ideal for low to medium power applications. In contrast, forward converters excel in efficiency and power density, making them suitable for higher power needs. Furthermore, push-pull converters are often used in higher power scenarios (Chakraborty et al., 2019).

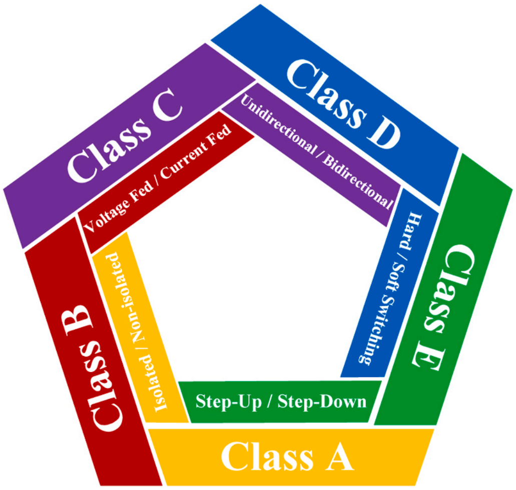


Fig. 1. Classification of the common DC-DC converters.

Non-isolated DC-DC converters—such as buck, boost, buck-boost, Cuk, and SEPIC—do not provide isolation between input and output terminals. This lack of isolation simplifies design and reduces costs while minimizing leakage inductance issues. Non-isolated converters typically deliver smoother voltage regulation (Blaabjerg et al., 2021). The Cuk converter is notable for its ability to handle a wide range of input voltages and continuous current, while the difference between SEPIC and Cuk lies mainly in voltage polarity.

The choice between isolated and non-isolated converters depends on specific application requirements, reliability, cost, and protection considerations. Isolated converters offer safety and reliability advantages but are generally bulkier and more expensive due to transformer use. Conversely, non-isolated converters are more compact and cost-effective but suffer from lack of electrical isolation and consequent issues. Thus, the application context defines the appropriate converter selection.

4.2. Voltage-fed/current-fed

The utilized component (i.e., capacitor or inductor) in the DC-DC converter input may categorize them to the VF or the CF. The VF converters employ a parallel capacitor, while the CF converters utilize an inductor. The structural layout of both is shown in Fig. 3, in a non-isolated format. The VFs are prevalent in inverters (Misal and Bhasme, 2017) and are mainly designed to suppress input voltage ripple, crucial for applications like fuel cells (Rathore and Prasanna, 2012a). In VF converters, feedback control strategies, particularly PWM, adjust the power switch's duty cycle to stabilize output voltage among varying load conditions (Sha and Fu, 2023). As it is expected, there are other available control schemes and various topologies for the VF converters (Sha et al., 2019; Kan et al., 2013). Besides, the VF converters may provide faster dynamic response (Forouzesh et al., 2017).

Conversely, the CF converters focus on stabilizing input current to ensure consistent input and output current, making them ideal for applications requiring precise current control, such as motor drives and high-current power supplies (Zhang et al., 2022). The CF converters have a higher reliability and are more resilient to short-circuit faults compared to the VF converters (Nag and Mishra, 2013). The CF converters also offer smaller current ripple compared to the VF converters. This is particularly advantageous in the PV power conversion (Wang et al., 2022), where small current ripple causes small deviations from MPPT. This makes the CF converters a suited choices for the MPPT (Zhang et al., 2022; Rathore and Prasanna, 2012b; Rathore et al., 2011). The CFs suffer from challenges like higher conduction losses and slower

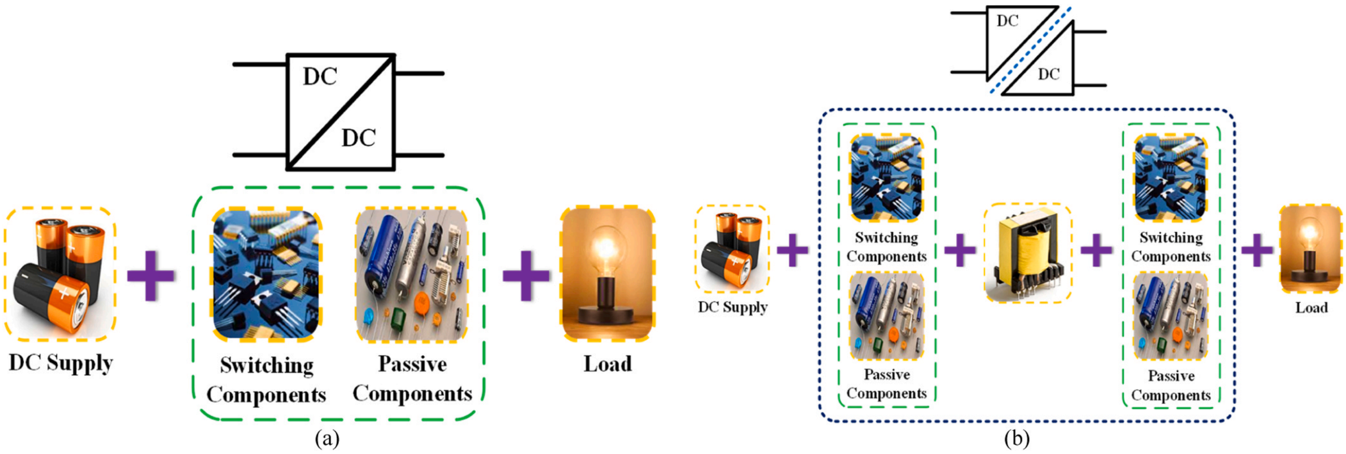


Fig. 2. Structural layout of (a) non-isolated and (b) isolated DC-DC converters.

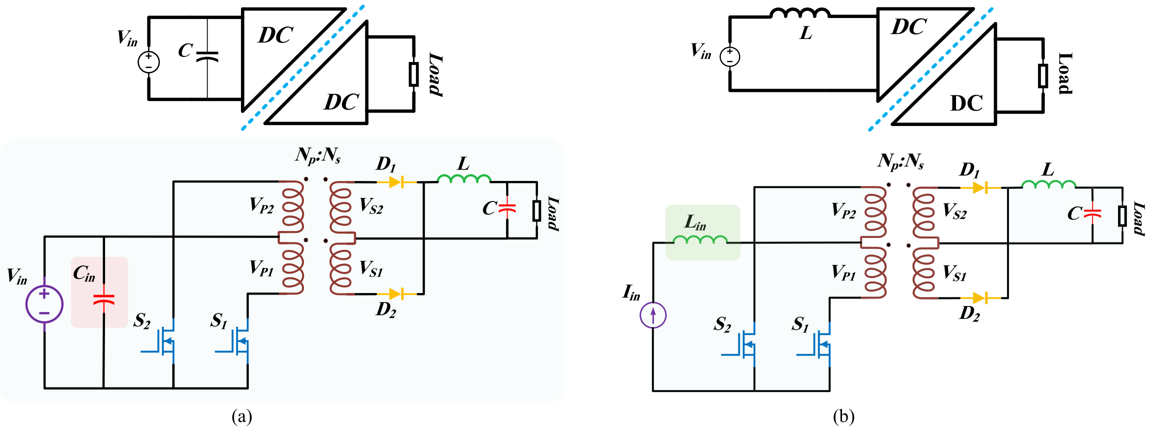


Fig. 3. General structural layout with a push-pull converter sample of (a) isolated voltage-fed and (b) isolated current-fed DC-DC.

dynamic responses compared with the VF converters, depending on the system and application (Misal and Bhasme, 2017; Chaudhury and Kastha, 2023). Despite their bulkier inductors, the CF converters are suitable for sensitive applications like medical devices due to their short-circuit protection feature and low current ripple at high frequencies (Zhang et al., 2022).

4.3. Unidirectional/bidirectional

The DC-DC converters are classified based on power flow direction into unidirectional and bidirectional. Unidirectional converters allow power to flow solely from a DC source to a load, enabling energy transfer or absorption separately. As previously mentioned, the DC-DC converters can take place in multiple categories. Therefore, for example, unidirectional converters can be isolated/non-isolated, voltage-fed/current-fed, soft switched/ hard switched and step-up/step-down. Non-isolated and isolated unidirectional DC-DC converters with a typical layout are illustrated in Fig. 4(a) and (b), respectively. Unidirectional converters may be employed on various applications including power supplies, battery chargers, voltage regulators, the LED drivers, motor

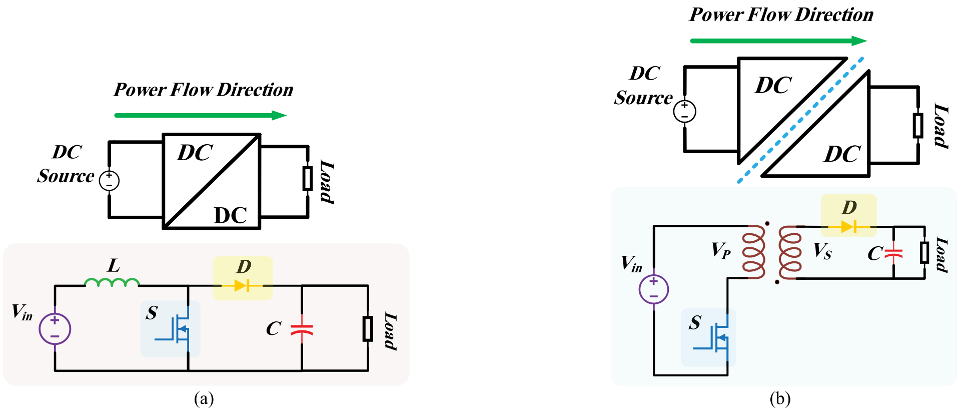


Fig. 4. Unidirectional DC-DC converters general layout (a) non-isolated unidirectional typical Boost converter (b) isolated unidirectional typical Flyback converter.

drives, mobile devices, energy harvesting systems, etc (Bhaskar et al., 2020a).

In contrast, bidirectional converters facilitate power flow in both directions, allowing charging and discharging of loads using same converter. In Fig. 5, a non-isolated bidirectional DC-DC converter with a typical layout is illustrated. The bidirectional power flow nature of these converters, makes them an attractive choice for the RESs, the DC microgrids (Xu et al., 2020), and transportation applications.

In a DC microgrid, DC-DC converters play a crucial role in balancing loads by dynamically adjusting the power flow between various loads and sources. This adjustment ensures a stable supply-demand equilibrium, enhancing the overall stability and reliability of the microgrid, while guaranteeing a continuous power supply to critical loads (Arunkumari and Indragandhi, 2017). Additionally, bidirectional converters facilitate microgrid islanding by enabling self-healing operations during disturbances and outages (Afzal et al., 2022). Bidirectional DC-DC converters are particularly beneficial for RESs, specifically the PV systems and wind farms. They would integrate energy storage systems, such as batteries or super-capacitors, within the PV systems and wind farms. This integration enables the PV systems to charge and discharge the storage facilities during periods of high energy generation and demand, respectively. Such capability is vital for these energy systems, as they often operate under significant uncertainties that may compromise the stability and reliability of microgrids (Wu et al., 2021). Moreover, these converters play a pivotal role in the EV charging systems by supporting the Vehicle-to-Grid (V2G) functionalities. This allows the EVs not only to draw energy from the grid, but also to return it when necessary, effectively acting as distributed energy storage units (Zahid et al., 2015). In this capacity, they provide valuable support services, including frequency regulation and peak shaving.

Unidirectional DC-DC converters benefit from simpler control schemes compared with their bidirectional counterpart. However, bidirectional DC-DC converters provide bidirectional power flow that lead to more flexibility and enables the energy recovery procedure. In some applications, a bidirectional DC-DC converter can handle the duties of two unidirectional DC-DC converters.

4.4. Hard-switched/soft-switched

Hard-switched and soft-switched DC-DC converters represent two fundamental categories of power converters that utilize distinct switching methodologies. Hard-switched DC-DC converters use a simple approach where voltage and current transition simultaneously. This operational technique leads to increase the switching losses and the EMI, limiting the power rating in some applications. Their simplicity and ease of implementation are notable, but in high-power scenarios, where the volume and size of the converter is of concern, a significant increase in switching frequency is required to reduce the size and weight of the magnetic components (It must be noted as the frequency increments, the power density will go high and then become lower, such phenomenon is dominated by the non-linear relationship in practical magnetic material and also the semiconductor thermal needs). Nevertheless, this frequency increase also may lead to higher switching losses, limiting hard-switched converters to lower power applications, motor drives, and switching power supplies. It must be noted that in some high-power applications frequency increment is not welcomed, as it increases the EMI issues. So, some of designers attempt to keep the operational frequency as low as possible (Cheng et al., 2021).

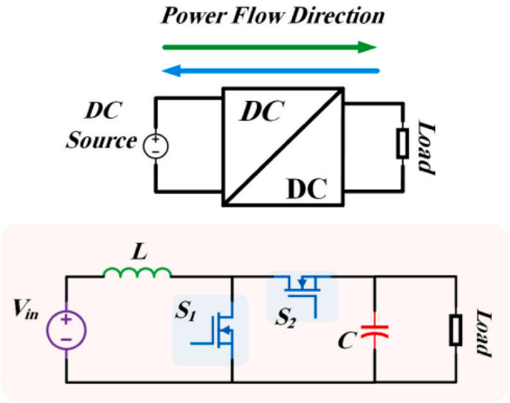


Fig. 5. Non-isolated bidirectional typical DC-DC boost converter.

Soft-switched DC-DC converters, on the other hand, employ various techniques to minimize the switching losses and the EMI. By utilizing resonant circuits, these converters can switch at near-zero or zero voltage or current, significantly reducing noise and loss, thus, making them more efficient for higher power applications (Rathore et al., 2015). Soft-switched converters are primarily categorized into four groups: (i) Quasi-Resonant (QR) converters; (ii) Multi-Resonant (MR) converters; (iii) resonant transition-based converters; and, (iv) resonant power converters (Salem et al., 2018).

The decision making between adopting hard-switched or soft-switched DC-DC converters depends on the specific application requirements, such as power density, efficiency, transient response, and the EMI level. Hard-switched converters tend to be more straightforward and cost-effective, while soft-switched converters provide enhanced efficiency and superior performance.

4.5. Step-up/step-down

The DC-DC converters are mainly divided to step-up and step-down categories in accordance with their voltage conversion ratio. Some of the most common DC-DC converters are buck-boost, Cuk, SEPIC, flyback, two-switch flyback, forward, two-switch forward, magic-cap forward, push-pull, HB, FB, phase-shifted FB, etc. Traditional step-down DC-DC converters were based on resistor division, leading to high resistive loss and poor efficiency (Hart, 2011). In conventional step-down MLDCCs those are also according to diode clamps, flying capacitors, etc., voltage unbalance issue would appear (Huang et al., 2015). Some of the recent works have been focused on step-down DC-DC converters with improved performance that have overcame the previous drawbacks (Minami and Ishitani, 2020; Ambagahawaththa, 2021; Xu et al., 2019; Choi and Jeong, 2022; Larsen et al., 2019; Hong et al., 2019). These converters can be utilized in battery management system (BMS) of the EVs, at the end of the HVDC lines, etc.

Step-up converters increase output voltage by storing energy in passive components or magnetic devices and releasing it through power switches at specific intervals. The PWM-based boost converter is a widely used fundamental step-up converter but faces challenges with Right-Hand-Plane (RHP) control issues and limited voltage conversion ratio (Hart, 2011). Classification of voltage boosting techniques have been demonstrated in Fig. 6. These techniques are briefly introduced, as follow:

Switched capacitors: This technique efficiently enhances output voltage level through a network of capacitors arranged in series, parallel, or both, with switches that alternate their connections. During the charging phase, capacitors connect to the input DC source in parallel, allowing them to charge. In the discharging phase, they connect in series to increase the output DC voltage (Qian et al., 2012; Kord et al., 2023). This technique offers simplicity, reasonable efficiency, and modular implementation, along with flexible gain extension (Forouzesh et al., 2017; de Carvalho et al., 2021). However, it suffers from limited power level, harder voltage regulation, and di/dt issues, making it suitable for low-power applications (Qian et al., 2012; de Souza et al., 2021).

Voltage multiplier circuits: The VMCs are famous for their simplicity (Navamani et al., 2018). Similar to the SC networks, capacitors are the main component of these circuits (Ahmad et al., 2020). There are many VMCs that utilized inductors to benefit from higher voltage conversion

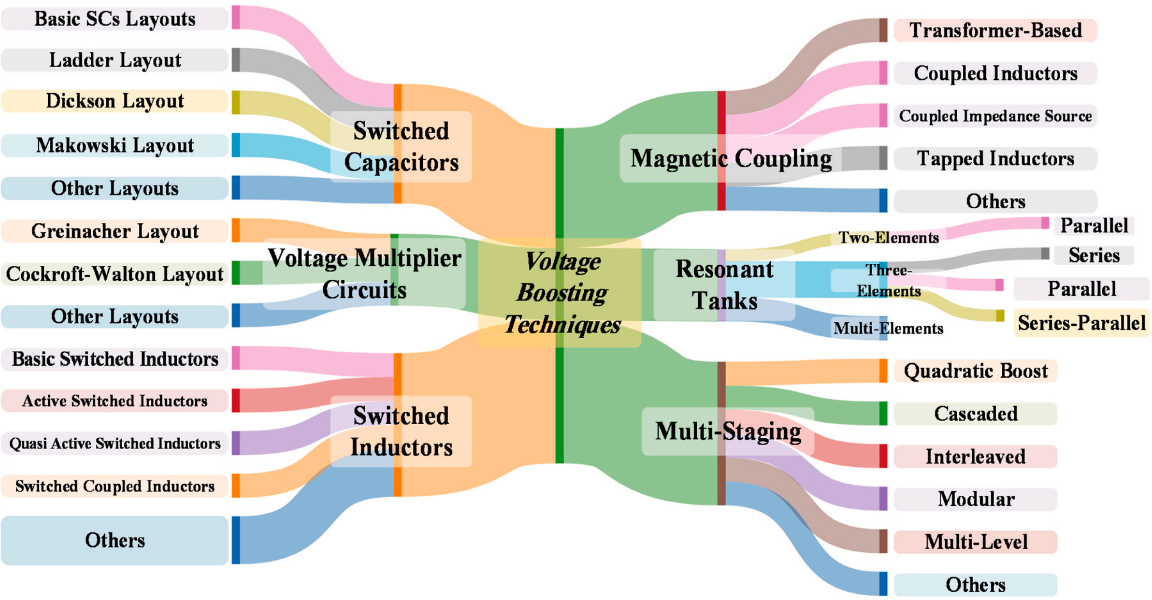


Fig. 6. Most common voltage boosting techniques.

ratios (Fardoun and Ismail, 2010; Alzahrani et al., 2019; Kothapalli et al., 2020). Some VMCs are able to minimize the voltage stress (Forouzesh et al., 2017). Greinacher (Altimania et al., 2020; Alzahrani et al., 2017) and Cockroft-Walton (Pulvirenti, 2022; Rani et al., 2017) are two generic layouts of the VMCs. To simultaneously achieve high voltage gain and low switching losses, the VMCs could be integrated with the Resonant Tanks (RTs) (Uno and Kukita, 2014). Moreover, they benefit from compact size and low weight due to their efficient combination of capacitors and diodes, mostly. However, these circuits are not suitable for high power applications and proposing new VMC layout requires more creativity and innovation (Ahmad et al., 2020).

Switched inductors: This technique operation comprises two phases: first, a DC input source energizes the inductor(s); subsequently, this stored energy is released in a way to elevate the output DC voltage. Conventional SL-based converters utilize diodes for implementing the energizing and de-energizing phases, whereas there are layouts that utilizes active switches (e.g., MOSFET and IGBT) on this matter. Additionally, quasi-active switched inductors (QA-SLs) have emerged, offering high voltage gain with reduced stress on components (Forouzesh et al., 2017; Balasubramanian et al., 2017; Liu and Li, 2015). Switched coupled inductors have attracted attention due to their need for less magnetic cores count compared with conventional SLs (Kumar et al., 2019; Kang et al., 2021; Rao and De, 2022). Nonetheless, leakage inductance effect is more severe and design procedure needs more consideration. Besides, changing the winding turns in switched coupled inductors could have more significant impact on output DC voltage. Generally speaking, the SL-based DC-DC converters benefit from higher voltage gain than the SC assisted counterpart (Tang et al., 2014b, 2013). Unlike the SC technique, the SL do not suffer from di/dt issues in charging phase (Axelrod et al., 2008). In this technique, lower value of inductors and capacitors would be also employed in high frequencies. The SLs may be utilized for higher power level compared with the SCs scheme.

Magnetic coupling: The bulkiest components of the DC-DC converters are the inductors, primarily due to their ferrite core (FCO). The magnetic coupling voltage boosting technique employs coupled inductors or a transformer to transfer energy between the input-output terminals and increase the DC voltage level. In magnetically coupled DC-DC converters, the switches root mean square (RMS) current, inductors RMS currents, and diodes blocking voltages would increase (Bao et al., 2021).

Utilization of built-in transformers provide uniform magnetic flux distribution through the core, resulting in need for a smaller ferrite core that results in lower weight and more compactness (Li et al., 2011). These transformers may assist voltage boosting and soft switching. Benefiting from both features is also feasible. Coupled inductors have been a long-standing component of magnetic coupling voltage boosting techniques, widely used in various researches (Wu et al., 2017; Schmitz et al., 2020; Yao and Wang, 2022). This technique is characterized by the use of a reduced number of cores. This design choice considerably decreases the overall system size, thereby reducing the cost of the system. Also, tapped inductors are of coupled inductors family (Vazquez et al., 2007; Cheng, 2006).

Resonant tanks: In some of the isolated DC-DC converters, the RTs are prevalent and necessary units, characterized by their integration with reactive elements, namely inductors and capacitors. Their primary role is to minimize switching losses, achieving near-zero levels and thereby enhancing converter efficiency. Beyond this, RTs can provide voltage gains exceeding one in various topologies, increasing their versatility across applications. They are classified into three categories: (i) two-element; (ii) three-element; and (iii) multi-element tanks (Bughneda et al., 2022). RTs offer soft switching capabilities leading to decreased EMI, reduced switching losses, and enhanced efficiency. In addition, they enable the adoption of higher switching frequencies, making them well-suited for applications like the PVs, the EVs and the wireless power transfer (WPT) (Chen and Xu, 2021; Reddy et al., 2023).

Multi-staging: MSDCCs are power electronic systems that consist of multiple stages of DC-DC power conversion units. These converters are primarily utilized in low to high-power applications. Despite their complexity and higher component count compared with their single-stage counterparts, which contribute to increased costs. Nonetheless, their advantages in terms of power handling capacity and voltage gain make them a valuable choice for many applications (Forouzesh et al., 2017). There are several types of the MSDCCs, including quadratic gain, cascaded, interleaved, modular, multilevel, and hybrid converters.

The quadratic gain DC-DC converters (QGDCCs) can be optimized for higher voltage gains by combining stages to provide second-order voltage gain, thus, enhancing their applicability in the RESs, the EVs, the Fuel Cell (FC) systems (Jayachandran et al., 2022), and industrial automation. The voltage gain is derived from the magnetic flux principle during inductor charging and discharging, obviously. The quadratic gain boost converter benefits from several advantages, including high voltage gain, and design procedure flexibility. Some researchers have concentrated on merging certain switches of the quadratic gain DC-DC converter (QGDCC) into a single switch, resulting in increased current stress on the switch and reduced reliability (Gholizadeh et al., 2023). In general, these converters are suitable for low-power applications.

In the context of cascaded DC-DC converters (CDCCs), integrating step-up converters with diverse voltage boosting techniques is prevalent. This may involve using switched capacitors (Xiong and Tan, 2016; Shindo et al., 2011) or coupled inductors (Pan et al., 2019; Hu and Gong, 2013) alongside PWM boost methods to enhance voltage gain. Additionally, step-up converters of the aforementioned types may be combined with the VMCs (Zhang et al., 2015; Andrade et al., 2015). Thus, various step-up topologies can be interconnected, providing a high degree of flexibility in the design of the CDCCs (Kumari et al., 2022).

In contrast to the CDCCs, interleaved DC-DC converters (IDCCs) feature stages that are interconnected in parallel rather than in series. Various voltage boosting techniques, as mentioned earlier, can be utilized within the branches of interleaved converters (Nouri et al., 2020; Guepfrih et al., 2022; Nouri et al., 2018). It is important to note that interleaving itself does not directly increase the output DC voltage, especially when the gate drive signals are not phase shifted; instead, this task is carried out by the modules situated within the branches. Interleaving serves as a method to enhance the current level and power density of the converter. Besides, interleaved converters benefit from lower current ripple (Frivaldsky et al., 2019). However, the increase in component count associated with this configuration results in higher production costs.

The Modular DC-DC Converters (MDCCs) are a type of the DC-DC converters designed with modularity in mind, enabling customization and scalability to support a variety of applications, particularly in high-power domains such as the RESs (Li et al., 2020), the EVs (ElMenshawy and Massoud, 2020), the FCs (Afkar et al., 2022), and the HVDC transmission lines (Li et al., 2019b). These converters offer a high degree of flexibilities in terms of input and output voltage ranges, thanks to the integration of multiple converter modules, each with its own distinct input and output voltage range (Khan, 2007). This modular approach enables diverse voltage configurations through parallel or series connections. Above all, the MDCCs enhance power density and reliability compared to traditional converters, as their redundant design allows continued operation despite single module failures (Ferreira, 2013). However, they present challenges such as control complexity, increased costs and related issues.

The MLDCCs constitute a highly regarded category of power converters, known for their ability to deliver substantial power levels, even up to the megawatt range, for a diverse array of applications, including the RESs and the EVs (Rosas-Caro et al., 2018). MLDCCs enhance the EMI performance, reliability, transient responses, low voltage stress, low harmonic, and overall efficiency of the converter (Mahdizadeh and Afjei, 2021). The intricate design process of the MLDCCs necessitates careful consideration of input/output voltage ranges, power density, and control complexity. Further details will be discussed in the subsequent section.

The various types of the MSDCCs, including the QGDCCs, the CDCCs, the IDCCs, the MDCCs, and the MLDCCs, each offer some advantages and are suitable for various applications. To fully benefit from merits and features of these diverse groups of converters, they can be combined to create hybrid MSDCCs. For instance, cascaded converters can be interleaved to achieve high voltage gain, while simultaneously reducing current ripple and providing higher current rating (Dutta et al., 2019; Leal et al., 2023). Similarly, the MLDCCs can be designed in a modular manner to avoid whole system failure during minor events, enabling operators to manage the situation without suspending the system operation (Monteiro et al., 2020; Du et al., 2016; Shao et al., 2019). The MSDCCs are constantly evolving, with new advances and innovations being developed regularly. In the following section, the latest research and developments in the MSDCCs will be presented. Furthermore, the primary focus of this paper, providing a comprehensive overview of the current state of the art MSDCCs, would be addressed.

5. Recent advances in multistage step-up DC-DC converters

In this study, several critical assumptions have been established to facilitate the analysis and evaluation of MSDCCs performance. These assumptions are instrumental in streamlining the complexity inherent in such systems, allowing for a focused examination of their operational characteristics. The following points outline the key assumptions considered in this review:

- The leakage inductance and its impact has been neglected.
- The snubber elements have not been taken into account in converters components counts.
- The steady state operation of the under study MSDCCs has been considered and their transient behavior has been ignored.
- The input voltage has been assumed constant.
- All capacitors have been assumed large enough to maintain the constant voltages during the switching period(s).
- The parasitic components effects have not been taken into account.
- The continuous current mode (CCM) operation has been considered.
- The single-input-single-output DC-DC converters were mainly considered in this study, however, where it was necessary the multi-input-multi-output converters have been analyzed as well.
- The majority of the reviewed literature has been selected from publications dating from 2018 onward.

5.1. Quadratic gain DC-DC converters

The QGDCCs predominantly exhibit second-order voltage gains. Also, some of these converters can be developed to higher order converters such as cubic or nth power ones by complying some mostly certain amount of principles (Li et al., 2022). Huge number of researches on the QGDCCs are concentrated on combination of well-known available structures together or combining them with voltage boosting circuits, etc.

5.1.1. Main feature discussion

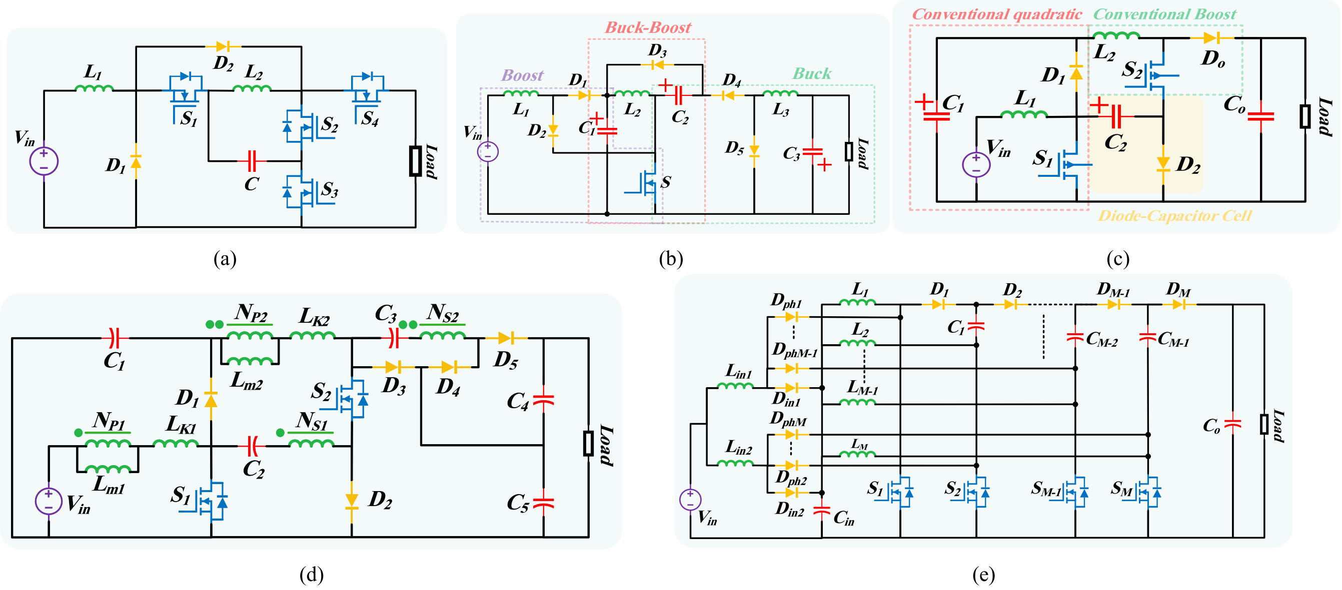
Many factors must be considered for designing a DC-DC converter such as input voltage/current ripple, output voltage/current ripple, wide range voltage regulation, power density, the EMI, control scheme, voltage gain, protection, stability, etc. In (Mayo-Maldonado et al., 2018), a novel buck-boost QGDCC topology is proposed that suppresses output voltage ripple, leading to using smaller capacitors. Cuk converters are known for their stability and reduced switch voltage stress while being compatible with the MPPT control schemes, making them versatile for various applications. C. Dal'Agnol have investigated a step-up/down converter by combining the conventional boost and the Cuk converters (Dal'Agnol et al., 2023). In Lee and Do (2018a), the authors have investigated a QGDCC capable to provide higher voltage gain than the conventional quadratic gain boost converter, utilizing a built-in transformer and passive clamping circuits to elevate and lower the voltage gain and voltage stress, respectively. Another research has been turned to the SEPIC-based dual winding QGDCC claiming that it can support full range duty cycle control with smooth input current, utilizing only a single switch (Esmaeili et al., 2021). S. Esmaeili et al. introduced a SEPIC-based high-gain QGDCC that incorporates a manipulated transformer and a VMC, enabling high adjustable voltage gains at low duty cycles (Esmaeili et al., 2023). Two types of two switch non-isolated QGDCC are presented in (Shahanasmol et al., 2020), obtaining high step-up voltage gains by modifying the combination of conventional buck-boost and boost converters. A. T. Marzoni et al. have proposed a QGDCC with continuous input current providing higher authority to select the desired duty cycle (Marzoni et al., 2022).

Proposing structures with a single switch is prevalent, where the converter is operated in hard switching. This would increase the efficiency and decreases the switching loss, whereas increases the switch voltage stress, most of the times (Oliveira et al., 2019). However, it must be considered that lowering the switches count needs to be argumentative and it must not impose other issues.

In Zaid et al. (2020), the authors claim that by combining a boost stage with a VMC, high gain can be achieved with the low switch voltage stress. S. Gopinathan et al. have introduced a family of the QGDCCs by improving a switched inductor-capacitor converter mentioned in (Yang et al., 2009), placing diode-capacitor modules with different parts of the base converter to improve the voltage gain and reduce the voltage stress (Gopinathan et al., 2022). Pires et al. have proposed a bidirectional QGDCC suitable for energy storage devices such as batteries and super-capacitors (Pires et al., 2017), shown in Fig. 7(a). Another step-up/down cell is proposed in Hosseini et al. (2020), appropriate for bidirectional converters specifically for the V2G and the Grid-to-Vehicle (G2V) applications. This bidirectional QGDCC can be structured modular, benefiting from ultrahigh gain in both directions of power flow. In Akhormeh et al. (2020), a bidirectional high-gain QGDCC utilizing merely two switches per direction is explored, resulting in reduced conduction and switching losses while achieving competitive voltage gains compared with cascaded converters, utilizing only a single coupled inductor with dramatically low current ripple. Some researchers are interested in single switch QGDCCs due to its more simple and cheaper drive circuit (Ghafour et al., 2022). However, these converters suffer from high active switch current stress, limiting their application. N. Zhang et al. have investigated a quadratic gain buck-boost converter that combines conventional buck, boost, and buck-boost converters into a single converter, providing wider voltage gain than mentioned traditional converters (Zhang et al., 2017a). Also, as this converter meets continuous current on its both sides, its input and output filters design would be much easier. The aforementioned converter is shown in Fig. 7(b) with distinguished blocks. The continuous input current is welcomed for the RES and Batteries applications (Gholizadeh et al., 2019; Golizedeh et al., 2020). Another high gain boost QGDCC with continuous input current and common ground between input and output terminals is investigated by H. Arvani et al. based on a SL cell (Arvani et al., 2023).

In general, traditional buck-boost converters suffer from poor efficiency when high voltage gain is required J.C. Rosas-Caro et al. have proposed an improved buck-boost converter that deals with the mentioned issue and provides near zero current ripple at both sides with continuous input current (Rosas-Caro et al., 2018). Most of the proposed QGDCCs are non-isolated as they do not utilize bulky transformers and inductors (Rosas-Caro et al., 2018; Gholizadeh et al., 2019, 2020). S. Mahdizadeh and E. Afjei have proposed a converter composed of a Zeta and buck-boost converter, providing high voltage gain even at 0.5 duty cycle (Mahdizadeh and Afjei, 2021). In (Alizadeh et al., 2022), a three winding coupled inductor QGDCC based on impedance source is presented that benefits from low components stresses with high efficiency and high voltage gain. J. He et al. have investigated a semi-sophisticated QGDCC that gains from a three winding coupled inductor and a SC cell, providing more voltage regulation flexibility (He et al., 2022). Also, this converter contains only a single switch. In Habibi et al. (2022), two three-winding coupled inductor based QGDCCs are proposed that prepare high voltage gain using a single switch, at the cost of circuit complexity and bulky components. Another single switch QGDCC is proposed in Kumar and Krishnasamy (2021), drawing less continuous input current and imposes low voltage stress on the end capacitor for low power applications. S.V.K. Naresh et al. have investigated a non-isolated high gain QGDCC that utilizes the inductors' asymmetric input voltage (Naresh et al., 2021). This concept is defined for the first time that can be employed in future researches. The aforementioned QGDCC illustrates superiority among other same rated QGDCCs by adding a diode-capacitor cell between two cascaded conventional boost converters, as shown in Fig. 7(c). A. Mostaan et al. have proposed a bipolar buck-boost converter which can provide symmetric negative and positive output voltages (Mostaan et al., 2023), benefiting from three semi-conductor switches, turning ON/OFF synchronously, presenting commonly demanded merits such as continuous and smooth input current suitable for RESs applications.

In Korada and Ayyanar (2022), a high gain QGDCC adaptive with the Zero Current Switching (ZCS) and the Zero Voltage Switching (ZVS) to overcome the hard switching challenges to improve the overall efficiency of the converter, is presented. A highly efficient low power converter with a single switch is presented in Wang et al. (2018), providing high voltage gain and low components' stress, enabling the



(a) (b) (c)

(d) (e)

Fig. 7. Some of the proposed quadratic gain DC-DC converters in literature (a) a bidirectional quadratic gain DC-DC converter proposed by V. F. Pires et al. (b) a novel quadratic step-up/down converter composed of boost, buck-boost, and buck converters (c) an improved quadratic converter with diode-capacitor cell (d) an ultrahigh step-up quadratic converter that includes two switched inductors and a switched capacitor circuits (e) a high gain and high power M-phase quadratic DC-DC converter based on extended duty cycle boost converter.

ZCS on diodes by utilizing the leakage inductance.

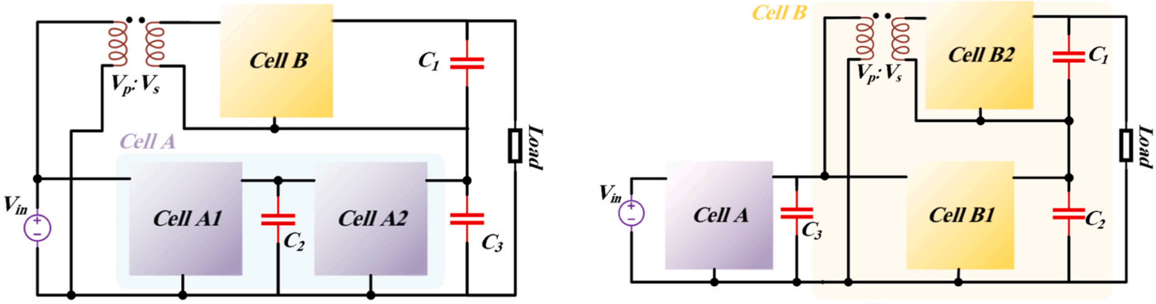
By assigning more voltage boosting cells to the converter, higher voltage conversion ratio may be achieved, obviously. Although, designers must be able to achieve high voltage gains without just adding well-known circuits. They should investigate converters based on offering structures based on basics of power electronics and control schemes than just combining existing circuits. Previous literatures are mostly according to combination of two converters or adding only a few numbers of passive components. On this basis, in Abbasi et al. (2022), an ultrahigh step-up QGDCC is investigated with the help of two SLs and a SC circuits combined with two boosting stages, leading to maximum voltage gain of 40, as shown in Fig. 7(d). In Subhani et al. (2023), an ultrahigh gain converter based on the SC circuit has been introduced which can lower the voltage stress of the switches through the master-minded network, providing high voltage gain with low duty cycle to solve the reverse recovery issue of the diodes. T. Rahimi et al. have proposed an ultrahigh gain step-up converter having a simple looking structure (Rahimi et al., 2021a). Their layout includes a traditional boost converter at the beginning to guarantee the input current continuity, a Luo converter to amplify the voltage at the second stage, and a modified voltage doubler at the end to double the voltage gain, providing high voltage gain with a lower duty cycle. Resonance concept is beneficial in ultrahigh gain converters, as well. In Nikbakht et al. (2023), an ultrahigh gain converter consists of several coupled inductors (two built-in transformers) and a VMC is investigated with the QR operation, providing over 95 % efficiency at 480 W rated power. A. Gupta et al. have proposed a quadratic gain extended boost converter with ultrahigh gain which is a combination of traditional extended duty cycle boost converters, providing high voltage gain with moderate duty cycles and low voltage stresses on switching components, as shown in Fig. 7(e) (Gupta et al., 2022). Also, they have constructed a 1 kW 4-phase prototype to validate their work. This converter can be extended to numerous phases to provide higher output voltages, as the voltage gain is proportional to the phases count directly. Generally speaking, the extended duty cycle boost converters are composed of an interleaved boost converter and a SC, enabling the high power and high voltage gain features (Roy and Ayyanar, 2016).

Stacking and cascading techniques are some common schemes used to achieve the quadratic gain. Despite the corresponding advantages of cascading schemes, they suffer from high components count and reduced overall efficiency, respectively. To overcome these issues and benefit from the merits of both schemes, combinations of both schemes have been investigated in Andrade and da Silva Martins (2017). Consequently, they proposed two types of quadratic gain boost with stacked-cascaded zeta converters, as demonstrated in Fig. 8, capable to provide high voltage gain with acceptable components count, voltage gain and efficiency. Another zeta-based converter, referred to as symmetrical double zeta QGDCC is proposed in de Sa et al. (2020) that reduces the voltage stress on switches and enhances the voltage gain.

5.1.2. Performance parameters comparison

To have a better comparative view, components count, voltage gains, diodes voltage stresses, switches voltage stresses, and efficiencies of the reviewed converters are listed in Table 1. The existence of transformers, coupled inductors, and SCs for voltage boosting purposes is investigated. It can be observed from Table 1 that the SCs are utilized in (He et al., 2022; Abbasi et al., 2022; Subhani et al., 2023) converters. Only Wang et al. (2018) has utilized a transformer without benefiting from coupling advantages of self-inductances, boosting the voltages only with the help of transformer turn ratio and induces the isolation nature to the converter. Various research works such as (Lee and Do, 2018a; Esmaeili et al., 2023; Akhormeh et al., 2020; Alizadeh et al., 2022; He et al., 2022; Habibi et al., 2022; Abbasi et al., 2022; Nikbakht et al., 2023) achieved high voltage gains by integrating the coupled inductors (and built-in transformers) with the converter structure with isolating it, at the cost of higher EMI, higher weigh, and higher volume. It must be noted in Table 1; ferrite cores have been taken into account in total components count. Each coupled inductor component, without considering the windings count, has been considered as a single element. As these windings can be placed around a single ferrite core. It can be observed from the mentioned table that the converters proposed in He et al. (2022); Rahimi et al. (2021a); Nikbakht et al. (2023) have the most components count, equal to 16, as (He et al., 2022; Nikbakht et al., 2023) benefit from coupled inductors and the SCs to provide higher voltage gain. Converters investigated in Hosseini et al. (2020) and Gupta et al. (2022) can be designed in several modules or phases, respectively. Consequently, their components count have the potential to overtake others. It must be mentioned that n, i, and M denote the turn ratio, modules count, and phases count, respectively.

It must be mentioned that some of the performance parameters of the reviewed converters are Not Reported (NR), defined with NR. To have a clearer insight to compare the voltage gain of introduced quadratic gain step-up converters, their ideal voltage gains in CCM curves are illustrated in Fig. 9. It can be observed that ultrahigh voltage gains would be possible with the aid of coupled inductors. The ultrahigh step-up converter proposed in Abbasi et al. (2022) presents the highest voltage gain among others due to utilizing both coupled inductors and the SCs. With a glimpse on the above Table, it can be derived that this astonishing gain is mainly due to the second order of the turn ratio. It should be pointed out that to have a fair comparison, turn ratios of all of the converters have been set to 2. In addition, in the voltage gain relation of Alizadeh et al. (2022), g denotes the ratio of leakage and magnetizing inductances, which has been set to zero. The converter proposed in Gupta et al. (2022) differ from others as it can be designed and manufactured in various phases. The voltage gain is directly proportional to the number of phases. Nonetheless, phase number has been set to 2, avoiding from skyrocketing the components count. The voltage gain of 385 has been achieved only with the aforementioned turn ratio. Obviously, by increasing the turn ratio value, attractive voltage gains may be achieved, as displayed in Fig. 9. In addition, it would be derived from Table 1, converters (Hosseini et al., 2020; Gupta et al., 2022) have the potential



(a) (b)

Fig. 8. Structures resulted from combining the stacking and cascading the DC-DC converters in literature (a) structure I (b) structure II.

Table 1
Performance comparison of the reviewed quadratic gain dc-dc converters.

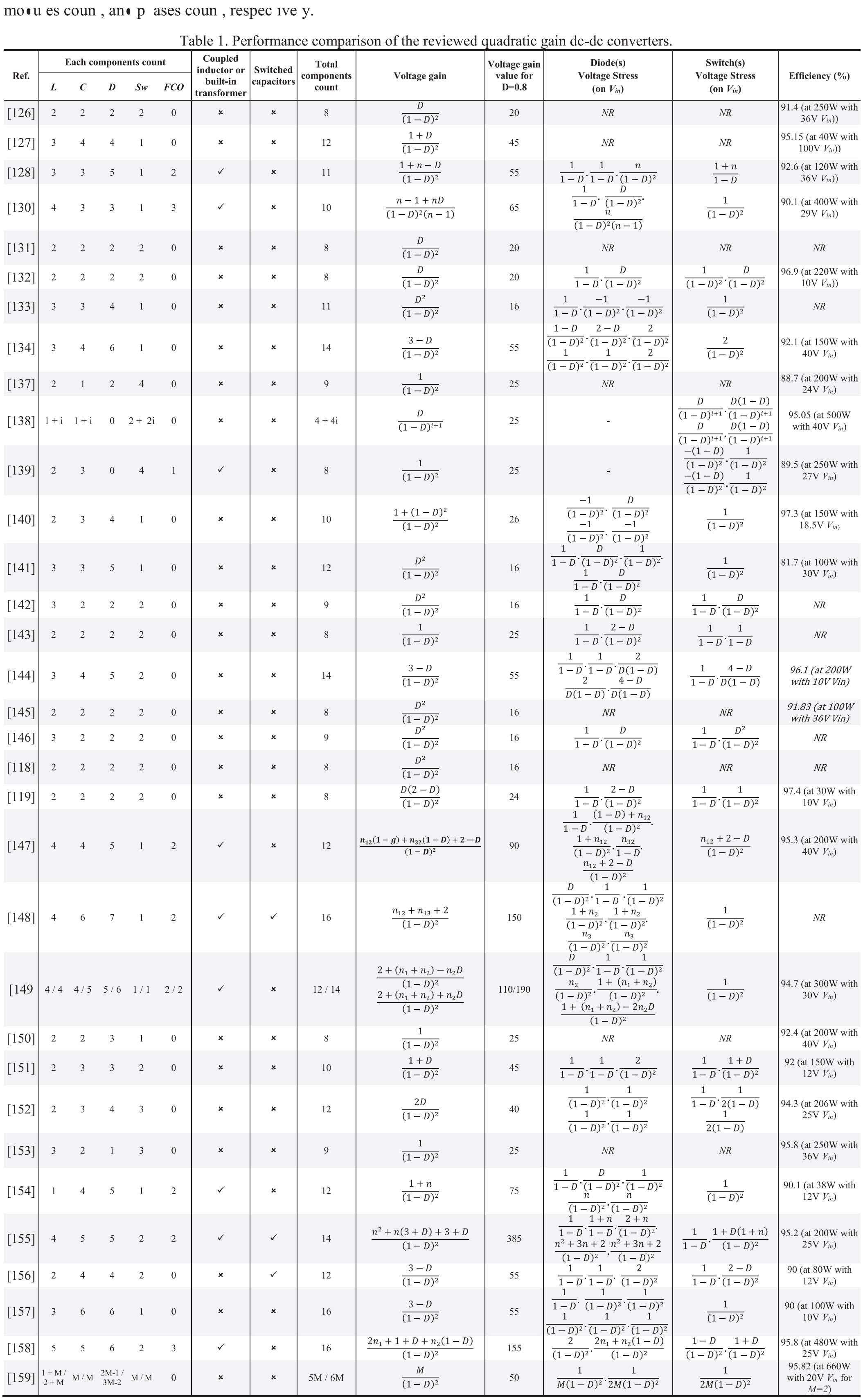


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Table 1. Performance comparison of the reviewed quadratic gain dc-dc converters.

Ref.	Each components count					Coupled inductor or built-in transformer	Switched capacitors	Total components count	Voltage gain	Voltage gain value for D=0.8	Diode(s) Voltage Stress (on V_{in})	Switch(s) Voltage Stress (on V_{in})	Efficiency (%)
	L	*C*	*D*	*Sw*	*FCO*								
[126]	2	2	2	2	0	×	×	8	$\frac{D}{(1-D)^2}$	20	*NR*	*NR*	91.4 (at 250W with 36V V_{in}))
[127]	3	4	4	1	0	×	×	12	$\frac{1+D}{(1-D)^2}$	45	*NR*	*NR*	95.15 (at 40W with 100V V_{in}))
[128]	3	3	5	1	2	✓	×	11	$\frac{1+n-D}{(1-D)^2}$	55	$\frac{1}{1-D}.\frac{1}{1-D}.\frac{n}{(1-D)^2}$	$\frac{1+n}{1-D}$	92.6 (at 120W with 36V V_{in}))
[130]	4	3	3	1	3	✓	×	10	$\frac{n-1+nD}{(1-D)^2(n-1)}$	65	$\frac{1}{1-D}.\frac{D}{(1-D)^2}.$ $\frac{n}{(1-D)^2(n-1)}$	$\frac{1}{(1-D)^2}$	90.1 (at 400W with 29V V_{in}))
[131]	2	2	2	2	0	×	×	8	$\frac{D}{(1-D)^2}$	20	*NR*	*NR*	*NR*
[132]	2	2	2	2	0	×	×	8	$\frac{D}{(1-D)^2}$	20	$\frac{1}{1-D}.\frac{D}{(1-D)^2}$	$\frac{1}{(1-D)^2}.\frac{D}{(1-D)^2}$	96.9 (at 220W with 10V V_{in}))
[133]	3	3	4	1	0	×	×	11	$\frac{D^2}{(1-D)^2}$	16	$\frac{1}{1-D}.\frac{-1}{(1-D)^2}.\frac{-1}{(1-D)^2}$	$\frac{1}{(1-D)^2}$	*NR*
[134]	3	4	6	1	0	×	×	14	$\frac{3-D}{(1-D)^2}$	55	$\frac{1-D}{(1-D)^2}.\frac{2-D}{(1-D)^2}.\frac{2}{(1-D)^2}$ $\frac{1}{(1-D)^2}.\frac{1}{(1-D)^2}.\frac{2}{(1-D)^2}$	$\frac{2}{(1-D)^2}$	92.1 (at 150W with 40V V_{in})
[137]	2	1	2	4	0	×	×	9	$\frac{1}{(1-D)^2}$	25	*NR*	*NR*	88.7 (at 200W with 24V V_{in})
[138]	1 + i	1 + i	0	2 + 2i	0	×	×	4 + 4i	$\frac{D}{(1-D)^{i+1}}$	25	-	$\frac{D}{(1-D)^{i+1}}.\frac{D(1-D)}{(1-D)^{i+1}}$ $\frac{D}{(1-D)^{i+1}}.\frac{D(1-D)}{(1-D)^{i+1}}$	95.05 (at 500W with 40V V_{in})
[139]	2	3	0	4	1	✓	×	8	$\frac{1}{(1-D)^2}$	25	-	$\frac{-(1-D)}{(1-D)^2}.\frac{1}{(1-D)^2}$ $\frac{-(1-D)}{(1-D)^2}.\frac{1}{(1-D)^2}$	89.5 (at 250W with 27V V_{in})
[140]	2	3	4	1	0	×	×	10	$\frac{1+(1-D)^2}{(1-D)^2}$	26	$\frac{-1}{(1-D)^2}.\frac{D}{(1-D)^2}$ $\frac{-1}{(1-D)^2}.\frac{-1}{(1-D)^2}$	$\frac{1}{(1-D)^2}$	97.3 (at 150W with 18.5V V_{in})
[141]	3	3	5	1	0	×	×	12	$\frac{D^2}{(1-D)^2}$	16	$\frac{1}{1-D}.\frac{D}{(1-D)^2}.\frac{1}{(1-D)^2}.$ $\frac{1}{1-D}.\frac{D}{(1-D)^2}$	$\frac{1}{(1-D)^2}$	81.7 (at 100W with 30V V_{in})
[142]	3	2	2	2	0	×	×	9	$\frac{D^2}{(1-D)^2}$	16	$\frac{1}{1-D}.\frac{D}{(1-D)^2}$	$\frac{1}{1-D}.\frac{D}{(1-D)^2}$	*NR*
[143]	2	2	2	2	0	×	×	8	$\frac{1}{(1-D)^2}$	25	$\frac{1}{1-D}.\frac{2-D}{(1-D)^2}$	$\frac{1}{1-D}.\frac{1}{1-D}$	*NR*
[144]	3	4	5	2	0	×	×	14	$\frac{3-D}{(1-D)^2}$	55	$\frac{1}{1-D}.\frac{1}{1-D}.\frac{2}{D(1-D)}$ $\frac{2}{D(1-D)}.\frac{4-D}{D(1-D)}$	$\frac{1}{1-D}.\frac{4-D}{D(1-D)}$	*96.1 (at 200W with 10V Vin)*
[145]	2	2	2	2	0	×	×	8	$\frac{D^2}{(1-D)^2}$	16	*NR*	*NR*	*91.83 (at 100W with 36V Vin)*
[146]	3	2	2	2	0	×	×	9	$\frac{D^2}{(1-D)^2}$	16	$\frac{1}{1-D}.\frac{D}{(1-D)^2}$	$\frac{1}{1-D}.\frac{D^2}{(1-D)^2}$	*NR*
[118]	2	2	2	2	0	×	×	8	$\frac{D^2}{(1-D)^2}$	16	*NR*	*NR*	*NR*
[119]	2	2	2	2	0	×	×	8	$\frac{D(2-D)}{(1-D)^2}$	24	$\frac{1}{1-D}.\frac{2-D}{(1-D)^2}$	$\frac{1}{1-D}.\frac{1}{(1-D)^2}$	97.4 (at 30W with 10V V_{in})
[147]	4	4	5	1	2	✓	×	12	$\boldsymbol{\frac{n_{12}(1-g)+n_{32}(1-D)+2-D}{(1-D)^2}}$	90	$\frac{1}{1-D}.\frac{(1-D)+n_{12}}{(1-D)^2}.$ $\frac{1+n_{12}}{(1-D)^2}.\frac{n_{32}}{1-D}.$ $\frac{n_{12}+2-D}{(1-D)^2}$	$\frac{n_{12}+2-D}{(1-D)^2}$	95.3 (at 200W with 40V V_{in})
[148]	4	6	7	1	2	✓	✓	16	$\frac{n_{12}+n_{13}+2}{(1-D)^2}$	150	$\frac{D}{(1-D)^2}.\frac{1}{1-D}.\frac{1}{(1-D)^2}$ $\frac{1+n_2}{(1-D)^2}.\frac{1+n_2}{(1-D)^2}.$ $\frac{n_3}{(1-D)^2}.\frac{n_3}{(1-D)^2}$	$\frac{1}{(1-D)^2}$	*NR*
[149	4 / 4	4 / 5	5 / 6	1 / 1	2 / 2	✓	×	12 / 14	$\frac{2+(n_1+n_2)-n_2D}{(1-D)^2}$ $\frac{2+(n_1+n_2)+n_2D}{(1-D)^2}$	110/190	$\frac{D}{(1-D)^2}.\frac{1}{1-D}.\frac{1}{(1-D)^2}$ $\frac{n_2}{(1-D)^2}.\frac{1+(n_1+n_2)}{(1-D)^2}.$ $\frac{1+(n_1+n_2)-2n_2D}{(1-D)^2}$	$\frac{1}{(1-D)^2}$	94.7 (at 300W with 30V V_{in})
[150]	2	2	3	1	0	×	×	8	$\frac{1}{(1-D)^2}$	25	*NR*	*NR*	92.4 (at 200W with 40V V_{in})
[151]	2	3	3	2	0	×	×	10	$\frac{1+D}{(1-D)^2}$	45	$\frac{1}{1-D}.\frac{1}{1-D}.\frac{2}{(1-D)^2}$	$\frac{1}{1-D}.\frac{1+D}{(1-D)^2}$	92 (at 150W with 12V V_{in})
[152]	2	3	4	3	0	×	×	12	$\frac{2D}{(1-D)^2}$	40	$\frac{1}{(1-D)^2}.\frac{1}{(1-D)^2}$ $\frac{1}{(1-D)^2}.\frac{1}{(1-D)^2}$	$\frac{1}{1-D}.\frac{1}{2(1-D)}$ $\frac{1}{2(1-D)}$	94.3 (at 206W with 25V V_{in})
[153]	3	2	1	3	0	×	×	9	$\frac{1}{(1-D)^2}$	25	*NR*	*NR*	95.8 (at 250W with 36V V_{in})
[154]	1	4	5	1	2	✓	×	12	$\frac{1+n}{(1-D)^2}$	75	$\frac{1}{1-D}.\frac{D}{(1-D)^2}.\frac{1}{(1-D)^2}$ $\frac{n}{(1-D)^2}.\frac{n}{(1-D)^2}$	$\frac{1}{(1-D)^2}$	90.1 (at 38W with 12V V_{in})
[155]	4	5	5	2	2	✓	✓	14	$\frac{n^2+n(3+D)+3+D}{(1-D)^2}$	385	$\frac{1}{1-D}.\frac{1+n}{1-D}.\frac{2+n}{(1-D)^2}.$ $\frac{n^2+3n+2}{(1-D)^2}.\frac{n^2+3n+2}{(1-D)^2}$	$\frac{1}{1-D}.\frac{1+D(1+n)}{(1-D)^2}$	95.2 (at 200W with 25V V_{in})
[156]	2	4	4	2	0	×	✓	12	$\frac{3-D}{(1-D)^2}$	55	$\frac{1}{1-D}.\frac{1}{1-D}.\frac{2}{(1-D)^2}$	$\frac{1}{1-D}.\frac{2-D}{(1-D)^2}$	90 (at 80W with 12V V_{in})
[157]	3	6	6	1	0	×	×	16	$\frac{3-D}{(1-D)^2}$	55	$\frac{1}{1-D}.\frac{1}{(1-D)^2}.\frac{1}{(1-D)^2}$ $\frac{1}{(1-D)^2}.\frac{1}{(1-D)^2}.\frac{1}{(1-D)^2}$	$\frac{1}{(1-D)^2}$	90 (at 100W with 10V V_{in})
[158]	5	5	6	2	3	✓	×	16	$\frac{2n_1+1+D+n_2(1-D)}{(1-D)^2}$	155	$\frac{2}{(1-D)^2}.\frac{2n_1+n_2(1-D)}{(1-D)^2}$	$\frac{1-D}{(1-D)^2}.\frac{1+D}{(1-D)^2}$	95.8 (at 480W with 25V V_{in})
[159]	1 + M / 2 + M	M / M	2M-1 / 3M-2	M / M	0	×	×	5M / 6M	$\frac{M}{(1-D)^2}$	50	$\frac{1}{M(1-D)^2}.\frac{1}{2M(1-D)^2}$	$\frac{1}{2M(1-D)^2}$	95.82 (at 660W with 20V V_{in} for M=2)

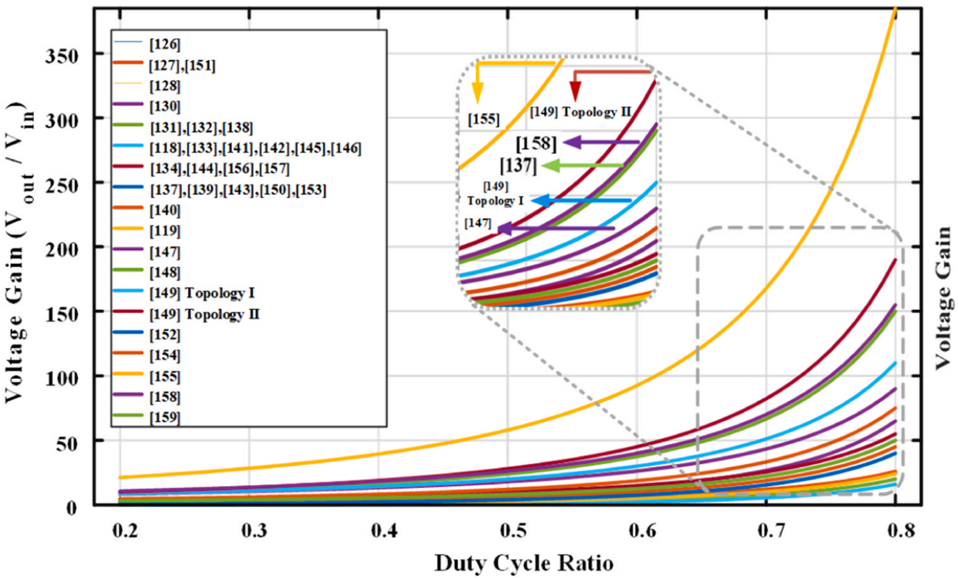


Fig. 9. Quadratic gain DC-DC converters voltage gains comparison for 0.2–0.8 duty cycles.

to be extended. However, these values are determined in ideal conditions; leakage inductances, conduction loss, reverse recovery voltage of diodes, etc., must not be ignored, during the design and manufacturing procedures.

As the QGDCC proposed in Abbasi et al. (2022) proposes the highest voltage gain compared with others listed in Table 1, its voltage gain versus duty cycle and turn ratio variations is depicted in Fig. 10. Furthermore, to exhibit the behavior of turn ratio increment on the voltage gain of the QGDCCs utilizing built-in transformers or coupled inductors, they have been compared in Fig. 11. The duty cycle value of 0.5 has been chosen and the turn ratio has been swept from 1 to 5. It can be observed that except (Esmaeili et al., 2023; Abbasi et al., 2022), other QGDCCs present linear behavior to turn ratio increment. In Esmaeili et al. (2023), the voltage gain value decreases with the increase of turn ratio value. Obviously, increasing the turn ratio would lead to higher voltage gain. Nevertheless, it should be considered that this would result in higher leakage inductance and higher voltage stress on switching components. Thus, a trade-off is necessary.

Voltage stress and current stress are two prominent factor in power electronics converters. It is recommended to choose switching components with 2–3 times of the rating voltage and current to provide reliability and avoid the switch failure. Obviously, components with higher rating voltage/current would be more expensive and bulky. Thus, it is recommended to lower the voltage/current stress of electronic components to lower the converter total cost and ensure its operation reliability. The voltage stresses of mentioned literatures in Table 1 are depicted in Fig. 12. In addition, the current stress relations are listed in Table 2. It can be observed from Fig. 12 (a) that converters proposed in Alizadeh et al. (2022); Habibi et al. (2022); Abbasi et al. (2022); Nikbakht et al. (2023) have the highest diodes voltage stresses. It should be noted that these converters have the highest voltage gains, as well. Therefore, diodes those placed near the output terminal suffer from higher voltage stresses. The voltage stresses of diodes and active switches are defined in accordance with the input voltage. In many studies, output voltage is preferred. As it can be observed from Fig. 12 (b), converters (Alizadeh et al., 2022; Abbasi et al., 2022; Subhani et al., 2023; Nikbakht et al., 2023) suffer from the highest active switches voltage stresses. Furthermore, converter proposed in Arvani et al. (2023) do not show a pure increasing behavior. From 0.2–0.6 duty cycles its active switch voltage stress is reducing and after that it start to increase,

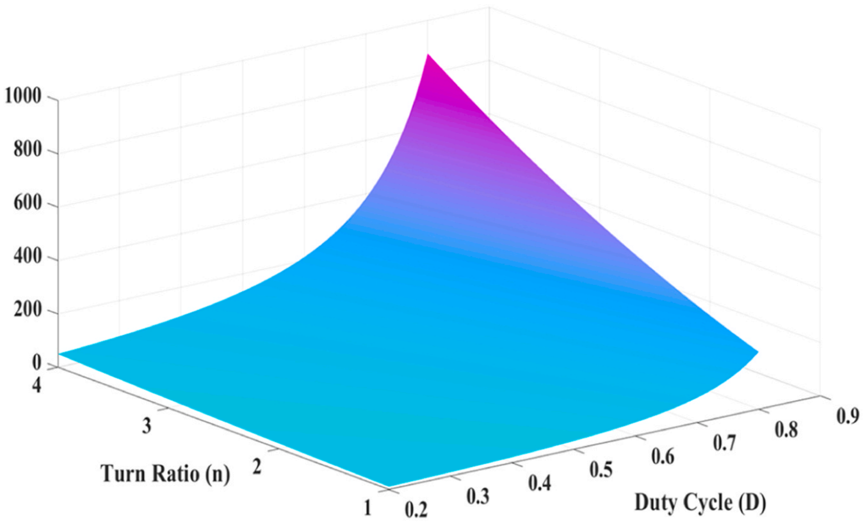


Fig. 10. Voltage gains comparison for 0.2–0.8 duty cycles of the converter proposed in Abbasi et al. (2022).

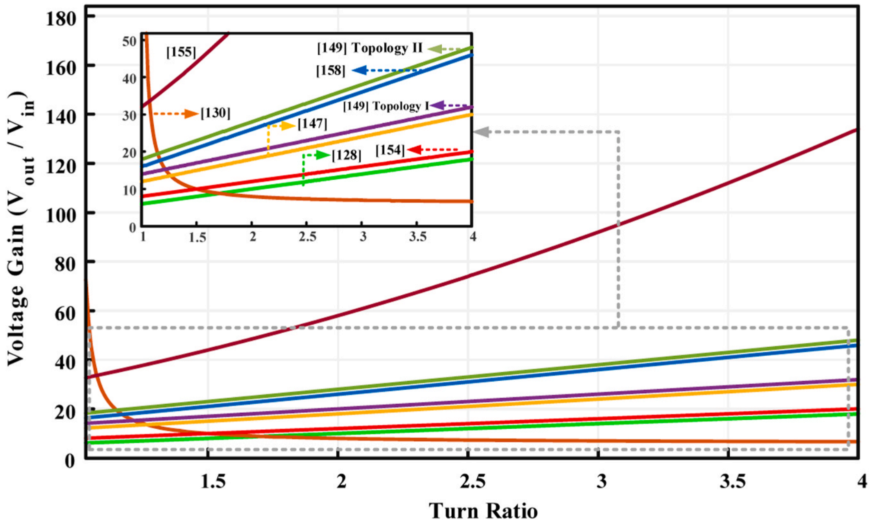


Fig. 11. Quadratic gain DC-DC converters voltage gains comparison for 1–4 turn ratios with 0.5 duty cycle value.

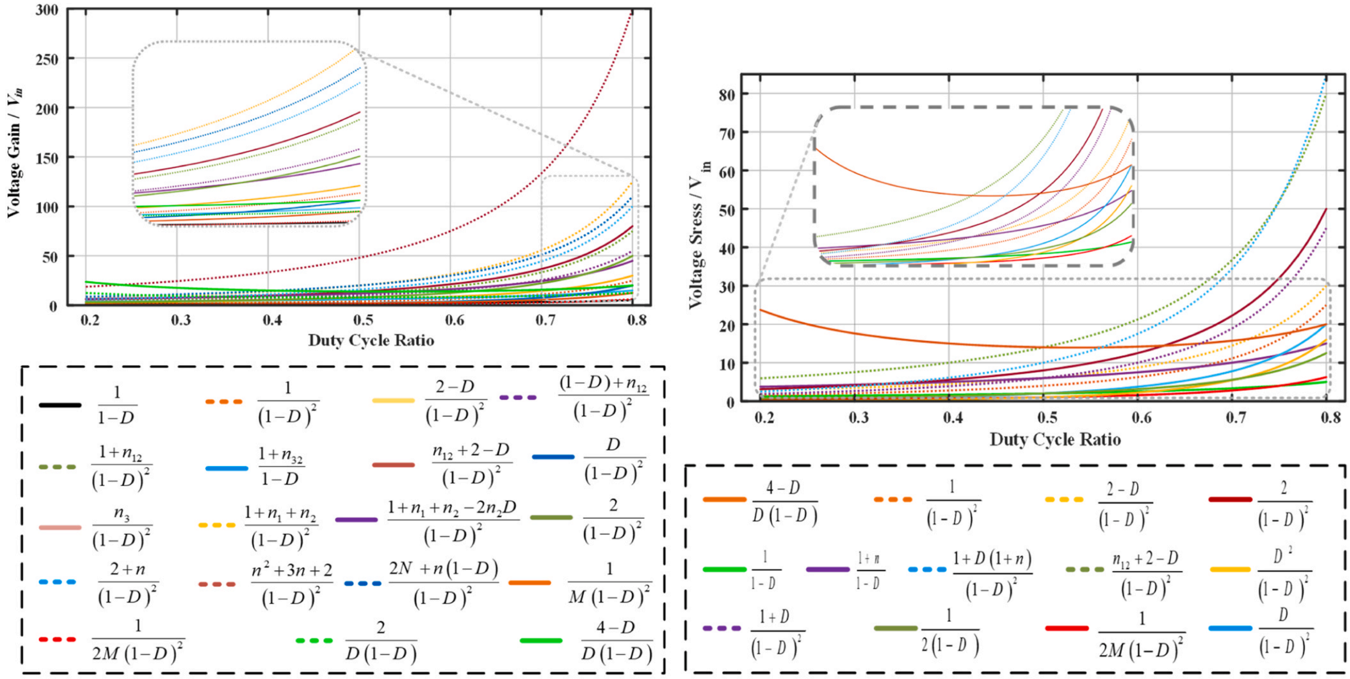


Fig. 12. Quadratic gain DC-DC converters voltage stresses comparison for 0.2–0.8 duty cycles of (a) diodes (b) active switches.

smoothly.

The quadratic gain step-up converter has attracted considerable attention owing to its plethora of prominent attributes. Notably, it is capable of providing high voltage gains with low active switches count, thereby providing acceptable efficiency and simple drive strategies. Furthermore, these converters may provide the compactness and reduced complexity potentials, rendering it an attractive solution for various applications. Nevertheless, it is necessary to acknowledge that quadratic gain step-up converters are not widely used for high-power and high-current applications, necessitating the deployment of alternative solutions in such scenarios.

6. Cascaded DC-DC converters

6.1. Main feature discussion

The CDCCs, a common technique employed to increment voltage gain, entail the serial interconnection of multiple DC-DC converters, each manipulated to yield a specific output voltage, as shown in Fig. 13 (Costa da Silva et al., 2023). The input voltage is supplied to the first converter, whose output serves as the input for the subsequent converter in the sequence, continuing until the desired voltage is achieved. Through the judicious components selection and designing each stage for its intended output, cascaded converters can achieve acceptable efficiency suitable for a plethora of applications. The overall voltage gain is the product of the individual gains, potentially resulting in high voltage gains; however, this principle compromises the overall system

Table 2
Current stress of the reviewed quadratic gain dc-dc converters.

Ref.	Diode(s) Current Stress	Switch(s) Current Stress	Ref.	Diode(s) Current Stress	Switch(s) Current Stress	Ref.	Diode(s) Current Stress	Switch(s) Current Stress
[132]	$\frac{I_o}{1-D}.I_o$	$\frac{D^2I_o}{(1-D)^2}.\frac{D(2D-1)I_o}{(1-D)^2}$	[133]	$\frac{DI_o}{1-D}.\frac{DI_o}{1-D}.$ $\frac{2D(D-1)I_o}{(1-D)^2}.\frac{\sqrt{1-D}I_o}{1-D}$	$\frac{D^2I_o}{(1-D)^2}$	[134]	NR	$\frac{(2+D-D^2)I_o}{(1-D)^2}$
[138]	-	$\frac{I_o}{1-D}.\frac{I_o}{(1-D)^2}.$ $\frac{I_o}{1-D}.\frac{I_o}{(1-D)^2}$	[141]	$\frac{D^2I_o}{1-D}.\frac{D^3I_o}{(1-D)^2}.$ $DI_o.DI_o.(1-D)I_o$	$\frac{(D-D^2+D^3)I_o}{(1-D)^2}$	[142]	$\frac{DI_o}{1-D}.DI_o$	$\frac{DI_o}{1-D}.\frac{D^2I_o}{(1-D)^2}$
[143]	$\frac{DI_o}{1-D}.DI_o$	$\frac{DI_o}{(1-D)^2}.\frac{DI_o}{1-D}$	[144]	$\frac{2I_o}{(1-D)^2}.\frac{2I_o}{D(1-D)}.$ $\frac{I_o}{D(1-D)}.\frac{I_o}{D(1-D)}.\frac{I_o}{(1-D)}$	$\frac{(1+D)I_o}{D(1-D)^2}.\frac{(1+D)I_o}{D(1-D)}$	[146]	$\frac{DI_o}{1-D}.DI_o$	$\frac{D^2I_o}{(1-D)^2}.\frac{DI_o}{1-D}$
[149]	$\frac{D(2+(n_1+n_2)-n_2D)I_o}{(1-D)^2}.$ $\frac{D(2+(n_1+n_2)+n_2D)I_o}{(1-D)^2}.$ $\frac{(2+(n_1+n_2)-n_2D)I_o}{1-D}.$ $\frac{(2+(n_1+n_2)+n_2D)I_o}{1-D}.$ $I_o.I_o.I_o$	$\frac{(\mathbf{1}+(\boldsymbol{n_1}+\boldsymbol{n_2})+(\mathbf{2}-\boldsymbol{n_2})\boldsymbol{D}-\boldsymbol{D}^2)\boldsymbol{I_o}}{(\mathbf{1}-\boldsymbol{D})^2}$ $\frac{(\mathbf{1}+(\boldsymbol{n_1}+\boldsymbol{n_2})+(\mathbf{2}+\boldsymbol{n_2})\boldsymbol{D}-\boldsymbol{D}^2)\boldsymbol{I_o}}{(\mathbf{1}-\boldsymbol{D})^2}$	[151]	$\frac{\sqrt{1-D}I_o}{1-D}.\frac{D\sqrt{1-D}I_o}{1-D}.$ $\sqrt{1-D}I_o$	$\frac{2D\sqrt{D}I_o}{(1-D)^2}.\frac{D\sqrt{D}I_o}{1-D}$	[157]	$\frac{(3-D)I_o}{1-D}.\frac{D(3-D)I_o}{(1-D)^2}.$ $I_o.I_o.I_o.I_o$	$\frac{(2+D-D^2)I_o}{(1-D)^2}$

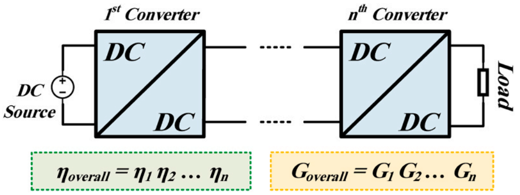
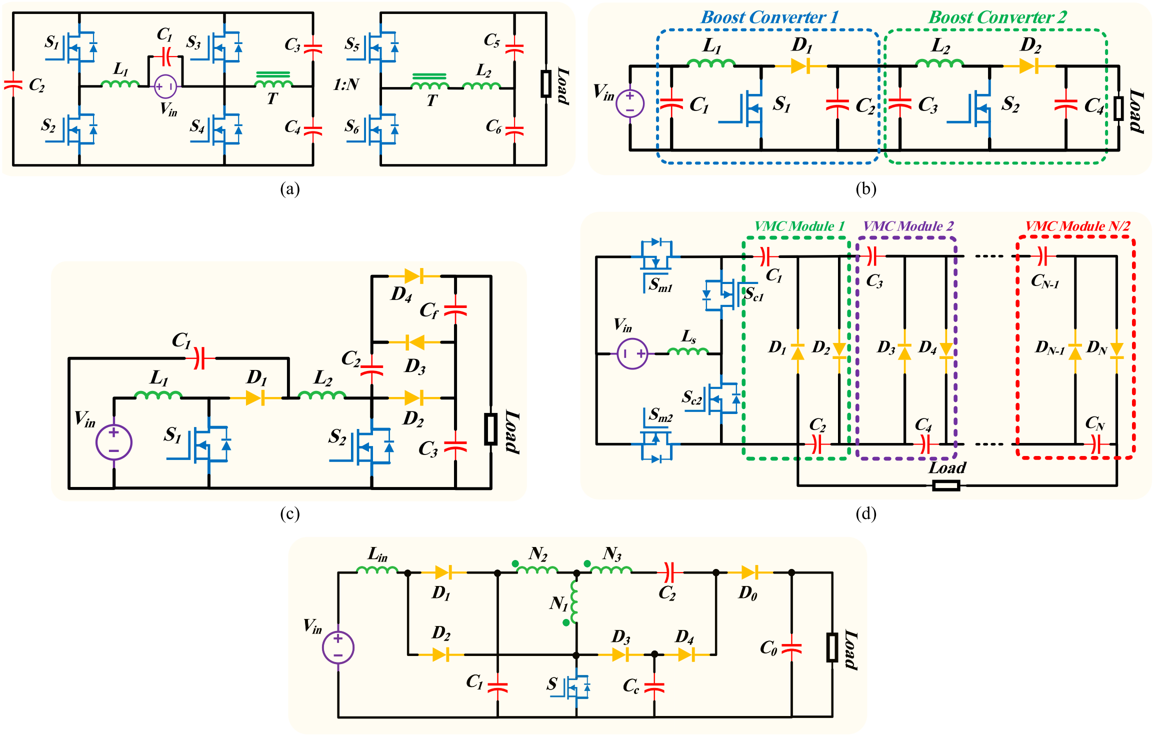


Fig. 13. General layout of multistage cascaded DC-DC converters.

efficiency (Costa da Silva et al., 2023).

Y.E. Majeed et al. have proposed a power delivery system using traditional cascaded boost DC-DC converter, stabilizing and adjusting the output current and voltage (Majeed et al., 2018). In this proposed system, each pair of turbines is connected to two paralleled conventional boost converters, defining a cell. These cells are connected to each other in series (first stage) and at last, they would be connected to another boost converter (second stage) to increase the DC voltage level. The EVs do not utilize a single huge battery as the energy source. They use several smaller batteries connected in series/parallel to provide more safety and reliability. On this matter, X. Qi et al. have proposed a reliable CDCC, as shown in Fig. 14 (a), providing bidirectional operation, higher



(a) (b)

(c) (d)

(e)

Fig. 14. Some of the proposed cascaded DC-DC converters in literature (a) an integrated bidirectional cascaded converter proposed by X. Qi et al. (b) the traditional cascaded step-up converter containing two conventional boost converters (c) a VMC coupled cascaded converter proposed by V. S. Rao et al. (d) a Cockcroft-Walton VMC based cascaded high step-up converter (e) a high step-up cascaded three-winding coupled inductor with reverse proportion with turn ratio converter.

reliability, and compactness (Qi et al., 2021, 2020). Another way to charge the EVs is the WPT technology. A WPT system contains various sections. However, the system control may be assigned to its DC-DC converter. Thus, it is vital for the WPT system to be controlled in accordance with various loads and mismatch conditions. On this basis, achieving high voltage gain is not the main concern. A CDCC is proposed for this application in Fu et al. (2013), utilizing traditional boost and buck converters for the first and the second stages, respectively.

Reliable and simple control strategy is vital for grid-connected PV systems. They must able to respond rapidly to various situations and they must be highly adaptable with the MPPT, as well. The DC-DC converters of the PV systems must overcome predictable and unpredictable mostly natural disturbances, as shadows and climate conditions significantly affect the output voltage (Pokharkar et al., 2024). The cascaded form of the traditional boost converter, as depicted in Fig. 14 (b), is one of the most utilized DC-DC converters as it benefits from high efficiency, low cost, MPPT friendly, etc (Vighetti et al., 2011). J. Fu et al. have proposed a CDCC by placing a boost and a buck-boost converter in series (Fu et al., 2014). In addition, they have combined switches into a single switch to benefit from simpler control procedure. To achieve higher voltage gains, converters with higher voltage conversion ratio can be utilized in each stage. In Chen et al. (2010), a quadratic gain is obtained by utilizing boost and Flyback converters in first and second stages, respectively. M. Hosseinzadeh et al. have proposed a high gain converter that utilizes a coupled inductor with only one switch, utilizing a clamp circuit for energy recovery purposes (Hoseinzadeh et al., 2019). A two-stage CDCC capable of converting 30 V input to 1363 V output was presented in Khosroshahi et al. (2019), utilizing a modified buck-boost converter and a high step-up converter with coupled inductors.

N. Totonchi et al. have proposed a high step-up DC-DC converter with the help of a VMC and self-lift Luo converter, using a single switch (Totonchi et al., 2020). The proposed converter would provide 9 times voltage amplification with duty cycle value of 0.5. In Mei et al. (2021), a bidirectional CDCC is introduced that utilizes a SC circuit as the second stage and coupled inductor-based converter in the first stage. In this converter, the simple inductors are replaced by coupled inductors. V.S. Rao et al. have modified a VMC-based quadratic boost converter and proposed a CDCC (Rao and Sundaramoorthy, 2022). It includes two inductors and provides positive output polarity with improved efficiency. In addition, it benefits from low volume and compactness, as shown in Fig. 14 (c). C.M. Young et al. have proposed a step-up cascaded converter according to Cockcroft-Walton VMC (Young et al., 2012), as shown in Fig. 14 (d). Their converter is able to provide suitable DC voltage for n + 1 level inverter. The above-mentioned converter can be expanded to achieve higher DC voltage levels by adding more Cockcroft-Walton VMCs in series. In Hu et al. (2019), a CDCC is proposed by utilizing two parallel coupled inductors in the input that reduces the input current ripple, followed by a VMC. Besides, it provides the ZCS and high voltage gain with acceptable efficiency. Another ripple-free input current converter is suggested in Lee and Do (2018b), utilizing coupled inductors series with the input terminal as the first stage. In the second stage, another coupled inductor is placed, capable to increase the voltage gain by raising the turn ratio value. Voltage gain of coupled inductor based converters mostly raises with the increase of turn ratio. However, F. Li et al. have proposed a CDCC that its voltage gain increase with the inductors turn ratio increment is constrained (Li and Liu, 2016), as illustrated in Fig. 14 (e). In Saadat and Abbaszadeh (2016), the authors could achieve high voltage gain by cascading a quadratic boost converter and a SC network, using a coupled inductor for more increment of voltage conversion ratio, while requiring only a single switch. Q. Pan et al. have presented a CDCC that utilizes a quadratic boost converter, two VMCs, and a coupled inductor (Pan et al., 2019). This converter can provide ultrahigh voltage gains with low values of duty cycle. In Hu et al. (2020), a cascaded converter is proposed based on interleaved dual coupled inductors at the input section to reduce the switches current stresses and current ripple. For the voltage boosting purpose, voltage doubler capacitors are integrated with the converter circuit. In this converter, voltage stress of switches can be reduced to 1/6 of output voltage for a specific turn ratio. R. Kumari et al. have investigated a DC-DC converter by cascading a boost and a SEPIC converter to achieve high voltage gain and high efficiency (Kumari et al., 2021). An ultrahigh gain CDCC is investigated by Hasanpur et al., cascading two boost and buck-boost converters (Hasanpour et al., 2020). Furthermore, to attain higher voltage gain, a coupled inductor and a VMC are accommodated in the circuit structure and the leakage inductor of the coupled inductor is manipulated to be recycled in the VMC's capacitors, leading to more voltage boosting.

6.1.1. Performance parameters comparison

The voltage gains and components counts of discussed CDCCs are listed in Table 3. adhering to the component counting rules outlined in the previous subsection. It can be observed that the SCs are utilized in Mei et al. (2021); Saadat and Abbaszadeh (2016), while transformer is only used in Qi et al. (2021, 2020). Moreover, deploying coupled inductors is a favorable voltage boosting technique in the CDCCs. Number of modules in Young et al. (2012) is set to 2, as the turn ratio has been se to 2 for all of the listed converters to have a more comparison. The Hu et al. (2020) has the most components count among these converters, equal to 16. It can be seen that the CDCC proposed in Hasanpour et al. (2020) may achieve the highest voltage gain among others with the help of the VMCs and coupled inductors, 275 for D= 0.8. The voltage gains versus duty cycle ratio curves of introduced converters are given in Fig. 15. It is important to note that their ideal voltage gain in the CCM is taken into account. Converters introduced in Hoseinzadeh et al. (2019); Khosroshahi et al. (2019) take the third and second places from the voltage gain perspective, respectively. For under 0.3 value of duty cycle, the converter proposed in Young et al. (2012) has the highest voltage gain compare with others, except (Hasanpour et al., 2020). This is mostly due to the first order duty cycle in the voltage conversion ratio relation. However, its voltage amplification rate can be incremented by increasing the turn ratio, may lead to leakage inductance issues.

Diodes and active switches voltage stress on Vin are illustrated in Fig. 16. It can be observed that converters (Hu et al., 2019; Hasanpour et al., 2020) have the highest voltage stresses on their diodes. Furthermore, converters proposed in Khosroshahi et al. (2019); Lee and Do (2018b) suffer from high diodes voltage stresses, as well. by comparing the results obtained from Table 3 and Fig. 16, it can be deduced that the diodes and switches of the last stages of the CSDCCs suffer from higher voltage stresses, mostly. Analyzing the Fig. 16 (b), converters investigated in Totonchi et al. (2020); Hasanpour et al. (2020) have the highest voltage stresses on their active switches. Obviously, by placing the switch(s) near the output terminal may lead to the reduced voltage stress, while current stress would be increased. It should be noted that the high voltage stress on the diodes and switches of the converter proposed in Hasanpour et al. (2020) does not mean that it is not an appropriate or it is not reliable. Components voltage stresses and voltage gain of the converter are two performance parameter of a power electronics converter that must be considered simultaneously. The higher voltage gain may be achieved with higher components voltage stresses. However, during the design procedure, all of the parameters must be considered and the high voltage gain or the high component voltage stress would not be an advantage or disadvantage, solely. This fully depends on the application specifications.

The CDCCs simplify design processes and enhance flexibility by integrating diverse topologies. For instance, a cascaded configuration can utilize a low input current ripple converter in the initial stage, followed by a high-gain structure to achieve the desired DC voltage. Nevertheless, this type of converter also presents certain drawbacks. The notable drawback is that the efficiency of the cascaded topology is the product of the efficiency at each stage, thereby potentially leading to reduction in the overall efficiency of the system.

Table 3
Performance comparison of the reviewed cascaded dc-dc converters.

Ref.	Each components count					Coupled inductor or built-in transformer	Switched capacitors	Total components count	Voltage gain	Voltage gain value for D=0.8	Diode(s) Voltage Stress (on V_{in})	Switch(s) Voltage Stress (on V_{in})	Efficiency (%)
	L	*C*	*D*	*Sw*	*FCO*								
[169]	2	2	3	1	2	×	×	8	$\frac{D}{(1-D)^2}$	20	*NR*	*NR*	*NR*
[170]	3	3	4	1	2	✓	×	10	$\frac{1+nD}{(1-D)^2}$	65	$\frac{D}{(1-D)^2}\cdot\frac{1}{1-D}\cdot$ $\frac{n}{(1-D)^2}\cdot\frac{1}{(1-D)^2}$	$\frac{1}{(1-D)^2}$	92.5 (at 280W with 40V V_{in})
[171]	3	4	5	1	2	✓	×	12	$\frac{(1+n)(1+D)}{(1-D)^2}$	135	$\frac{1}{1-D}\cdot\frac{1}{1-D}\cdot\frac{n+D}{(1-D)^2}\cdot$ $\frac{n+D}{(1-D)^2}\cdot\frac{1+n}{(1-D)^2}$	$\frac{1}{(1-D)^2}$	*NR*
[173]	3	5	6	1	2	✓	×	14	$\frac{2+n+nD}{(1-D)^2}$	140	$\frac{1}{1-D}\cdot\frac{D}{(1-D)^2}\cdot\frac{1}{(1-D)^2}\cdot$ $\frac{1+n}{(1-D)^2}\cdot\frac{1+n}{(1-D)^2}\cdot\frac{1+n}{(1-D)^2}$	$\frac{1}{(1-D)^2}$	*NR*
[174]	3	4	6	1	3	×	×	14	$1+\frac{2}{(1-D)^2}$	51	$\frac{1}{1-D}\cdot\frac{1+D}{(1-D)^2}\cdot$ $\frac{1}{(1-D)^2}\cdot\frac{1}{(1-D)^2}\cdot\frac{2}{(1-D)^2}$	$\frac{2}{(1-D)^2}$	*NR*
[175]	2	5	0	6	1	✓	✓	12	$\frac{3-D}{(1-D)^2}$	55	-	$\frac{1}{1-D}\cdot\frac{1}{1-D}\cdot\frac{1}{(1-D)^2}$ $\frac{2-D}{(1-D)^2}\cdot\frac{2-D}{(1-D)^2}\cdot\frac{2-D}{(1-D)^2}$	*NR*
[176]	2	4	4	2	2	×	×	12	$\frac{2}{(1-D)^2}$	50	*NR*	$\frac{1}{(1-D)^2}\cdot\frac{1}{1-D}$	97.1 (at 345W with 57.3V V_{in})
[177]	1	2n	2n	4	1	×	×	5+4n	$\frac{2n}{1-D}$	20	$\frac{1}{1-D}$	$\frac{1}{1-D}$	91.6 (at 200W with 24V V_{in})
[178]	4	4	4	2	2	✓	×	12	$\frac{4+2n}{1-D}$	40	$\frac{2}{1-D}\cdot\frac{2+2n}{1-D}$ $\frac{2+2n}{1-D}\cdot\frac{1}{1-D}$	$\frac{1}{1-D}\cdot\frac{1}{1-D}$	96 (at 450W with 25V V_{in})
[179]	5	2	3	1	3	✓	×	8	$\frac{1+n_2D}{(1-D)^2}$	65	$\frac{1}{1-D}\cdot\frac{D}{(1-D)^2}\cdot\frac{1+n_2}{(1-D)^2}$	$\frac{1}{1-D}$	90 (at 200W with 24V V_{in})
[180]	4	4	5	1	2	✓	×	12	$\frac{2n_2+n_3-1}{(1-D)^2(n_2-1)}$	125	$\frac{1}{1-D}\cdot\frac{D}{(1-D)^2}\cdot\frac{1}{(1-D)^2}\cdot$ $\frac{n_2+n_3}{(1-D)^2(n_2-1)}\cdot$ $\frac{n_2+n_3}{(1-D)^2(n_2-1)}$	$\frac{1}{(1-D)^2}$	91.4 (at 400W with 38V V_{in})
[181]	3	5	6	1	2	✓	✓	14	$\frac{n(2+3D)+2-D}{(1-D)^2}$	125	$\frac{1}{1-D}\cdot\frac{D(n+1)}{2(1-D)^2}\cdot\frac{n}{(1-D)^2}\cdot$ $\frac{n}{(1-D)^2}\cdot\frac{D(n-1)+2}{2(1-D)^2}\cdot$ $\frac{n}{(1-D)^2}$	$\frac{D(n-1)+2}{2(1-D)^2}$	92.96 (at 250W with 24V V_{in})
[182]	4	6	6	2	2	✓	×	16	$\frac{4+2n}{1-D}$	40	$\frac{2}{1-D}\cdot\frac{2}{1-D}\cdot\frac{2}{1-D}\cdot$ $\frac{2}{1-D}\cdot\frac{2n}{1-D}\cdot\frac{2n}{1-D}$	$\frac{1}{1-D}\cdot\frac{1}{1-D}$	94.3 (at 400W with 20V V_{in})
[183]	3	3	3	1	0	×	×	10	$\frac{D}{(1-D)^2}$	20	*NR*	*NR*	*NR*
[184]	3	4	5	2	2	✓	×	13	$\frac{3+D+2n(1+D)}{(1-D)^2}$	275	$\frac{1}{1-D}\cdot\frac{1}{1-D}\cdot\frac{2+2n}{(1-D)^2}\cdot$ $\frac{2+2n}{(1-D)^2}\cdot\frac{2+2n}{(1-D)^2}$	$\frac{1}{1-D}\cdot\frac{1+D}{(1-D)^2}$	94.15 (at 160W with 24V V_{in})

7. Interleaved DC-DC converters

7.1. Main features discussion

Interleaved structures of the DC-DC converters are well-known for their qualification in current ripple suppression, high-current, and high-power applications, where their capacity to manage substantial power flows is particularly noteworthy (Guo et al., 2020). Their capability to distribute the current stress of the primary switch is beneficial, resulting in mitigating the risk of overheating and prolonging the lifespan of the converter. In addition, interleaving technique may enhance the reliability by structuring the converter into multiple phases; if one phase fails, others compensate (Rahimi et al., 2020). Nevertheless, the switching control system must be precisely designed to ensure switches coordination which could compromise the overall performance of the converter. This type of the MSDCCs is widely utilized in high-power devices and has garnered attentions among industry due to its unique capabilities and advantages (Kumar et al., 2023).

As previously mentioned, coupled inductor is an effective voltage boosting technique. To increase the rated current and power of the converter, interleaving may be deployed (Ye et al., 2024). S. Dwari et al. have suggested a modified interleaved boost converter, utilizing an active diode-capacitor clamp to lower the switches voltage stress (Dwari and Parsa, 2010). An interleaved high step-up ZVT DC-DC converter, facilitated with a voltage doubler cell. This cell consists a three winding built-in transformer and two pairs of voltage doubler circuits (Li et al., 2012). Another three-winding coupled inductor based interleaved converter is given in Li et al. (2023), as depicted in Fig. 17 (a). This converter's voltage gain is dramatically enhanced by combining the three-winding coupled inductor with passive clamp circuit. The voltage gain is further improved with a VMC. To remove the existence of bulky capacitors, a three phase coupled inductor bridge is presented in Hu et al. (2014) based on voltage quadrupler. Y.F. Wang have introduced a high step-up bidirectional interleaved converter with the help of coupled inductors (Wang et al., 2015). It is a developed version of conventional dual-phase interleaved boost converter by adding SCs and enabling it to be built in higher phases count. Another switched inductor and capacitor-based IDCC is reported in Zhang et al. (2017b). The main drawback of this converter is that it needs one switch for each capacitor, leading to more complex control scheme, higher cost and conduction

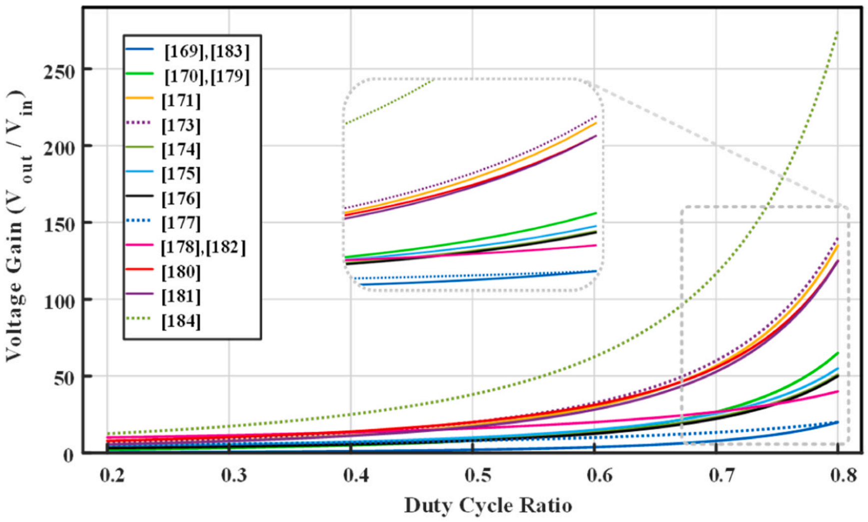
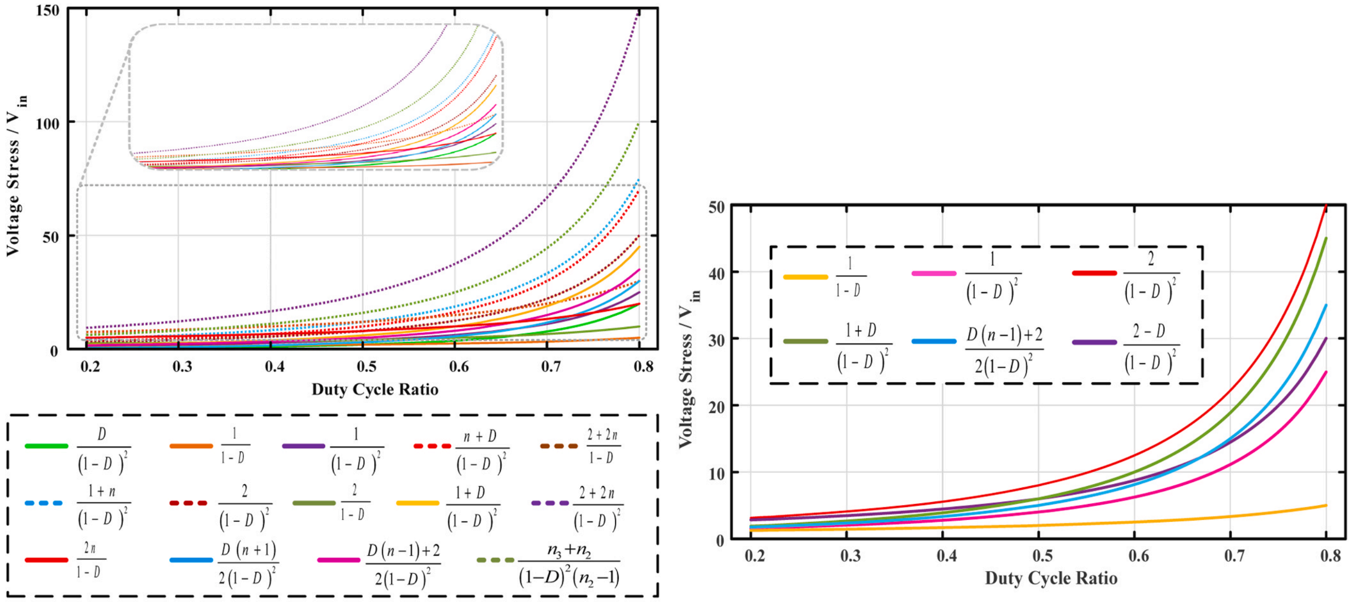


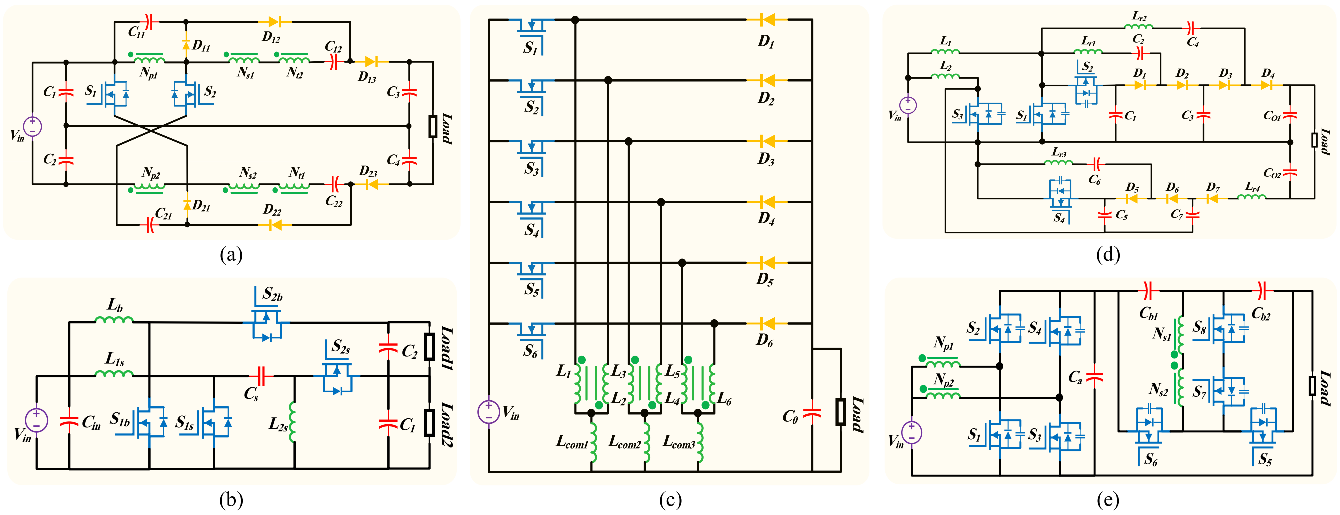
Fig. 15. Cascaded DC-DC converters voltage gains comparison for 0.2–0.8 duty cycles.



(a) (b)

Fig. 16. Cascaded DC-DC converters voltage stresses comparison for 0.2–0.8 duty cycles of (a) diodes (b) active switches.

losses. One of the main drawbacks of traditional boost converter is its RHP zero, bringing about control issues. H. Liu et al. have proposed a two-phase interleaved boost converter that utilizes four inductors coupled with each other winded around a single ferrite core, leading to higher power density and lower cost (Liu and Zhang, 2016). Furthermore, it eliminates all of the RHP zeroes, providing more reliable and stable operation. To satisfy both the DC and the AC loads in a DC grid, a hybrid interleaved converter is put forward in Bussa et al. (2017), feeding both type of loads. This converter has interleaved two conventional boost converters, replacing the lower switch with a HB voltage source inverter. This gives rise to higher DC voltage gain and less AC harmonics distortion. H. Bahrami et al. have developed an IDCC by connecting an interleaved bidirectional buck-boost converter and a dual active HB converter by employing a coupled inductor, resulting in high voltage gain and reduced switches voltage stresses (Bahrami et al., 2017). For the further increase of the maximum transmission power of dual active bridge DC-DC converters, C. Jiang et al. have proposed a converter that its low voltage side switches are replaced with two bidirectional buck-boost converters (Jiang and Liu, 2020). Z. Yan et al. have proposed a non-isolated IDCC, suppressing current ripple and reducing the converter volume by employing a built-in transformer (Yan et al., 2019). Due to the utilized T-type neutral-point-clamped circuit, the bidirectional power flow would be achieved. A bidirectional dual-output interleaved boost-SEPIC converter is presented in Prabhakaran and Agarwal (2019). The input of the boost and the SEPIC converters are paralleled, while their output is connected in series, as illustrated in Fig. 17 (b), appropriate for the bipolar DC microgrids. Another single-input dual-output IDCC is presented in (Chapparya et al., 2023), a boost-zeta version this time to feed DC grid loads. A single-input multi-output IDCC is presented in Hassani et al. (2020), capable to provide more than five output voltage levels. The first stage is facilitated with a paralleled coupled inductor, which its first branch only benefits from the corresponding coupled inductor for voltage boosting. The second branch employs a modified SEPIC converter in addition to its coupled inductor to provide higher voltage level. Besides, the voltage amplification procedure continues with a VMC, providing two other



(a) (b) (c) (d) (e)

Fig. 17. Some of the proposed interleaved DC-DC converters in literature (a) a symmetric interleaved high step-up DC-DC converter based on three winding coupled inductors (b) a novel boost-SEPIC based interleaved DC-DC converter (c) a high power six-phase dual interleaved buck-boost converter utilizing a three interphase transformer (d) a nonisolated interleaved high step-up soft-switched DC-DC converter based on Dickson switched capacitor network (e) a bidirectional interleaved converter.

output voltages. Other voltage levels may be obtained with the combination terminals of the mentioned outputs. T. Lit et al. have investigated a novel high step-up IDCC, connecting a coupled inductor-based asymmetric VMC at the end stage (Liu et al., 2019). Also, a lossless passive clamp circuit with a common capacitor supports this VMC to provide high efficiency aside the high voltage gains. In Granados-Luna et al. (2019), a high power density two-phase dual interleaved buck-boost converter is introduced and a 32 kW prototype has been constructed and studied to validate the structure-performance. This converter uses an interphase transformer which doubles the ripple frequency with two switching arms, suppressing the input current ripple. Another 32 kW IDCC is reported in Velázquez-Elizondo et al. (2022), by structuring six buck-boost arms and each pair of arms is dually interleaved in a interphase transformer with a common inductor, as depicted in Fig. 17 (c). This converter can support high power density with low components count, whereas suffer from hard switching and its consequences.

In Alghaythi et al. (2020), a high step-up DC-DC converter is proposed, utilizing two coupled inductors and a VMC to avoid aforementioned problems. To achieve high voltage gain and high power capability, H. Lei et al. have proposed a NHSDC converter, combining the interleaved boost converter and Dickson SC network, as shown in Fig. 17 (d) (Lei et al., 2019). This converter provides high output voltages with medium-range duty cycles, utilizing resonant networks into the SCs network for the ZVS and ZCS operation. An ultrahigh gain IDCC is designed in Moradisizkoohi et al. (2019), with the contribution of SCs and inductors. An active clamp circuit and a VMC are employed to provide soft-switching operation and voltage boosting with the reduction of the reverse recovery issue of diodes capability, respectively. However, it suffers from high components count and complexity. K.A. Singh et al. have proposed a compact coupled inductor-based interleaved boost converter with low components count (Singh et al., 2021). Nevertheless, its voltage gain fully depends on the capacitor, necessitating the bulky capacitors to achieve high voltage gains. Soft-switching operation may not be achieved using clamped circuits, all the time. In Dung et al. (2019), an IDCC is suggested, consisting of two stages. First stage includes a conventional form of bidirectional interleaved buck-boost converter, while a three phase series LC resonant converter takes the second stage. A bidirectional IDCC is investigated in Hu et al. (2021), which is according to coupled inductor technique. The utilized coupled inductor in this converter can either operate as an input filter and a transformer, as shown in Fig. 17 (e). R. Rahimi et al. have proposed an interleaved coupled inductor-based high step-up DC-DC converter, employing two double-winding coupled inductors and a three-winding built-in transformer integrated with the SC-based VMCs, benefiting from the ZCS operation and low voltage stresses obtained by manipulating the leakage inductances and employing passive diode-capacitor clamp circuits, respectively (Rahimi et al., 2021a). P. Mohseni et al. have reported two combination patterns groups of ultrahigh step-up DC-DC converters benefit from coupled inductors, ferrite core transformers, and the VMCs (Mohseni et al., 2021). In addition, two stages of SC networks are utilized for incrementing the voltage gain and providing the ZVS operation simultaneously. In the first pattern, the secondary-side of coupled inductors and ferrite core transformer have series connection, while the secondary-side of coupled inductors are connected in series with the primary-side of ferrite core transformer, in the second pattern. Finally, the VMCs are connected to the secondary-side of the ferrite core transformer. Another soft-switched IDCC is proposed by J. Wan et al., utilizing an auxiliary circuit connected between the branches providing the ZCS and the ZVS for the auxiliary circuit and converter main switches, respectively, composed of two switches, two diodes, an inductor, and a capacitor (Wan et al., 2023).

7.1.1. Performance parameters comparison

The voltage gains, voltage stresses, and current stresses of diodes and active switches of the IDCCs reported in literature are given in Table 4. The IDCC proposed in Rahimi et al. (2021a), benefit from the highest voltage gain among others. The high voltage gain is not desired all the time. A good converter should make a trade of between all of the performance parameters in accordance with the application requirements. In step-up DC-DC converters, diodes and active switches in vicinity of the load suffer from higher voltage stress, while in current stress case, those near the supply terminal face more challenges. In a high or ultrahigh step-up DC-DC converter, it is desired to lower the voltage stress to voltage gain ratio. In addition, the proportionality of voltage and current stresses of switching components is recommended.

The interleaving technique divides the current into multiple paths, resulting in reduced current ripple and stress and enabling the use of switches with lower current ratings. This facilitates the deployment of the converter in high-power applications. Moreover, this technique enhances thermal management by subjecting each switch to lower current levels and stress. These converters may also well-suited for applications prioritizing reliability, as the remaining branches can compensate for any branch failure, in some cases. However, some of the interleaved

Table 4
Performance comparison of some of the reviewed interleaved dc-dc converters.

Ref.	Voltage gain	Diode(s) Voltage Stress (on V_{in})	Switch(s) Voltage Stress (on V_{in})	Diode(s) Current Stress (on I_O)	Switch(s) Current Stress (on I_O)
[189]	$\frac{2(n+1)}{1-D}$	$\frac{2(n+1)}{1-D}$	$\frac{1}{1-D}$	*NR*	*NR*
[190]	$\frac{3+4n+D}{1-D}$	$\frac{1}{1-D}.\frac{1}{1-D}.\frac{1+2n}{1-D}.$ $\frac{1+2n}{1-D}.\frac{1+2n}{1-D}.\frac{1+2n}{1-D}$	$\frac{1}{1-D}.\frac{1}{1-D}$	$\frac{1}{1-D}I_O$	$\frac{1}{1-D}I_O$
[191]	$\frac{4n}{1-D}$	*NR*	$\frac{n}{1-D}$	*NR*	*NR*
[207]	$\frac{4n+2}{1-D}$	$\frac{2n+1}{1-D}.\frac{2n+1}{1-D}.\frac{2n+1}{1-D}.\frac{2n+1}{1-D}$	$\frac{1}{1-D}.\frac{1}{1-D}$	$\frac{2}{1-D}I_O.\frac{2}{1-D}I_O.\frac{2}{1-D}I_O.\frac{2}{1-D}I_O$	$\frac{3(2n+1)}{1-D}.\frac{3(2n+1)}{1-D}$
[210]	$\frac{2n+1}{1-D}$	-	$\frac{1}{1-D}.\frac{1}{1-D}.\frac{1}{1-D}.\frac{1}{1-D}.$ $\frac{n}{1-D}.\frac{n}{1-D}.\frac{2n}{1-D}.\frac{2n}{1-D}$	-	*NR*
[211]	$\frac{4+2(n_{21}+n_{31})+n_{121}+n_{122}}{1-D}$	$\frac{2}{1-D}.\frac{1}{1-D}.$ $\frac{4+2(n_{21}+n_{31})+n_{121}+n_{122}}{2(1-D)}.$ $\frac{n_{21}+n_{31}+0.5n_{121}+0.5n_{122}}{1-D}.$ $\frac{2+2(n_{21}+n_{31})+n_{121}+n_{122}}{1-D}$	$\frac{1}{1-D}.\frac{1}{1-D}.$	$I_O.I_O.I_O.I_O.I_O$	$\frac{2+n_{21}+n_{31}+0.5n_{121}+0.5n_{122}}{1-D}I_O.$ $\frac{2+n_{21}+n_{31}+0.5n_{121}+0.5n_{122}}{1-D}I_O$
[212]	$\frac{2+M(n_{121}+n_{122})}{1-D}$	$\frac{2(n_{121}+n_{122})}{1-D}$	$\frac{1}{1-D}.\frac{1}{1-D}.\frac{2}{1-D}.\frac{1}{1-D}$	$\frac{2I_O}{1-D}.$	$\frac{2D+M(n_{121}+n_{122})}{2(1-D)}I_O.$ $\frac{2D+M(n_{121}+n_{122})}{2(1-D)}I_O.-I_O.-I_O$

converters suffer from higher components count, weight, volume, and cost.

8. Multilevel DC-DC converters

The MLDCCs are designed to manage power flow efficiently and reliably in various applications, including the RESs, the BMSs, charging stations, transportation, etc (Qian et al., 2011a; Monem et al., 2013; Lim et al., 2020). The structure typically includes multiple stages, each consisting of power switches and voltage sources, which are connected in a specific configuration to achieve the desired output voltage. In addition, these converters are capable to produce various levels of output voltages and they are able to lower voltage on semiconductors. The general layout of most common type of the MLDCCs, the MMCs, is depicted in Fig. 18.

As SC technique can provide various output voltage levels, it is fully adaptive with MLDCCs. A multilevel boost converter facilitated with SC-based voltage double stages is presented in Ganesan and Prabhakar (2013); Rosas-Caro et al. (2010). Conventional boost converter has organized the main part of this converter, followed by mentioned the VMCs. Each stage consists of a diode and two capacitors, capable to provide high voltage gains. Nevertheless, it suffers from voltage unbalance issues along the capacitors, and inefficiency against the high current applications. Flying capacitors is another voltage boosting methods, common in multilevel inverters, could be utilized on this manner. W. Qian et al. have proposed flying-capacitor-based MLDCC, providing high voltage gains, low current stress, and bidirectional operation (Qian et al., 2011b). It can provide voltage gains two times higher than the conventional corresponding structure by symmetrizing. Furthermore, this converter can be configured in a modular form, allowing for greater flexibility and adaptability in its construction and design. However, high components count with hard switching would affect its merits. Ladder topology is a simplified layout of flying capacitors structure. In Lopez et al. (2012), the classical ladder-based MLDCC is studied. Furthermore, the symmetric ladder and the double ladder topologies are introduced, as depicted in Fig. 19. These three topologies provide same voltage gains, but their current distribution differ. The double ladder structure also imposes less output voltage drop, while requires two more active switches in overall. A multilevel buck/boost converter is presented in Costa et al. (2014), may be designed to be a buck, boost, or buck-boost converter based on the capacitors charging/discharging principle, as depicted in Fig. 20. A 5-level 10 kW prototype is provided in this research work to validate its performance, however, it still suffers from lack of soft switching. A. Gandomkar et al. have developed the conventional four level clamped capacitor MLDCC (Gandomkar et al., 2016). Their proposed converter has three power components arms, consisting of an active switch middle arm connected to the DC source and two upper and lower diode arms, can be replaced with active switches to provide bidirectional operation. This converter is capable to have a fast dynamic response, appropriate for offshore wind turbines. However, soft switching had not been welcomed. A three-winding transformer based MLDCC is proposed in Rathore et al. (2020), capable to achieve high voltage gain. In this converter, a HB converter is utilized in the first stage and two voltage doubler circuits are provided on the other side of the transformer. This structure provides higher flexibility in voltage regulation. In addition, this converter supports the soft switching in its first stage. There are other available MLDCCs, not relying only on the SC technique. D. Ghaderi has suggested a MLDCC with parallel input and serial output (Ghaderi, 2019). This converter is

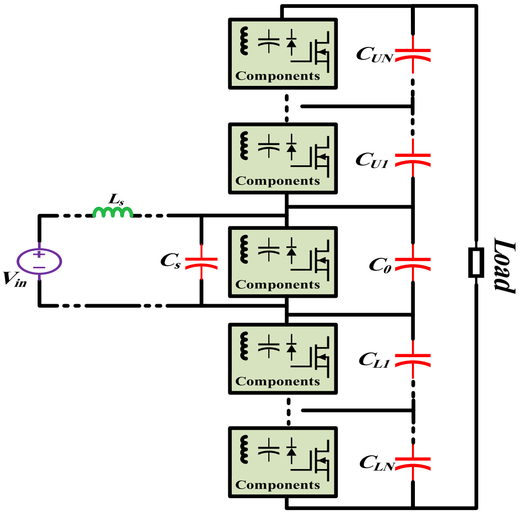
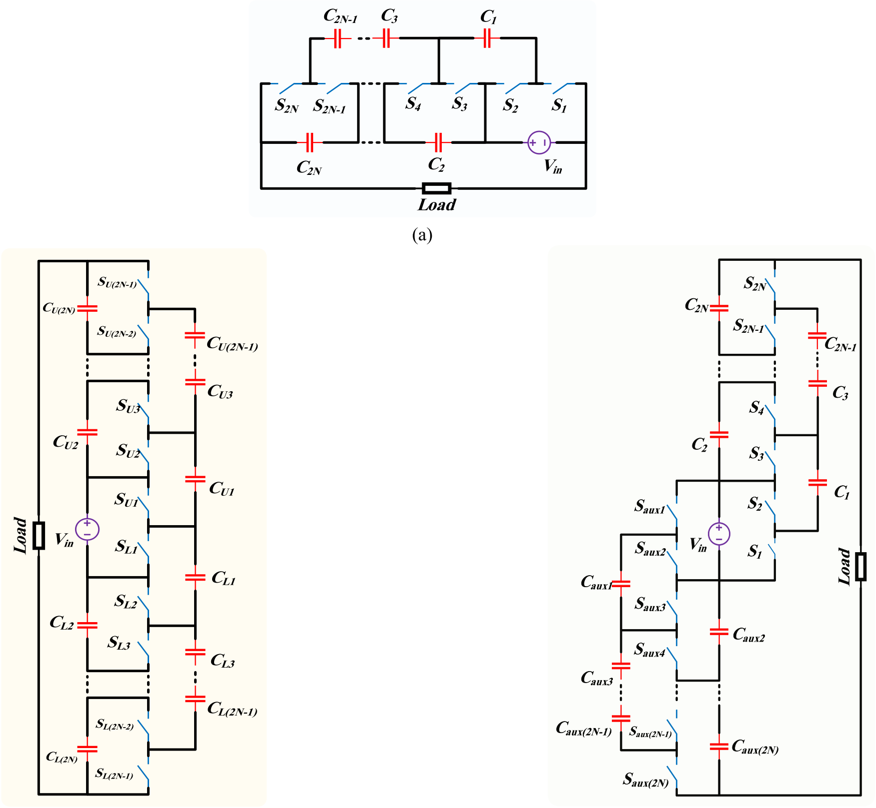


Fig. 18. General layout of modular-multilevel DC-DC converters.

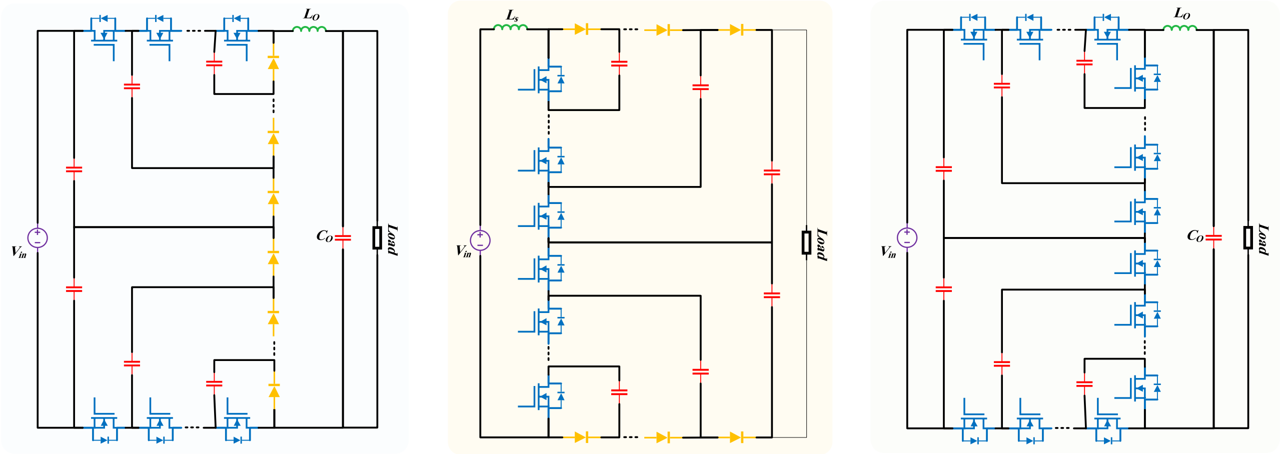


(a)

(b)

(c)

Fig. 19. Common ladder topologies (a) classical ladder topology (b) symmetric ladder topology (c) double ladder topology.



(a)

(b)

(c)

Fig. 20. The multilevel buck/boost DC-DC converter proposed in (Singh et al., 2021) (a) buck arrangement (b) boost arrangement (c) bidirectional arrangement.

based on a modified layout of boost converter, presenting long life span and easy control procedure, appropriate for the PV applications. Another three-winding employed MLDCC is investigated by H. L. Jou et al., enabling the converter to provide higher voltage gains (Jou et al., 2015). In this converter, the second and third windings are connected to uncontrollable FB circuits, composed of diodes, providing the outputs. This outputs may be connected in series/parallel with the help of an auxiliary switching circuit, composed of a MOSFET/IGBT and two diodes, enabling the various output voltage generation option. Despite the existence of the transformer provides the leakage inductance to be used for energy recycling and soft switching purposes, no attention has been paid to in this work. V. Rathore et al. have proposed a modified three-winding-based isolated MLDCC, providing high voltage gain and low switches voltage stress simultaneously (Rathore et al., 2022). An active switch FB converter connects the DC source to the primary winding of the transformer, while two voltage doubler rectifiers are place on the other sides. The main outstanding feature of this converter is that it fully supports the ZVS operation by manipulating the transformer’s leakage inductor, voltage doubler circuits capacitors, and the parasitic capacitors of the FB converter switches, leading to high efficiency and improved performance.

The MLDCCs provide an outstanding opportunity to achieve various voltage levels with a single converter. These converters may be extended easily and provide wide range of possible structures to be implemented. However, they present some drawbacks such as high components count, cost, etc. Furthermore, in the SC-based MLDCCs, capacitors voltage unbalance should be considered and managed.

8.1. Modular DC-DC converters

The MDCCs are designed to deliver high efficiency, flexibility, and reliability across a diverse range of applications. The modular design paradigm facilitates the utilization of identical modules, thereby simplifying the design, manufacturing, and maintenance processes. Each module can be designed to manage a specific power level or voltage range, thereby enabling the creation of a scalable and flexible system that can be adapted to various requirements (Darwish, 2024). The deployment of the MDCCs is particularly advantageous in applications where high power density, high efficiency, and high reliability are required, such as in data centers, HVDC systems, microgrids, and other similar contexts (Erat and Vural, 2022).

In the HVDC systems, low voltage gain MDCCs may be utilized to interconnect various voltage level DC sources together, as a multi-input configuration. In Li et al. (2019b), a hybrid MDCC is proposed that provides high efficiency and low cost, by utilizing cascaded HB converters modules. Hu et al. have proposed new modular configuration of the DC-DC converters to respond the HVDC systems requirements (Hu et al., 2015). Modules are configured in matrix form, defining row and column strings that provides more design flexibility. Each module consists of two coupled inductors, two HB cells, and two clamped capacitors. This converter is investigated in three structures: (i) row interleaved; (ii) column interleaved; and, (iii) hybrid. Each structure may be used in accordance with the current and voltage requirements of the desired system. The general structural layout and voltage gain versus duty cycle of hybrid structure are illustrated in Figs. 21 and 22, respectively. furthermore, their voltage gains and diodes voltage stresses are given in Table 5. The point to be mentioned here is that N and T denote the turn ratio and modules count, respectively. In addition, s, p, and x stand for series cells count, parallel cells count, and number of columns in the cell group. For the Medium-Voltage Direct Current (MVDC) applications such as the RESs, reliable high voltage and high power converters is required to feed the load. A Cuk-based MDCC is proposed on this manner by Alfares et al. (2022), as displayed in Fig. 23 (a). In this converter, each module is configured as an isolated

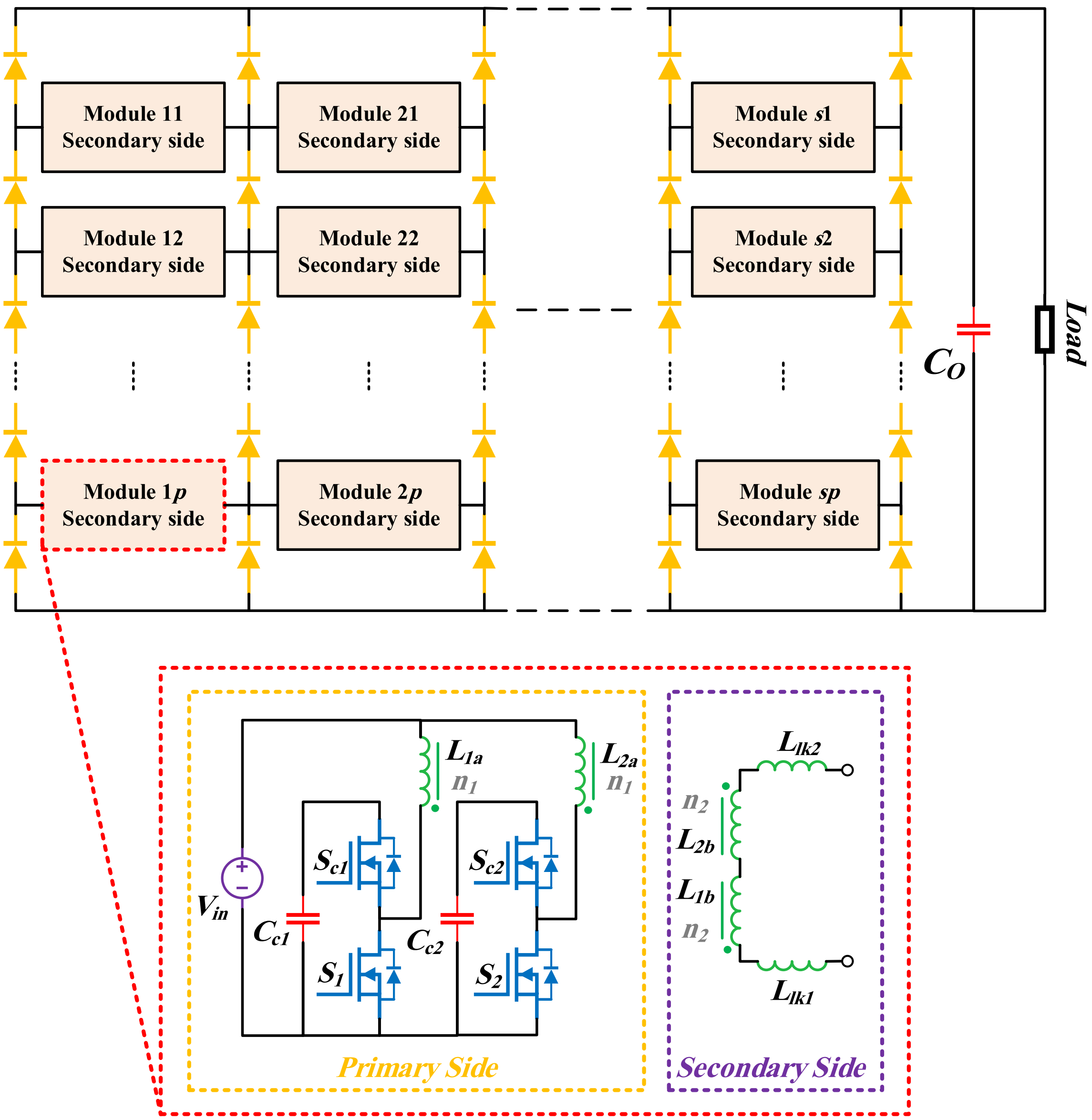


Fig. 21. The general structure of ultrahigh step-up modular multilevel DC-DC converter proposed in Hu et al. (2015).

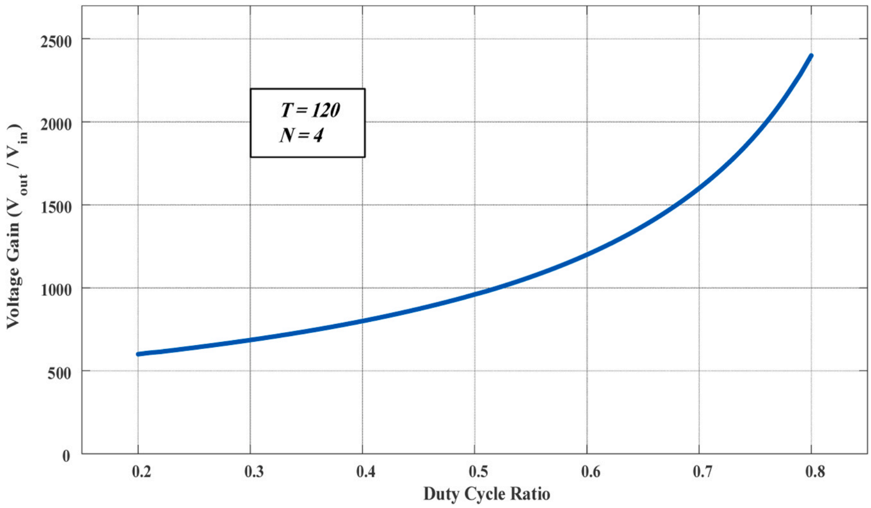
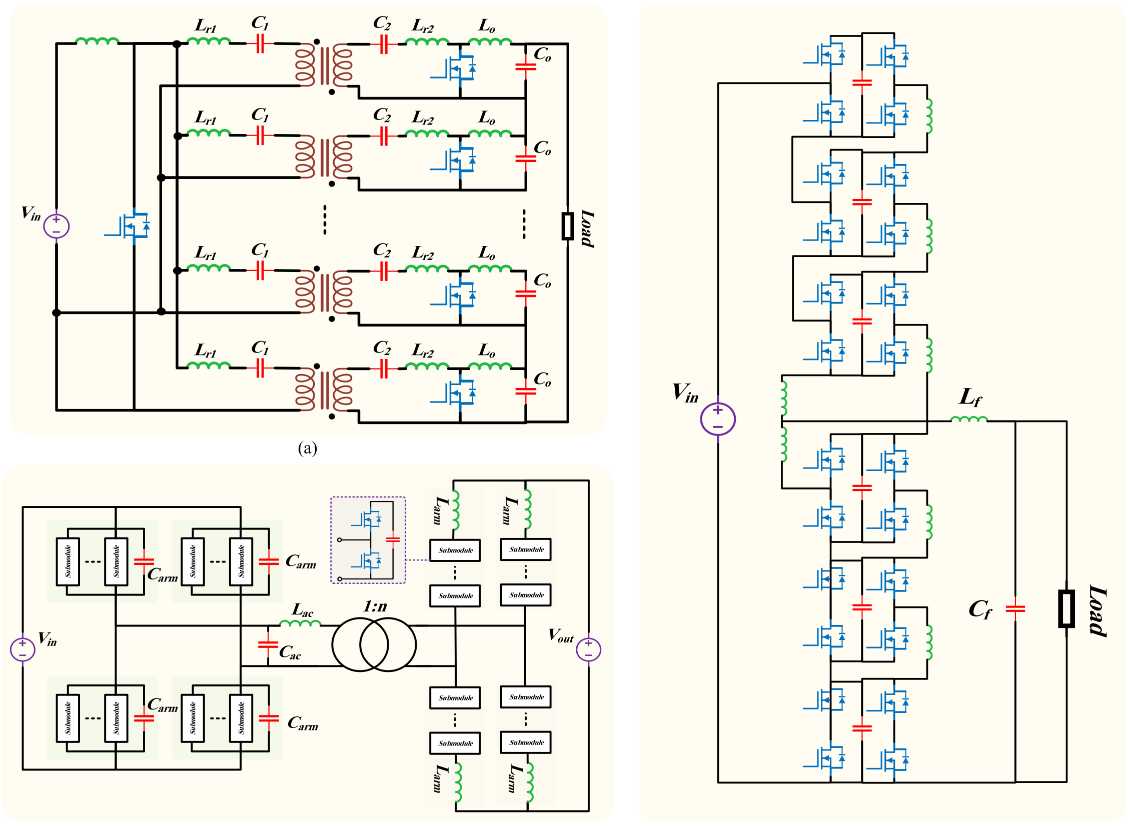


Fig. 22. The voltage gains vs. duty cycle curve of the hybrid arrangement of modular-multilevel DC-DC converter proposed in Hu et al. (2015).

Table 5
Voltage gains and voltage stresses of converter reported in Hu et al. (2015).

Converter type	Voltage Gain (T = x. s)
Row interleaved	pN/(1-D)
Column interleaved	sN/(1-D)
Hybrid	xsN/(1-D)
Diodes voltage stress (on Vin)	N/(1-D)
Active switches voltage stress (on Vin)	2 N/(1-D)

bidirectional single-switch and single-diode converter with the ZVS. Moreover, the aforementioned converter may be multi-ported to facilitate the utilization of various DC sources, including the batteries, the PVs, and the wind turbines aside each other. B. Li et al. have proposed a high-power MDCC, manipulating the current/voltage stresses, reducing the footprint with low cost, etc (Li et al., 2020). In this converter, there are the HB converters modules with series connection branches paralleled with low voltage side to decrease the current stress and it is followed by the FB modules branches which are in series connection with the high voltage side to share the voltage stress. In Wang et al. (2020b), a



(a)

(b)

(c)

Fig. 23. Some of the proposed modular DC-DC converters in literature (a) a Cuk based modular DC-DC converter (b) a hybrid dual active bridge modular multilevel DC-DC converter with LC resonant tank (c) a H-bridge based modular multilevel DC-DC converter facilitated with auxiliary inductor circuit.

bidirectional isolated MDCC is investigated based on hybrid dual active bridge layout. The upper switches of the FB converter are replaced with the HB submodules, providing bidirectional fault handling capability and eliminating the need of bulky capacitors. A transformerless multi-input multi-output high step-up MDCC is presented in Saadatizadeh et al. (2022). The heart of this modular converter is a single-input dual-output module may be extended using the VMCs to achieve higher voltage gains and higher input and output ports counts.

A modular-multilevel resonant (MMR) DC-DC converter is introduced in Shao et al. (2019), to provide high voltage conversion with high efficiency. This converter is obtained based on conventional LLC resonant converter, replacing each switch to series-connected HB converter modules and splitting the resonance inductor to two inductors. It can change the DC voltage level with providing soft switching and easy fault-tolerant operation. Another MMR based on a QR technique is presented, employs distributed stray inductances in each module and the SCs for increasing the voltage level (Cao and Peng, 2010), the modified version of a clamped capacitor MMC proposed in Khan and Tolbert (2007). These stray inductances not only need any magnetic core, but also they are originated from the parasitic inductances of wiring, leading to lower weight, volume, and cost. X. Zhu et al. have proposed a resonant MMCs based on conventional boost converter (Zhu et al., 2022). The inductor of the boost converter is replaced with SL modules to elevate the voltage gain, while the switches and diodes are replaced with series-connected HB submodules providing flexible control schemes. In Sun et al. (2020), the HB submodule is integrated with a QR submodule to form the main module. Then, these modules are connected in series in lower and upper arms to adjust the voltage gain. A family of transformer-coupled MMR DC-DC converters is proposed, by changing the connection option of stacked HB submodules (Xiang et al., 2020). S. Dey et al. have investigated a MMC that consists to arms and submodules of FB converter are stacked in lower and upper sides of each arm, appropriate for HVDC applications (Dey and Bhattacharya, 2020). A hybrid dual active bridge MMC is proposed in Ashraf et al. (2021) for HVDC interconnections. This converter consists of two legs at each side. At the line commutated converters side, on each arm, HB converters submodules are paralleled, while on other side (voltage source converter side) these submodules are stacked, as shown in Fig. 23 (b). Furthermore, a parallel LC RT and a transformer have been utilized to connect both sides to each other. Another DC-DC MMC for HVDC application is proposed in Kish et al. (2013), capable to interconnect similar and different voltage level networks with bidirectional fault blocking feature. It employs interleaved strings of cascaded HB and FB submodules providing the step-up/down operations. The capacitors of the MMCs suffer from voltage balancing issues. On this basis, H. Obara et al. have proposed a MMC, employing auxiliary inductor circuits to overcome this issue as shown in Fig. 23 (c) (Obara et al., 2022). In this work, the HB converter is employed in each module that forms a voltage level itself. Then, the auxiliary inductor connects the middle of each module’s right leg to the upper point of next module.

The MDCCs are widely used in various applications, including the RES integration, the HVDC, and motor drives. They offer higher reliability as well as inherent fault-tolerance and redundancy. However, they also present some challenges for design and operation, including higher complexity and cost due to the number of components required, sophisticated control algorithms, space constraints, and etc.

8.2. *Hybrid DC-DC converters*

Hybrid MSDCCs embody a distinctive class of power conversion converters that combines several structures to deliver exceptional performance attributes. These converters merge the synergistic benefits of “quadratic gain”, “cascaded”, “interleaved”, “modular”, and “multilevel” structures to facilitate high and ultrahigh voltage conversion ratios, high efficiency, enhanced power density, acceptable reliability, etc. The quadratic gain capability empowers these converters to attain remarkably high voltage conversion ratios from a relatively low input voltage, making them exceptionally well-suited for applications spanning RESs to the EV power trains. The cascaded architecture enables the modular expansion of the conversion stages, endowing greater flexibility and scalability to accommodate diverse power requirements, as well as the multilevel ones. The interleaved implementation of the individual converter stages helps to mitigate input current ripple, leading to improved EMI and reduced filtering necessities. Furthermore, interleaving provides lower current ripple, higher power and current density. The possible combinations of investigated structures are given in Fig. 24, in detail. It can be observed that there are 26 available hybrid structures, categorized to four groups consisting of two-members, three-members, four-members, and five-members hybrid MSDCCs. Each converter may benefit from advantages or suffer from some disadvantages, their employment would be verified in accordance with the application.

A bidirectional cascaded-interleaved DC-DC converter for the V2G and the G2V applications is suggested in Leal et al. (2021). In this converter, the classic interleaved buck-boost converter is cascaded, as illustrated in Fig. 25 (a). Besides, the same authors have enhanced the switching model by combining all switching intervals to have a better and more accurate controllers design (Leal et al., 2023). H. Chen et al. have proposed a cascaded-modular DC-DC converter appropriate for the MVDC systems (Chen et al., 2022). Unlike the most of previously mentioned modular converters, this structure contains three arms named, upper, middle, and lower arms. Modules are connected in series in each arm and two switch branches would sandwich the middle arm in a cascade form. In each branch switches have serial connection. In the upper branch, fault blocking submodules are also connected in series to overcome the DC fault conditions. This converter structure is demonstrated in Fig. 25 (b).

B.S. Revathi et al. have proposed a hybrid converter, categorized as a cascaded-interleaved-modular DC-DC converter (Revathi and Mahalingam, 2018). This converter starts with a three-phase interleaved stage to suppress the input current ripple and followed by voltage boosting modules in a cascading manner as the other stages. The second stage of the above-mentioned converter is consisting of three VMCs and coupled inductors, as depicted in Fig. 25 (c). An ultrahigh gain SC-based step-up DC-DC converter, may be developed to form a multilevel-cascaded-modular DC-DC converter, is introduced in Liang et al. (2012). This converter utilizes a conventional boost converter with coupled inductor instead of the independent one and cascaded VMCs modules are placed as the general layout of the MMCs to achieve the ultrahigh voltage conversion ratio, as depicted in Fig. 25 (d). A modular-multilevel DC-DC converter is investigated in Chen et al. (2020), the HB submodules form the basis of this converter and each of them is followed with duplicate chopping circuits in cascade manner, as depicted in Fig. 25 (e). This converter is useful for energy storage systems and a 7.2 kW prototype is provided by the authors.

V.J. Samuel et al. have proposed a quadratic-interleaved boost converter, by putting a basic quadratic boost converter in each interleaved branch, achieving high power, high voltage gain, and low input current ripple simultaneously (Samuel et al., 2020), depicted in Fig. 25 (f). Another converter of this type is suggested in Rahimi et al. (2021b), employing coupled inductors and a VMC to achieve a high step-up structure. It benefits from high voltage gain, reduced voltage stresses, and low current ripple. Its voltage gain depends on the leakage inductance. A high step-up interleaved dual coupled inductor active QGDCC is proposed by D. Rong et al., capable to achieve higher voltage gain and continuous input current compared with conventional active SL based DC-DC converters, by adding a diode-capacitor branch (Rong et al., 2024). A single-switch quadratic-cascaded boost converter, providing higher reliability and voltage gain. However, it suffers from high voltage stress on the switch (Kaya and Hameş, 2019). H. Deng et al. have proposed a multilevel-interleaved DC-DC converter to reduce the semiconductor components voltage ratings and lower the weight and volume of inductors, as shown in Fig. 25 (g) (Deng et al., 2021). In this

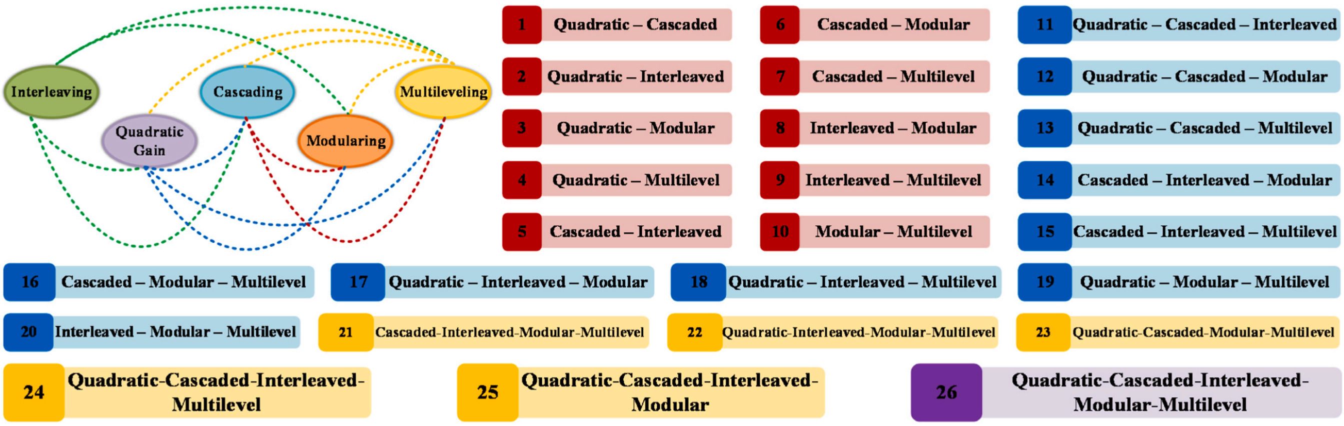


Fig. 24. Hybrid Multistage DC-DC converters combinations.

converter, multilevel section of converter is mainly employed to reduce the voltage rating of components and the interleaved section is utilized to overcome the current ripple issue. Another multilevel-interleaved converter is investigated in Rosas-caro (2017), employing SC ladder topology for voltage boosting purpose. By connecting two MLDCCs differentially and adding an inverting stage, an interleaved-multilevel DC-DC converter may be formed, providing direct power flow path between input and output ports, leading to voltage gain increment (Allehyani, 2023). A two-string interleaved-modular-multilevel DC-DC converter for the MVDC and the HVDC applications is investigated by Y. Gao et al., suffers from complexity (Gao et al., 2017). M.S. Bhaskar et al. have proposed a DC-DC converter of this type, providing numerous merits including non-inverting output voltage, direct voltage amplification proportion with number of modules, low input current ripple, low output voltage ripple, low switches voltage stresses, and high reliability (Bhaskar et al., 2020b). This converter is interleaved to provide more reliability and guarantee the converter operation during the one switch failure. In addition, the Cockcroft-Walton VMC modules are installed in multilevel configuration to provide high voltage gains, as shown in Fig. 25 (h). Another interleaved-modular-multilevel converter based on the HB submodules is proposed in Alhuwaishel et al. (2019), employing the 6.5 kV SiC switches, to be alternated with the bulky transformer of the MVDC transmission power system.

Fig. 25 (continued). Some of the proposed hybrid multistage DC-DC converters in literature (g) a hybrid MSDCC proposed (h) an interleaved-modular-multilevel DC-DC converter based on Cockcroft-Walton VMC.

9. Multistage DC-DC converters applications

The MSDCCs have become increasingly indispensable in a plethora of industries due to their unparalleled ability to efficiently transform and regulate the DC voltages. These converters are of paramount importance in applications where multiple DC output voltages are necessitated, as they provide a cost-effective and space-optimized solution in contrast to employing multiple single-stage converters. The uprising demand for high-efficiency power conversion in domains such as the RESs, the EVs, and electronics consumers has necessitated the development of cutting-edge MSDCC topologies. The MSDCCs offer several advantages that surpass their single-stage counterparts. By cascading multiple conversion stages or quadratic gaining them, they can achieve higher voltage conversion ratios. This remarkable feature is particularly advantageous in applications where the input voltage is low and the output voltage is high. Additionally, the MSDCCs can provide superior voltage regulation and enhance dynamic response, making them suitable for applications that necessitate precise output voltage control. The modular architecture of the MSDCCs also facilitates increased reliability and fault tolerance. In the event of a single module failure, the remaining modules and stages can continue operation, ensuring uninterrupted power delivery. This valuable advantage is paramount in critical applications such as sustainable energy sources, medical equipment, transmission and distribution systems, transportation electrification, advanced physics equipment, etc. As the demand for efficient and reliable power conversion persists, the MSDCCs will undoubtedly play an increasingly vital role in shaping the future of various industries. Their unparalleled versatility, scalability, and performance advantages make them a logical choice for wide range of applications.

Some of the well-known applications of the MSDCCs are shown in Fig. 26. Most of the technical publications have been focused on the DC microgrids and sustainable energy sources. The DC microgrids play a determinative role in modern power systems. The DC microgrids are emerging as a solution for efficient and reliable power systems. These localized DC systems integrate diverse DC power sources, such as the PVs, the FCs, and energy storage systems, onto a common DC bus. The DC-DC converters play a crucial role in these microgrids, enabling power conversion, regulation, and bidirectional power flow between the connected components. The integration of the RESs and the ability to operate independently from the main grid make the DC microgrids attractive for rural electrification and remote applications. Recent power electronics advancements have led to development of the DC microgrids. Interleaved, multilevel, modular, and hybrid structures of the DC-DC converters are mostly used in this type of microgrids which are categorized to monopolar and bipolar. Bipolar DC microgrids suffer from voltage imbalance among converters. The boost-SEPIC interleaved proposed by P. Prabhakaran et al. deals with this issue and provide high power capability due to its interleaved feature (Prabhakaran and Agarwal, 2019). Another interleaved converter with 24 and 48 DC voltage outputs is introduced in Chapparya et al. (2023), to feed the DC loads. A suitable interleaved three-level bidirectional converter is investigated to feed the single DC bus, utilizing two-phase interleaving (Kan et al., 2018). Bussa et al. have proposed a hybrid interleaved converter, capable to simultaneously address the DC and the AC loads considering the shoot-through protection (Bussa et al., 2017). To lessen the shoot-through condition occurrence possibility, Hu et al. have suggested a coupled inductor-based interleaved converter instead of the FB layouts (Hu et al., 2014). Therefore, the MLDCC may be useful as it may be more fault-tolerant (Oliveira et al., 2021). To enable the bidirectional power flow and fault handling with high efficiency and high power capability, modular structures would be useful (Wang et al., 2020b). A 60 V input and 1.1 kV output voltages with a 3 kW prototype cascaded-interleaved-modular DC-DC converter has been proposed to interconnect the DC loads and the DC power generation units to each other and manage the power flow with high voltage regulation capability (Revathi and Mahalingam, 2018). The Uninterruptible Power Supplies (UPSs) are prevalent in many networks, both AC and DC, to act

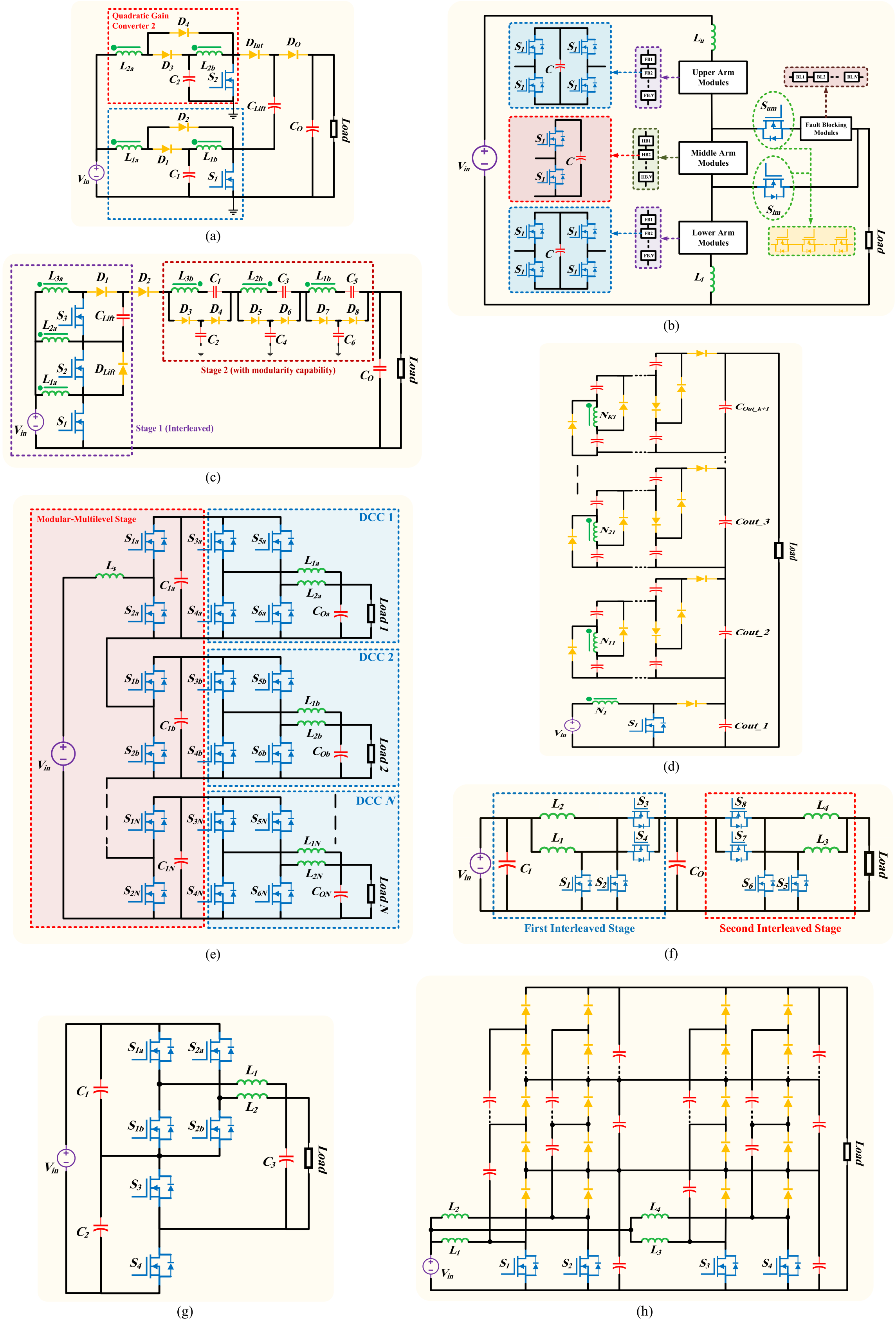


Fig. 25. Some of the proposed hybrid multistage DC-DC converters in literature (a) a bidirectional buck-boost cascaded-interleaved DC-DC converter (b) a cascaded-modular DC-DC converter for MVDC and HVDC systems (c) a flexible cascaded-interleaved-modular DC-DC converter (d) an ultrahigh gain switched capacitor based multilevel-cascaded-modular step-up DC-DC converter (e) a modular-multilevel DC-DC converter appropriate for high power applications (f) a quadratic-interleaved boost converter.

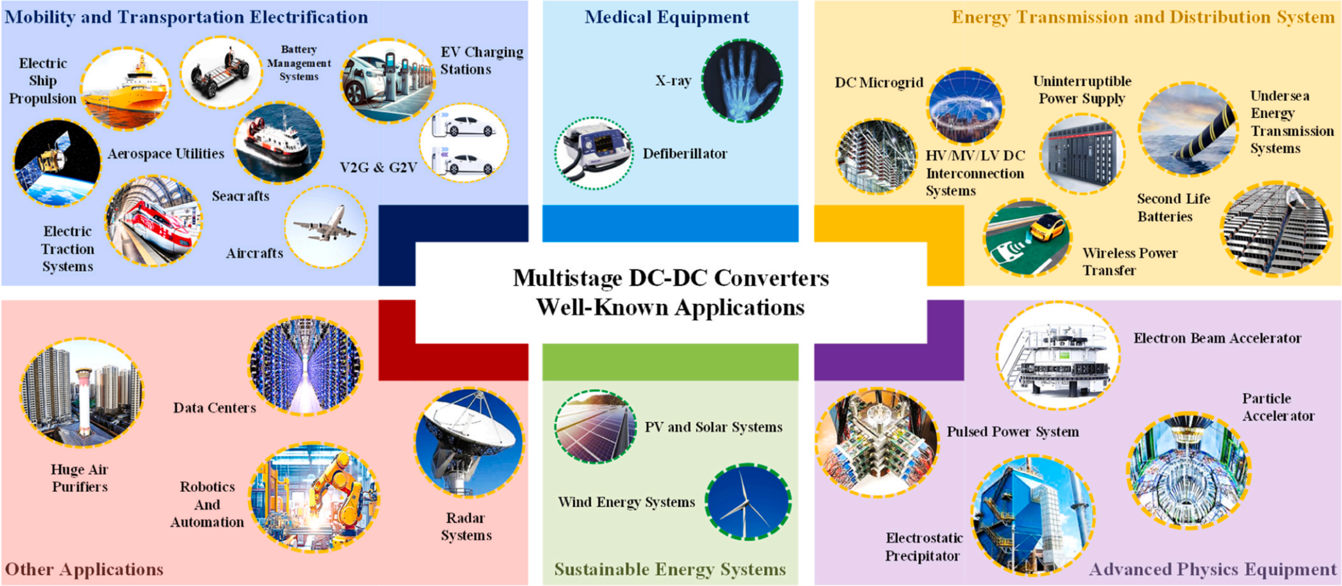


Fig. 26. Multistage DC-DC converters most common applications.

as a backup power source for sensitive loads such as medical equipment, etc. During grid failure, the prepared battery would be committed. On this manner, a bidirectional QGDCC is necessary to connect the battery to the inverter (Akhormeh et al., 2020).

The distinct voltage levels of the DC power transmission and distribution systems, namely the HVDC, the MVDC, and the low-voltage direct current (LVDC), serve diverse applications. The HVDC excels in long-distance, high-power transmission, while the MVDC and the LVDC are emerging for medium and low-voltage distribution networks, respectively. Crucially, the DC-DC converters facilitate the interconnection of these disparate DC networks, enabling voltage step-up or step-down, galvanic isolation, and bidirectional power flow control. This versatility enables the DC-DC converters to integrate the RESs, such as the PVs with the LVDC, the MVDC and the HVDC grids, thereby enhancing efficiency, reliability, and grid stability compared with traditional AC systems. The voltage rating of the LVDC, the MVDC, and the HVDC are 0.75, 10, and 100–800 kV, respectively (Lai et al., 2022). The MVDC mainly collects energy from different sustainable energy sources and inject it to the grid (Alfares et al., 2022). In addition, the MVDC is utilized to interconnect the offshore wind energy units with the HVDC interconnection (Li et al., 2020; Hu et al., 2015). The interconnection of these DC networks is assigned to MSDCCs. To provide a multi-terminal potential, interoperability, protection zone isolation, and various high voltage levels, the MMCs are mostly utilized (Ashraf et al., 2021). The MMC architecture, predicated upon its inherent scalability, facilitates the seamless addition or removal of converter modules to accommodate fluctuating power and voltage requirements. This level of modularity, in turn, increases the system's flexibility and capacity to adapt to the evolving needs of future grid expansions. Moreover, the modular design, by virtue of its inherent resilience, ensures that the failure of individual converter modules does not precipitate a complete system failure. The modular structure, owing to its enhanced fault tolerance and fault-blocking capabilities, is also instrumental in ensuring the safe and stable operation of the HVDC and the MVDC grids. These multifarious benefits, taken in aggregate, render the MDCCs the preferred choice for interconnecting diverse DC voltage levels in modern power transmission and distribution networks. However, other structures such as cascaded-modular converters have been studied, as well (Chen et al., 2022). There are other special applications in the field of energy transmission for the DC-DC converters. There are various utilities available under the sea to collect data, sampling, making videos, etc. Their input DC voltage must be regulated to be operated. Thus, the MSDCCs, specifically the modular-based ones, would be the best choice on this manner (Shao et al., 2019).

Sustainable energy sources are the main power generation units in microgrids. These energy sources are the most practical solution for climate change and decarbonization to lower the toxic gases and particles in air. The FCs, the PVs, and the wind energy units are the main members of this family. The PVs would deliver the power in voltage levels lower than 50 V, mostly 12–48 V, while the appropriate DC voltage for the DC microgrid buses is about 200–800 V. Various MSDCCs may be useful in accordance with rating power and systems requirements. For low power applications, such as smart home, the QGDCCs may be beneficial. Conventional step-up DC-DC converters suffer from output voltage range limitation. S. Esmaeili et al. have proposed a modified SEPIC QGDCC to face this issue (Esmaeili et al., 2023). Besides, another QGDCC is investigated for sustainable energy applications, the PV networks specifically, lowering the voltage stresses to achieve longer life span (Kumar and Krishnasamy, 2021). A. Gupta et al. have also proposed an ultrahigh gain step-up converter, providing flexible voltage regulation and adaptable with various loads (Gupta et al., 2022). To benefit from the MPPT control scheme more effectively, and integrate multiple strings of the PVs into a single voltage conversion system, cascaded structures may be employed (Rivera et al., 2011; Bratcu et al., 2010). For high power rating solar and wind farms, interleaved based converter should be utilized to provide high power density capability and low input ripple (Hassani et al., 2020; Hu et al., 2021). Both high gain and high power features may be obtainable by combining various structures, interleaving to guarantee the high power flow and others for elevating the voltage conversion ratio (Samuel et al., 2020; Alhuwaishel et al., 2019). Other non-interleaved combinations are mostly employed to achieve higher voltage conversion ratios. Wind energy units, another prevalent sustainable energy generation unit, produces variable output DC voltage which must be adjust to a specific voltage level to be connected to grid. For low power applications, such as Nano-wind turbines, some structures such as the CDCCs may be adopted as they are able to support multi-input layouts, leading to connect numerous Nano-wind turbines to provide a sufficient level of power (Majeed et al., 2018). In high power applications and higher scales, specificly the onshore and offshore wind turbines farms, hybrid structures of the MSDCCs should be employed (Gandomkar et al., 2016).

Mobility electrification is the best solution to prevent green gases emission due to the combustion engine-based transportation system. This may be manifested in private cars and public transportation such as train, bus, ships, aircrafts, etc. Accordingly, the energy management system of various kinds of electrified vehicles including plug-in hybrid electric vehicles (PHEVs), hybrid electric vehicles (HEVs), and battery electric vehicles (BEVs) requires a MSDCC. This converter must be able to deal with high power levels to feed the vehicle drive system. This may be satisfies by interleaved converters, as a 32 kW six-phase dual-interleaved DC-DC converter is proposed in Velázquez-Elizondo et al. (2022) on this matter. It is interesting to note that battery packs in electrified vehicles contain numerous cells and each of them may face different electrical conditions, called imbalance conditions. Due to various or unexpected incidents, the capacity of each cell may vary or some critical cases some of them may meet failure. Thus, the BMSs, including a MSDCC, would overcome these challenges by preparing appropriate connections between them and employing suitable control scheme (Moradisizkoohi et al., 2019; Obara et al., 2022). The point to be made here is that battery cells may be connected in series or parallel. However, the parallel connection is preferred as it avoids imbalance charging/-discharging phenomenon. On this basis, the IDCCs are recommended (Bahrami et al., 2017). On the other side of this system, in charging stations, the MSDCCs are employed to charge the EVs' battery packs with output voltage of 12–60 V, relies on the device characteristics (Lim et al., 2020). These chargers are generally categorized as off-board (DC fast chargers) and on-board. The off-board chargers are designed in high power levels (over 50 kW) and it is fully placed outside the EVs (Rathore et al., 2022). In addition, the MSDCCs play a key role in the V2G and the G2V technologies (Hosseini et al., 2020). The EVs are able to deliver their stored energy in peak load hours and being rewarded in accordance with the defined tariffs. As the battery capacity of the EVs, the HEVs, or the PHEVs reach lower than 70–80 % of their nominal value, they would be replaced. However, these second-life battery packs may be combined to form a large power source, may be employed in peak load hours of grid and satisfy the environmental requirements using a MLDCC (Monem et al., 2013). In addition to the urban EVs, the MSDCCs may be employed sea crafts and aircrafts. The more electrified the transportation system, the less pollution would appear. These converters would be utilized to connect various electronic sections of aircrafts or sea crafts to each other, maintaining different DC voltage levels, for instance, electric electro hydrostatic actuator, winding-deicing system, flight control system, cabin pressurization system, etc (Jiang and Liu, 2020; Chen et al., 2020).

10. Multistage DC-DC converters further considerations

In the preceding sections, various types of multistage DC-DC converters and their respective applications have been explored, providing a comparative analysis from a technical perspective. However, this may prove inadequate for a designer seeking a more comprehensive understanding. Comparing the reliability, component count, control complexity, voltage gain, power level, cost, and weight of multistage DC-DC converters is essential. Reliability assessment ensures that the converter will perform consistently over time under various operating conditions, which is crucial for applications in critical systems such as renewable energy and automotive sectors. A lower component count generally leads to reduced complexity and increased reliability, mostly, as fewer components minimize potential points of failure and lower manufacturing costs. Control complexity significantly affects the ease of implementation and maintenance; simpler control strategies can result in faster response times and easier troubleshooting. Understanding the power level capabilities is vital for selecting converters suitable for specific applications, ensuring they can handle the required load without overheating or failing. Cost analysis allows designers to balance performance with budget constraints, enabling more economical solutions without sacrificing quality. Finally, weight becomes a significant factor in portable or space-constrained applications, as lighter converters are often preferred to enhance portability and ease of installation. By evaluating these parameters collectively, designers can make informed decisions that optimize performance while addressing practical constraints across various applications.

On this matter, various MSDCCs were compared with each other from diverse perspectives in Fig. 27. It must be noted that this comparison has been made based on the general features of these converters and there may be some typical converters not following the specifications illustrated in Fig. 27. Each converter has its distinct application, and it is impractical to assume that a single converter is suitable for all applications. When designing a DC-DC converter, numerous factors must be carefully considered. These include input/output voltage/current ripple, components voltage/current stresses, wide-range voltage regulation, power density, the EMI, control scheme, voltage gain, protection mechanisms, stability, etc. It is noteworthy to mention that the optimal design for a DC-DC converter ultimately depended on the specific application, necessitating a balanced trade-off among the above-mentioned factors. It can be deduced from Fig. 27 that the MDCCs and IDCCs are able to achieve high power levels. However, they suffer from high cost, weight, and components count. In addition, MDCCs may impose higher control complexity compared with others. However, it must be mentioned that control complexity depends on various factors. Also, the MDCCs have the potential to achieve high and ultrahigh voltage gains by increasing their modules count. The QGDCCs are able to provide high voltage gains as well, while sacrificing the reliability, and some other technical features. Furthermore, due to technical limitations of the QGDCCs nature, they may not be employed for high power applications.

11. Summary, conclusion, and future research insights

11.1. Summary and conclusion

A comprehensive review on recent advances of various variants of the MSDCCs was carried out in this review paper. It was discussed that the DC-DC converters are categorized to five main classes including isolated/nonisolated, voltage-fed/current-fed, unidirectional/bidirectional, hard switched/ soft switched, and step-up/step-down. Various well-known voltage boosting techniques were briefly introduced. The MSDCCs were mostly seen in medium and high power utilities. Furthermore, they may be utilized in low power systems due to their

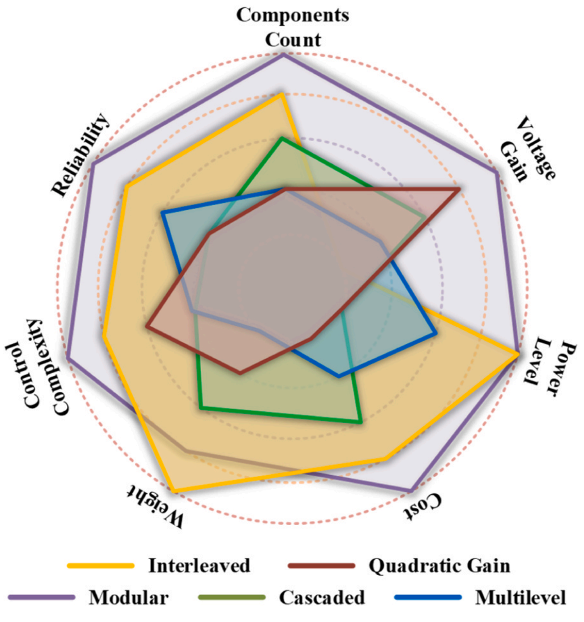


Fig. 27. Multistage DC-DC converters variants comparison.

high- and ultrahigh- voltage gains and other inherent features. It should be pointed out that the high voltage gains and high power capability of the MSDCCs may be achieved, but higher components count, cost, weight, volume, and complexity would be imposed. In general, the MSDCCs may be categorized to quadratic gain, cascaded, interleaved, modular, multilevel, and hybrid converters. The QGDCCs benefit from second order voltage gain, leading to high and ultrahigh voltage gains with employing only one or two switches, mostly. However, they were not appropriate for high power and high current applications. The CDCCs would be structured by serial interconnection of several DC-DC converters. They supported modular implementation that would result in design flexibility. The serial connection of the converters implied that the overall voltage gain of the system is the product of the individual voltage gains of each converter, leading to high voltage gains. The overall efficiency of converter would follow the same role, unfortunately. To achieve higher power level capability, interleaving would be adopted. In interleaved converters, the current would be divided into various paths, leading to less input current ripple and lower components rating would be required. Despite all these advantages, these converters suffered from high components count, cost and control complexity. In some applications, various voltage levels and multiple outputs were desired. The MLDCCs would fulfill this demand by arranging capacitors/modules and active/passive switches in a way leading to staircase incremental voltage outputs. These converters were mainly based on the SC networks, suffering from voltage imbalance among capacitors. Any converter or voltage boosting circuit may be designed to benefit from modularity. The MDCCs provide better flexibility and scalability, simplifying the design, manufacturing, and maintenance processes. The deployment of the MDCCs was particularly advantageous in applications where high power density, high efficiency, and high reliability were required. Nevertheless, these converters may propose the highest components count, control algorithm complexity, etc. To achieve a combination of aforementioned converters structures features, various MSDCCs may be synthesized.

11.2. Future research insights

Based on the comprehensive discussion presented in this paper, it can be concluded that the MSDCCs still need more studies in depth on various aspects. The MSDCCs are one of the hot topics in power electronics world due to their vital role in industry and their worthiness is raising more and more. Authors recommend the below research insights to resolve the current challenges of the MSDCCs:

Higher power levels: Interleaving and modularizing are the most common approaches to elevate the power capability of DC-DC converters, with the cost of high components count. This raise of components count just enhances the power level, not the voltage gain, specifically. Thus, it is desired to propose other techniques, improving the power level and density of converter without multiplying the number of components.

Control schemes: The IDCCs and the MDCCs provide unique features, but they suffer from control challenges. Their voltage regulation range is more restricted compared with other types. This situation would be worsened as the bidirectional operation is required. Then, precise and efficient control schemes for bidirectional IDCCs and MDCCs providing wide range of voltage regulation, varying load capable, and low complexity level are required.

Soft-switching techniques: Generally, soft-switching should be developed for the DC-DC converter over a wider load range. Implementing variable frequency control to expand the soft-switching region based on the load conditions has to be considered in the MSDCCs design procedure. There are numerous structures of all of the introduced MSDCCs operating with hard switching. It has been observed soft-switching has not been fully welcomed by the MSDCCs, the IDCCs and the MDCCs specifically. Active and passive ZCS and ZVS circuits may be combined with the MSDCCs to provide higher efficiency and improved thermal management. In addition, there is the potential to study the potential of combining the ZCS/ZVS circuit with the main switches using various technique, such as grafting method.

Effective thermal management solutions: Most of the MSDCCs contain numerous switches, generating heat. This heat would increase with the frequency increment. High temperatures would endanger the components reliability, leading to operation failure or/and undesirable characteristics. On this basis, advanced thermal modeling approaches are required to estimate the thermal behavior of the converter under various operation conditions. Then, effective thermal management techniques would play a beneficial role to dissipate the generated heat to achieve suitable temperatures during various operations. Thermal management techniques are not always of heat sinks or cooling methods, they may be utilized in the converter structure design procedure to provide a structure that generates less heat, inherently.

Wide bandgap semiconductors: The GaN and the SiC semiconductors would take the place of their current silicon based ones as they benefit from higher power density, compactness, higher efficiency (about 99 % in some cases), better thermal performance, etc. Materials with wide bandgaps can be operated at higher frequencies. Due to their recent advent in industry and application validity, they have not been studied in the MSDCCs, sufficiently. It is expected in the not so distant future, these components become more common, so, the MSDCCs employed with these semiconductors need to be fully investigated.

Authors have made effort to provide a comprehensive review on the MSDCCs structures without any partiality. Cons. and pros of each category have been discussed and recent research and advances on this topic have been addressed. It is anticipated that this survey will prove beneficial to both academia and industry.

Abbreviations

APWM	Asymmetric pulse width modulation	IDCC	Interleaved DC-DC converter
BEV	Battery electric vehicle	IHSDC	Isolated high step-up DC-DC
BMS	Battery management system	LED	Light emitting diode
BSS	Battery storage system	LVDC	Low-voltage direct current
CCM	Continuous current mode	MDCC	Modular DC-DC converter
CDCC	Cascaded DC-DC converter	MLDCC	Multilevel DC-DC converter
CF	Current-fed	MMC	Modular-multilevel converter
CLC	Closed loop control	MMR	Modular multilevel resonant
CSC	Current synchronized control	MPPT	Maximum power point tracking
DPS	Dual phase-shift	MR	Multi-resonant
EMI	Electromagnetic interference	MSDCC	Multistage DC-DC converter
EPS	Extended phase-shift	MVDC	Medium-voltage direct current
EV	Electric vehicle	NHSDC	Non-isolated high step-up DC-DC
FB	Full-bridge	HVDC	High-voltage direct current
FC	Fuel cell	NR	Not reported
FCO	Ferrite core	OLC	Open loop control
G2V	Grid-to-vehicle	PHEV	Plug-in electric vehicle
HB	Half-bridge	PS	Phase-shift
PV	Photovoltaic	SPS	Single phase-shift
PWM	Pulse width modulation	SVM	Space vector modulation
QA-SL	Quasi active switched inductor	TPS	Triple phase-shift
QGDCC	Quadratic gain DC-DC converter	UPS	Uninterruptible power supply
QR	Quasi-resonant	V2G	Vehicle-to-grid
RES	Renewable energy source	VF	Voltage-fed
RHP	Right-half-plane	VL	Voltage lifting
RMS	Root mean square	VMC	Voltage multiplier circuit
RT	Resonant tank	WPT	Wireless power transfer
SC	Switched capacitor	ZCS	Zero current switching
SL	Switched inductor	ZVS	Zero voltage switching

Nomenclature

D	Duty cycle	n_{xy}	Turns ratio of winding x to y
i	Module number	g	Leakage to magnetizing inductances ratio
M	Stages count	I_o	Output current
V_o	Output voltage	V_{in}	Input voltage

CRediT authorship contribution statement

Vahedi Hani: Supervision. **Shivaie Mojtaba:** Investigation. **Soltani Iman:** Methodology. **Abolghasemi Mahdi:** Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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