

DC-DC Converter Architectures

Abdurrahim Erat and Ahmet Mete Vural

Abstract—Direct Current (DC)-DC converter architectures constitute a fundamental component of modern power electronic systems, enabling efficient voltage regulation and energy transfer across various stages of electrical networks. The growing integration of renewable energy sources, the electrification of transportation, and the proliferation of portable electronic devices have significantly increased the demand for compact, reliable, and high-efficiency converter designs. Recent advancements in semiconductor technologies, particularly those based on wide-bandgap materials, have further accelerated the development and deployment of diverse converter topologies. This study provides a comprehensive review of both conventional and emerging DC-DC converter configurations, examining their operating principles, performance characteristics, suitability for specific applications, and design complexity. Furthermore, a bibliometric analysis has been conducted to identify prevailing research trends, influential contributors, and collaborative networks within the field. By critically evaluating the advantages and limitations of each topology, the study aims to support future research directions and technological innovations in power electronics.

Index Terms— Converter topologies, DC-DC converter, Isolated topologies, Non-isolated converters, Power electronics.

I. INTRODUCTION

IN RECENT YEARS, the evolution of DC-DC converter topologies has been inspired by the rising requirement for superior efficiency, modular, compact, and reliable power conversion solutions across various applications such as green power mechanisms, electric vehicle technologies, high-voltage DC power networks, multi-terminal DC power grids, and smart power networks. Recent studies have focused on enhancing the performance of DC-DC converter topologies through innovative topological designs, advanced control techniques, and the integration of wide-bandgap semiconductor technologies. These developments have significantly improved the efficiency, compactness, and reliability of DC-DC converters, facilitating their widespread application in various industrial sectors.

Abdurrahim Erat, is with Department of Electrical and Electronics Engineering University of Gaziantep University, Gaziantep, Turkey, (e-mail: a.rahim_erat@simak.edu.tr).

 <https://orcid.org/0000-0003-0606-9132>

Ahmet Mete Vural, is with Department of Electrical and Electronics Engineering University of Gaziantep University, Gaziantep, Turkey, (e-mail: mvural@gantep.edu.tr).

 <https://orcid.org/0000-0003-2543-4019>

Manuscript Received Jun 04, 2025; Accepted Jul 15, 2025.
DOI: [10.17694/bajece.1713384](https://doi.org/10.17694/bajece.1713384)

By utilizing an available DC power source, these converters adjust a fixed DC voltage to a regulated and variable level, as illustrated in Fig. 1. The widespread adoption of DC-DC converter architectures is primarily driven by advances in semiconductor device technologies, which serve as the foundational components of such systems.

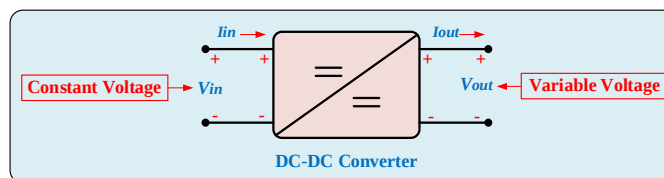


Fig.1. The schematic block configuration of a DC-DC converter

DC-DC converter technologies have recently become an exciting field of study for many researchers due to their numerous advantages and critical roles within various industrial environments. This study [1] reviews several DC-DC converter architectures and management strategies for electrifying transport. Particularly included are the difficulties and potential approaches for future research and development in creating innovative DC-DC power converter topologies. Due to several benefits, including increased longevity, ecological sustainability, lower maintenance levels, greater accessibility, and the capacity to generate higher amounts of electricity to meet load demands, photovoltaic-based power generation facilities have emerged as the most desirable option. This study [2] examines robust DC-DC converter configurations that facilitate the generation of energy systems powered by photovoltaics. The primary objective of this study is to provide an exhaustive guide to selecting the optimal converter topology for integrating solar energy. Various DC-DC converter structures are systematically evaluated based on key performance indicators, including supported power ranges, hardware intricacy, implementation costs, tracking capabilities, and overall energy conversion efficiency. To bridge the research gap in the domain of light charging of electrified vehicles, this paper [3] presents an extensive survey of the latest advancements in DC-DC converter architectures tailored for such applications. The distinctive operational features and limitations of each topology are critically analyzed. Moreover, the study identifies prevailing technical challenges and outlines prospective research pathways. The objective is to support future development efforts by offering insights that can inform the development and improvement of efficient charging systems for light electrified cars. For multi-terminal DC power networks, this research [4] provides a concise overview of contemporary DC-DC converter configurations, categorizing them as either isolated or non-isolated. Every topology is

assessed using essential performance standards. Excellent concentration of power and resilience to failure, bidirectional functionality, and dependability are key characteristics highlighted in setups suitable for HVDC operations. Current advances in bidirectional DC–DC conversion devices with broad voltage converting ranges for mixed energy storage technologies are reviewed in this study [5], with an emphasis on transformer-based isolated topologies and non-isolated topologies based on impedance networks. A thorough assessment approach is employed to evaluate seven isolated and eight non-isolated converter types. The article addresses the primary issues with converter design for hybrid energy storage systems, focusing future research on fault diagnostic techniques, electromagnetic compatibility, and the integration of wide-bandgap devices. Multi-level DC-DC converters are categorized in this evaluation [6] according to voltage category, isolation technique, electrical power transfer direction, power switching techniques, and voltage transformation.

Additionally, it provides an overview of other voltage boosting methods, such as multi-stage strategies and new structural developments. Additionally, multi-stage converters are categorized into important classes, including modular, multi-level, interleaved, cascaded, quadratic gain, and hybrid designs. The present article [7] provides a comprehensive examination of bidirectional DC-DC converters, emphasizing their vital role in photovoltaic power-generating facilities. The paper categorizes converters into two types: non-isolated and isolated. It also discusses the topologies, control methods, and switching techniques of each type. The authors emphasize the crucial importance of a higher level of power and reliability for the stable operation of photovoltaic systems. The study [8] provides the most recent advancements in DC-DC converter technology, with an emphasis on their topologies and control methods.

Although the number of studies on DC-DC converter topologies is increasing, literature still faces several significant limitations. Firstly, the results of many current studies are fragmented and inconsistent due to the lack of a common framework for assessing converter performance. Furthermore, the integration of wide-bandgap semiconductor technology under practical operating circumstances is not given enough attention. Few studies have been done on the scalability of converter designs for large-scale renewable systems and their flexibility in responding to dynamic, bidirectional energy flows. Furthermore, the majority of assessments fail to consider real-world implementation limitations, including industrial cost-performance trade-offs, electromagnetic interference (EMI) mitigation, and heat management. These research gaps underscore the necessity for a thorough assessment that considers the practical constraints and new requirements of current topologies, in addition to classifying them.

II. BIBLIOMETRIC ANALYSIS

A bibliometric survey conducted on July 7, 2025, using the Web of Science database and the keyword "DC-DC Converters" for the period 2016-2025 identified 7,321

publications. The dataset encompasses various types of scholarly outputs, with research articles (4080) and conference proceedings (3149; 43.0%) constituting the majority. Additionally, 209 review papers (2.9%) were identified, while the remaining entries, comprising early access articles, book chapters, editorial materials, and letters, account for a smaller portion of the total. These results reflect the prominence of original research and conference dissemination in the DC-DC converter domain, emphasizing the field's active development and its close link to ongoing technological innovation. The collected dataset was systematically examined across several bibliometric dimensions, including author productivity, citation patterns, journal distribution, country-wise contributions, keyword occurrences, article characteristics, and abstract content. The analysis was exclusively based on records indexed within the Web of Science Core Collection, ensuring the inclusion of high-quality and peer-reviewed scientific publications in the field.

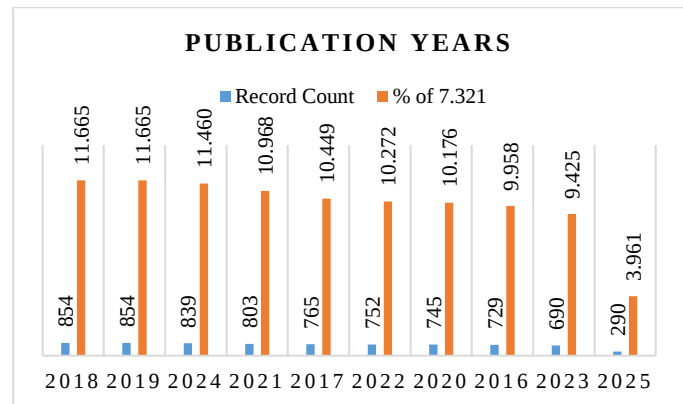


Fig.2. Annual distribution of publications related to DC-DC converter research based on Web of Science data

Fig. 2 illustrates the annual distribution of publications related to DC-DC converters over the past decade (2016–2025). As of the date on which the bibliometric analysis was conducted, a total of 290 documents had been indexed for the year 2025, indicating ongoing research activity within the current year. A total of 7321 publications were identified within the defined time frame. As of the date of the bibliometric analysis, the documents published in 2025 accounted for approximately 3.96% of the overall output, highlighting a modest yet ongoing contribution in the current year.

The co-occurrence keyword mapping is displayed in Fig. 3. The present research employed key keywords and authors' keywords from the Web of Science database to analyze co-occurrence keywords. Considering the weight of the item indicated by the dimension and color associated with every label and circle, the resultant diagram shows the associations among these terms. The program automatically groups similar nodes into color-differentiated clusters. Utilizing the VOSviewer approach, items are arranged according to their degree of relatedness.

Fig. 4 presents a collaboration network map illustrating the relationships among the most prolific authors in the field of DC-DC converters. As illustrated in the figure, Frede Blaabjerg occupies a central position within the collaboration map, having

authored 76 publications in the domain of DC-DC converters, which have collectively received 1887 citations. Frede Blaabjerg is followed by Bo Zhang, who ranks second with 53 publications and a total of 527 citations in the field, indicating his significant yet comparatively lower centrality within the scholarly network. Ranking third in terms of productivity is Dmitri Vinnikov, with 49 publications and 252 citations, reflecting his ongoing contributions to the field despite a comparatively lower citation impact. Fig. 5 illustrates the citation network among authors, highlighting the interconnections and influence patterns within the scholarly community engaged in DC-DC converter research. As observed in the figure, Frede Blaabjerg and Bo Zhang emerge as the most highly cited authors in the domain of DC-DC converters, reflecting their substantial academic influence and impact on the field.

illustrate joint authorship ties across borders. Notably, China and the United States stand out as key centers due to their significant representation and numerous collaborative connections, underscoring their pivotal positions in the global research landscape. Several European nations, including the United Kingdom, Denmark, Italy, and Spain, also display notable participation, establishing robust linkages both regionally and globally. Countries such as India, Iran, and Turkey have begun to emerge as significant contributors, reflecting an increase in their research output and growing involvement in international partnerships. The color coding, spanning from 2018 through 2022, reveals the evolution of these collaborations over time, with recent cooperative efforts highlighted in warmer hues.

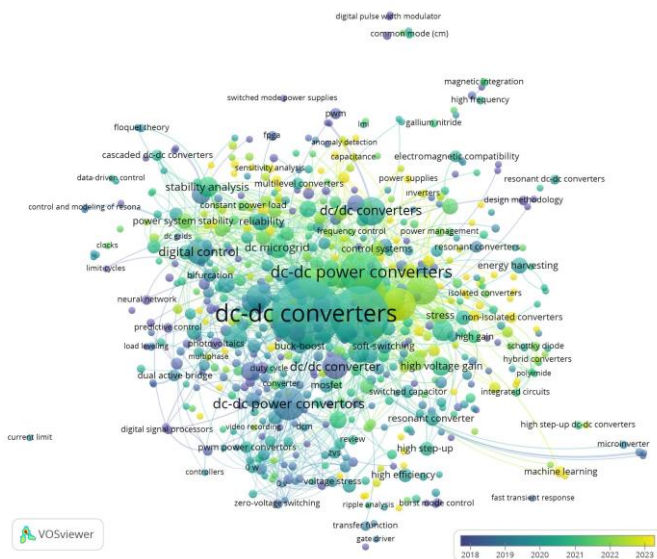


Fig.3. Network diagram study of the co-occurrence of author keywords utilizing VOS viewer

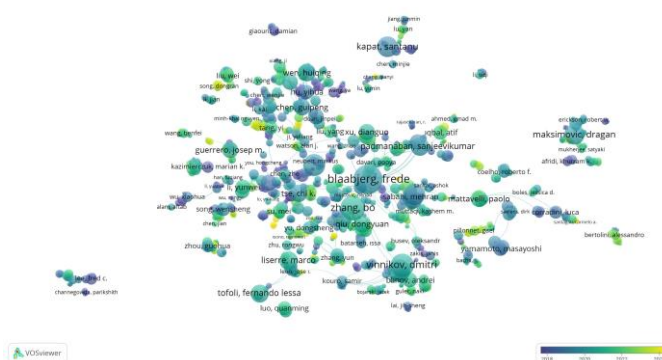


Fig.4. The author's cooperation network

Fig. 6 illustrates the global distribution of co-authorship networks, highlighting the collaborative dynamics among researchers from diverse countries and regions. The diagram illustrates the international collaboration network among countries associated with leading researchers in DC-DC converter studies. Each circle's size indicates the volume of publications originating from that nation, while the lines

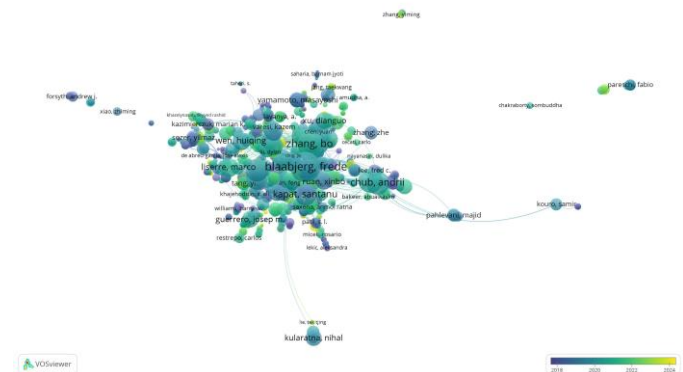


Fig.5. The network of authors' citations

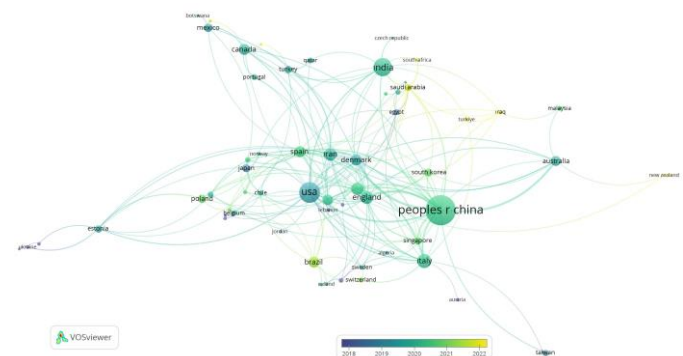


Fig.6. Geographical representation of collaborative authorship patterns across different countries and regions

III. CONVENTIONAL DC-DC CONVERTERS

The architecture of DC-DC converters encompasses a broad spectrum of configurations, each tailored to suit distinct industrial demands. These systems are capable of either elevating or reducing the direct current input voltage and may be engineered to provide multiple voltage outputs or terminals. The fundamental criterion for classifying DC-DC converter systems lies in the presence or absence of galvanic isolation, typically achieved through the integration of a transformer. Based on this distinction, the overarching classification scheme bifurcates DC-DC converters into isolated and non-isolated categories [9]–[13]. In certain DC-DC converters, electrical isolation between the input and output is achieved through the incorporation of a transformer, which functions as a key intermediary component. On the other hand, converter designs

that omit this element establish a continuous conductive path between the primary and secondary sides. A schematic representation summarizing the breadth of DC-DC converter typologies explored in the academic domain is provided in Fig. 7.

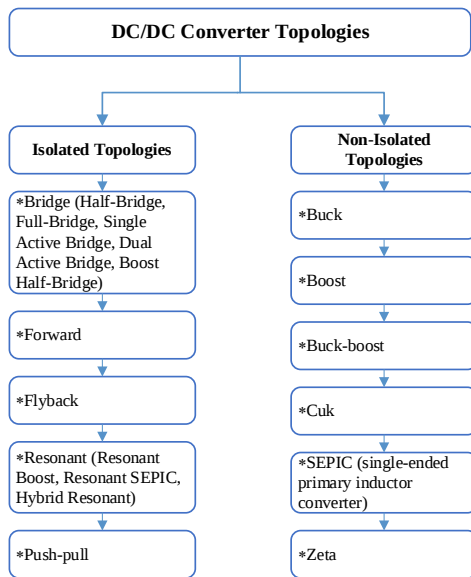


Fig.7. Conventional configurations of DC-DC converters

A. Isolated DC-DC Converter Architectures

In the context of DC-DC converter topologies, the term 'isolation' specifically denotes galvanic separation, signifying that there exists no uninterrupted electrical continuity between the converter's primary (input) and secondary (output) sections. Essentially, isolated DC-DC converter architectures separate the primary terminal and secondary terminal circuits to prevent direct current transfer, typically achieved through the integration of a transformer. This transformer-based separation divides the system into two electrically independent sections. In such isolated configurations, each side generally maintains its distinct ground reference. The energy conversion mechanism typically entails modulating the initial direct current into an alternating waveform, enabling transmission across a high-frequency transformer, after which the signal is rectified to regenerate a stable DC output. Isolated converter systems are often capable of achieving higher voltage conversion ratios compared to non-isolated types. However, challenges such as mitigating the influence exerted by the inherent leakage inductance of the transformer and managing the complexity of transformer construction remain critical design considerations [14].

1) Bridge topologies

Bridge-based isolated DC-DC converters form a highly adaptable class of power conversion systems, distinguished by their use of bridge networks composed of multiple switching elements in tandem with a high-frequency isolation transformer. This category comprises several frequently used designs, including but not limited to the half-bridge, full-bridge, single-active-bridge, dual-active-bridge, and the boost-configured half-bridge variant. Representative schematic diagrams of these bridge-derived topologies are displayed in

Fig. 8: Fig. 8(a) features the full-bridge arrangement, and Fig. 8(b) illustrates the half-bridge. At the same time, Fig. 8(c) depicts the dual active bridge. This schematic is adapted from the circuit diagrams in the referenced studies shown below the figure. Among these, the full-bridge circuit in Fig. 8(a) stands out for its ability to generate an output voltage nearly twice that of the half-bridge structure, primarily due to the incorporation of a greater number of active switching devices in its configuration [15]. Consequently, this converter configuration is capable of supporting significantly elevated output power levels. The voltage impressed upon the primary winding of the transformer depends on the conduction sequence of switching devices S1, S4, S2, and S3 and may alternate between positive (+Vs), negative (-Vs), or null values. On the secondary side, the resulting alternating waveform, induced magnetically through transformer action, is processed through a rectification stage to yield a direct current output. The instantaneous value of this secondary voltage fluctuates from zero to a peak amplitude, which is governed by both the transformer's turn ratio and the specific characteristics of the applied pulse-width modulation (PWM) strategy.

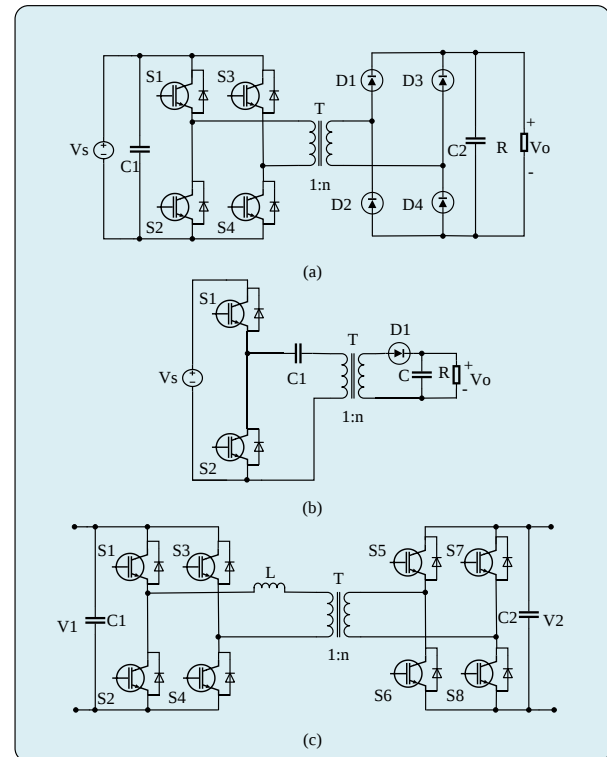


Fig.8. Bridge-type DC-DC converter configurations: (a) topology of the full-bridge converter, (b) topology of the half-bridge converter, (c) topology of the dual active bridge converter [16]–[19]

By contrast, the half-bridge converter configuration presented in Fig. 8(b) utilizes a high-frequency transformer to establish galvanic isolation, thereby enabling the output voltage to assume values that may exceed, fall below, or exhibit reversed polarity relative to the input source. This topology facilitates bidirectional power exchange, thereby enhancing energy transmission efficiency. During operation, the direction and magnitude of power flow are modulated through the active control of semiconductor elements, such as MOSFETs, IGBTs, IGCTs, or FETs, with switches S1 and S2 typically operating in

an alternating, complementary switching sequence. On the other hand, the dual active bridge (DAB) converter depicted in Fig. 8(c) exemplifies a more sophisticated bidirectional architecture, distinguished by its ability to achieve high-efficiency power transfer under varying load and operating conditions. It consists of two inverter stages linked through a coupling inductor and a high-frequency transformer. This innovative concept was first introduced by de Doncker et al. as a means to achieve flexible and efficient power transfer between two DC sources [20]. This topology demonstrates superior efficiency by enabling optimized control, a broad voltage conversion range, and minimal voltage stress during switching transitions, rendering it particularly advantageous for a wide range of industrial applications [21].

The dual active bridge configuration is particularly valued for its straightforward design, ease of scalability, superior efficiency, and high power density. It offers uniform switching behavior, ensures galvanic isolation, and minimizes the presence of passive or idle components, making it well-suited for high-performance power conversion applications [22]–[26]. This topology consists of a pair of H-bridge converter units connected via a high-frequency transformer, with the transformer's leakage inductance playing a dual role: ensuring electrical isolation and acting as a temporary reservoir for energy storage [27]. The single-active-bridge DC-DC converter design is particularly suitable for applications requiring unidirectional power flow, combining economical design with versatile control capabilities. Its basic structure features one actively controlled bridge and one diode-based passive bridge, connected through a transformer operating at high frequency [28]. Moreover, the single active bridge converter can be considered a unidirectional adaptation of the widely recognized DAB topology, which permits power flow in both input-to-output and output-to-input directions and is designed for high-power applications.

A promising strategy to improve galvanically isolated DC-DC converters, particularly for handling extensive variations in input voltage, is the implementation of the boost half-bridge converter architecture [29], [30]. Reference [31] introduces a well-recognized standard design for the half-bridge DC-DC converter with boost functionality. The works referenced in [31], [32] further explore an enhanced version of the traditional half-bridge DC-DC converter topology with boost functionality, detailing modifications and improvements over the conventional design. Due to its advantages such as reduced voltage oscillations associated with diode reverse recovery, zero-voltage switching, simplified input filtering requirements, broad input voltage compatibility, wide operational duty cycle range, elimination of DC magnetization in the power transformer, and absence of circulating currents [31], [33], the conventional half-bridge DC-DC converter with boost functionality finds applicability across numerous sectors. These include DC power distribution networks [32], photovoltaic energy systems [34], fuel cell technologies [35], electric and hybrid vehicle powertrains [36], as well as high-voltage and high-power grid infrastructures [37], among others. Despite its advantages, the boost half-bridge DC-DC converter exhibits several notable limitations. These include excessive DC magnetizing current within the power transformer, a relatively high proportion of electromagnetic components, considerable

uncontrolled power dissipation in the transformer, and pronounced voltage stress along with significant switching voltage fluctuations at the secondary rectifier diodes. Furthermore, the converter's performance may be adversely affected by rapid transient disturbances, such as audio-frequency noise, which can induce large instantaneous output currents through the external inductor [31].

With their high power-handling capabilities and galvanic isolation, bridge-based isolated DC-DC converters offer scalable and adaptable solutions suitable for various industrial and renewable energy applications. The complicated transformer design, higher component count, and related switching losses, however, make implementation extremely difficult. Furthermore, in situations of dynamic operation and partial load, the efficiency of these topologies may change significantly. To improve performance and dependability across a range of operating circumstances, future research should focus on developing fault-tolerant control mechanisms, sophisticated modulation techniques, and smaller transformer architectures.

2) Forward DC-DC converter architecture

The forward architecture is a type of isolated DC-DC topology designed to provide a stable and galvanically separated DC output from an input source that may be variable or unregulated. Fundamentally, this configuration is widely applicable across transformer-coupled DC-DC converters, especially those engineered to supply multiple output rails [15]. The secondary side voltage in a forward DC-DC converter is primarily governed by the turn's ratio of the transformer, enabling output levels that can exceed, match, or fall below the input voltage. In terms of operation, it exhibits characteristics akin to those of the flyback converter. This resemblance underpins its extensive adoption in low-power scenarios owing to its advantageous dynamic performance, economical design, and simplicity of implementation. Nevertheless, the forward converter is generally less appropriate for high input voltage conditions, as the primary switch experiences elevated voltage stress, potentially resulting in increased switching losses and reduced overall efficiency [38].

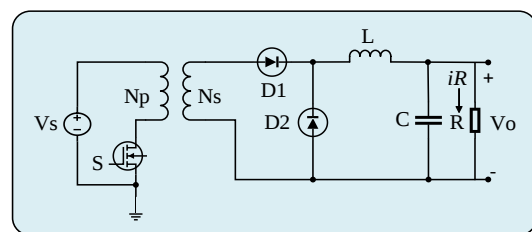


Fig.9. Basic schematic of a forward DC-DC converter configuration [39]

Fig. 9 presents the foundational layout of a forward-mode DC-DC converter. This schematic is adapted from the circuit diagrams in the referenced studies shown below the figure. In contrast to the flyback design, this topology enables current to flow simultaneously through the transformer's primary and secondary coils. At the same time, the switching device—typically a MOSFET—is activated, facilitating the direct delivery of power to the load. Energy is rapidly transferred to the secondary winding through the transformer's magnetic

coupling, with the output voltage determined by the transformer's turns ratio. During this interval, diode D1 is forward-biased, allowing current conduction, whereas diode D2 remains reverse-biased, blocking current. When the switching device is turned off, current ceases in both primary and secondary windings; however, the inductor on the secondary side sustains current flow by forward-biasing diode D2, while diode D1 becomes inactive. This operation, orchestrated by PWM, repeats continuously to maintain stable output voltage regulation.

Overall, the forward converter topology stands out for its simple control mechanism, compact structure, and suitability for low- to moderate-power applications that require multiple output voltages. Its efficiency and dynamic response make it a practical option for regulated DC supplies. However, its performance is limited under high input voltage conditions due to increased voltage stress across the switching device and greater switching losses. Future investigations should focus on optimizing voltage stress handling, exploring soft-switching techniques, and enhancing electromagnetic compatibility to extend its applicability to broader industrial domains.

3) Flyback DC-DC converter architecture

Originating as the isolated variant of the basic buck-boost converter, the flyback DC-DC converter is distinguished by its use of a transformer for galvanic isolation. Due to its straightforward design and inherent isolation properties, this topology is widely used in applications spanning a range of power levels, from low to medium. The incorporation of a high turns-ratio transformer allows substantial voltage amplification. Its widespread adoption in power electronics is attributed to its affordability, simple control mechanisms, compact footprint, and dependable electrical separation between the input and output circuits [40]–[43].

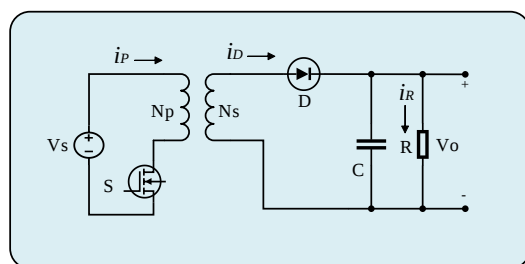


Fig.10. Common structural design of a flyback DC-DC converter [44], [45]

Fig. 10 illustrates the typical arrangement of a flyback DC-DC converter. This schematic is adapted from the circuit diagrams in the referenced studies shown below the figure. A notable benefit of this topology is its reduced component complexity, which facilitates a more straightforward implementation and cost efficiency. The capability to produce multiple output voltages is achieved by incorporating a few supplementary components—namely, an additional transformer winding, along with corresponding diodes and capacitors for each extra output. However, a notable limitation of the flyback design is its relatively limited lateral (cross-regulation) control, especially when compared to transformer-isolated converters based on buck-derived topologies such as forward and full-bridge converters [46]. While traditional

flyback DC-DC converters operating at fixed switching frequencies offer simplicity in both design and control, they suffer from significant switching losses under voltage stress conditions and present difficulties in managing efficient power switching through MOSFETs [47]. The flyback converter operates by energizing the transformer's primary coil when the input switch is activated, causing magnetic energy to accumulate in the core. During this period, the voltage induced in the secondary coil is reversed, which keeps diode D1 in a non-conductive state and prevents power from reaching the output. The output capacitor maintains the load voltage while energy is being stored. When the switch turns off, the magnetic field collapses, flipping the polarity across the windings. This change allows diode D1 to conduct, transferring the stored energy to the secondary circuit and onward to the load via the rectifier. This charging and discharging process repeats cyclically, controlled by the switching device, until the core's energy is fully released or the switch closes again.

In essence, the flyback converter remains a cost-effective and compact solution, especially for applications with low to medium power demands and stringent isolation requirements. Its ability to support multiple output voltages and minimal component count enhances its appeal in consumer electronics and auxiliary power supplies. Nevertheless, its limited cross-regulation performance, relatively high switching losses, and suboptimal efficiency at elevated power levels constrain its widespread industrial deployment. Future research directions should address these limitations by exploring resonant switching techniques, digital control schemes, and improved magnetic core designs to enhance overall converter performance and robustness.

4) Resonant DC-DC converter architecture

Resonant DC-DC converter architectures represent a distinctive category within power electronic systems, recognized for their ability to deliver high efficiency and refined control in electrical energy conversion. Unlike conventional switched-mode power supplies, resonant converter architectures are specifically engineered to minimize switching losses, thereby significantly improving overall performance. This section aims to explore the core operating principles, structural elements, and application areas of resonant DC-DC converter technologies. These topologies are well-established solutions, particularly favored in industrial sectors that demand reliable and efficient DC voltage regulation and enhancement [48]. Resonant DC-DC converter topologies are characterized by their ability to handle significant power levels, generate smoother waveform profiles, deliver superior performance, operate at elevated switching frequencies through optimized switching schemes, provide high-quality power conversion, and require significantly fewer electromagnetic components such as transformers and filters [48], [49]. Recent advancements in boost rectifier technologies have contributed to improvements in DC-DC resonant converter designs. An extensive survey covering contemporary resonant converter architectures is provided in reference [50].

Resonant DC-DC converters primarily utilize LC (inductor-capacitor) tank circuits to enhance the switching performance at specific resonant frequencies, thereby significantly reducing energy losses during switching transitions. The primary

categories of resonant converters consist of the series resonant and parallel resonant configurations. Series-resonance-based DC-DC converters are primarily used for voltage step-up applications, utilizing high-frequency operation to minimize switching losses and achieve superior output efficiency. In contrast, parallel resonant converters are preferred in scenarios that require a stable and regulated output voltage, thereby enhancing system stability. Beyond these fundamental types, resonant converter designs also encompass hybrid structures such as mixed resonant, resonant boost, and resonant SEPIC converters. In Fig.11, a combined converter is shown that integrates a boost stage with a series resonant circuit, linking a standard power input to the resonant network to maximize energy conversion efficiency. This schematic is adapted from the circuit diagrams in the referenced studies shown below the figure. When the input voltage remains beneath the upper limit, this topology behaves like a buck converter, employing phase control on the primary winding alongside combined conversion on the secondary side.

In contrast, at lower input voltages, it operates similarly to a boost converter, featuring a full-bridge arrangement on the primary side coupled with a boosting circuit on the secondary side [51]. By substantially reducing switching losses, resonant DC-DC converters achieve superior energy efficiency that frequently surpasses that of conventional converter topologies. Their unique operational principles significantly contribute to lowering high-frequency electromagnetic noise, thereby mitigating electromagnetic interference issues. Such converters ensure reliable and steady performance across varying load demands, rendering them adaptable to a broad spectrum of applications. Despite these advantages, resonant converter designs come with particular challenges. The complexity involved in designing resonant circuits demands advanced technical expertise, which can complicate the development process.

Additionally, the need for specialized components and precise tuning of design parameters often results in increased production costs. Resonant DC-DC converters have found significant applications across various sectors, including high-voltage power systems, electric vehicles, and medical devices. To conclude, resonant DC-DC converters represent a notable leap forward in power electronics, thanks to their superior efficiency and reduced electromagnetic interference. With ongoing technological advancements, the potential to create more advanced and effective converter architectures will grow, steering future investigations toward performance optimization and exploration of novel application areas.

High efficiency, less EMI, and smooth voltage control are all notable benefits of resonant DC-DC converters, particularly when high-frequency switching is involved. Their technical promise is demonstrated by the fact that they are suitable for delicate and high-power applications, such as medical equipment and electric cars. The intricacy of resonant circuit design, the requirement for precise tuning, and the high cost of specialized parts severely hinders adoption. Therefore, future research should focus on integrating sophisticated semiconductors and digital design automation tools to simplify design processes, create adaptive control algorithms, and lower implementation costs.

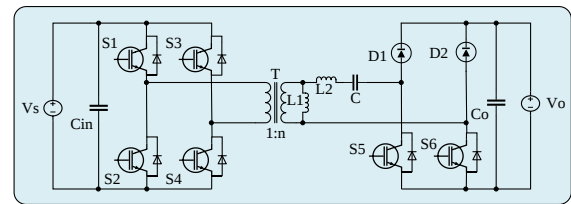


Fig.11. An integrated resonant DC-DC converter topology [51], [52]

5) Push-pull DC-DC converter architecture

The push-pull converter architecture is a key topology in power electronics, highly regarded for its efficiency and adaptability in adjusting DC voltage levels in either direction. This design utilizes a power transformer combined with PWM control and a specialized regulation scheme to manage input voltage transformation. While various forms of push-pull converters exist, this topology is particularly advantageous in applications demanding galvanic isolation and substantial power handling. It is found extensive use in sophisticated setups that incorporate renewable energy sources, such as pumps, solar panels, and battery management systems. Employing push-pull converters enables seamless integration of these diverse power sources with both traditional electrical grids and modern smart grid technologies. The demonstrated applications highlight the practical significance of push-pull converters in managing power flow across a range of electrical networks, including off-grid and remote installations lacking conventional infrastructure [53]. Fig. 12 depicts the fundamental circuit layout of a push-pull DC-DC converter. This schematic is adapted from the circuit diagrams in the referenced studies shown below the figure.

Push-pull DC-DC converter configurations are distinguished by their simple circuit architecture, which enables effective voltage regulation, galvanic isolation, and the achievement of high voltage transformation ratios. Such configurations leverage low-side switching, streamlined gate driver circuits, and enhanced transformer efficiency, making them particularly effective for applications operating at low voltage levels [54]–[56]. Moreover, owing to these beneficial features, push-pull converters are frequently utilized in applications ranging from medium to high power levels [57].

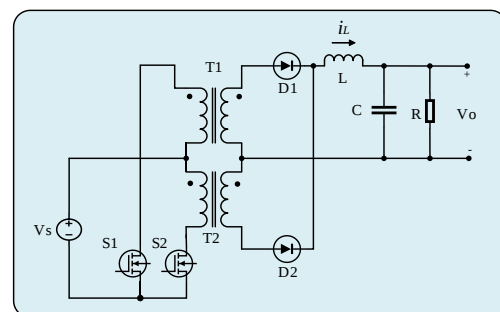


Fig.12. A basic push-pull DC-DC converter design [58]

Push-pull DC-DC converters achieve superior efficiency primarily by ensuring effective transformer coupling and minimizing switching-related losses. The transformer also provides inherent galvanic isolation between the input and output, contributing to enhanced safety and system dependability. This topology is capable of stepping voltages up and down, making it adaptable to a wide range of applications.

The operational principle involves alternately activating each half of the transformer's primary winding using two semiconductor switches, commonly MOSFETs or IGBTs. When the first switch is turned on, the current passes through one portion of the primary winding, inducing voltage on the secondary side. Once this switch is turned off, the second switch is turned on, allowing the current to flow through the opposite half of the primary winding. This alternating activation ensures a continuous flow of energy to the load.

On the secondary coil, the induced voltage undergoes rectification and smoothing through filtering elements to yield a consistent DC output. The transformation of the input voltage at the primary winding depends directly on the switching conditions of the two semiconductor devices, S1 and S2. While S1 is active, the transformer's magnetic flux increases steadily, generating a voltage on the secondary side. At this moment, diode D2 becomes conductive, allowing current to pass, whereas diode D1 stays non-conductive. The output inductor stores energy during this interval and supplies current to the load capacitor. Conversely, when S2 is activated and S1 is off, the transformer flux decreases in the opposite direction, reversing the polarity on the secondary winding. In this phase, diode D1 turns on, while diode D2 turns off, allowing current to flow through D1 and the inductor, thereby maintaining continuous energy delivery to the output. The output capacitor alternately charges and discharges, smoothing the voltage supplied to the load. This repetitive switching pattern persists uninterrupted, guaranteeing consistent power delivery and maintaining voltage stability [58].

The push-pull DC-DC converter is widely recognized for its effective voltage regulation, high efficiency, and inherent galvanic isolation, particularly in medium- to high-power applications. Its symmetrical structure and low-side switching simplify gate drive design and enhance transformer utilization. Despite these strengths, the converter faces limitations related to transformer core saturation, voltage imbalance, and high switch stress under asymmetric loading conditions. Consequently, future studies should focus on developing advanced core reset strategies, implementing real-time current balancing techniques, and exploring control schemes that improve stability under dynamic load variations.

B. Non-isolated DC-DC Converter Topologies

Non-isolated DC-DC conversion topologies constitute an essential class within power electronics, distinguished by their ability to regulate voltage levels without requiring galvanic isolation. Unlike their isolated counterparts, which employ high-frequency transformers to electrically decouple the input and output stages, non-isolated architectures feature a continuous conductive path, allowing direct energy transfer between the source and load terminals. In isolated designs, energy transfer is facilitated through transformer action, ensuring safety and isolation, particularly in high-voltage or sensitive applications. Conversely, non-isolated architectures eliminate the need for a transformer, offering simpler construction, reduced size, and cost-effective operation. These designs are particularly advantageous in systems where electrical isolation is not a mandatory requirement and space or efficiency constraints are critical [9].

Non-isolated DC-DC converter architectures are highly regarded for their superior efficiency, reduced physical dimensions, and cost-effective implementation, making them integral to a broad spectrum of modern electronic applications. The absence of galvanic isolation simplifies their circuit configuration, resulting in enhanced performance and compactness. A wide spectrum of non-isolated converter architectures, including buck, boost, buck-boost, Ćuk, SEPIC, and Zeta configurations, have been engineered to accommodate a range of voltage conversion and current regulation demands across various power processing scenarios. Consequently, these converters play a vital role across multiple domains, ranging from advanced power supply infrastructures to compact, portable electronic systems. Numerous studies in the literature have focused on fault detection and diagnostic methods specific to these converter types [59]. While isolated converters offer advantages in terms of electrical separation and safety, non-isolated designs often present a more pragmatic solution due to their simplicity and efficiency. Despite certain limitations such as constrained voltage gain, extended duty cycles, and occasional reliance on auxiliary components, galvanically non-separated DC-DC converter architectures remain a compelling alternative to their isolated counterparts [9].

1) Buck DC-DC converter architecture

The buck converter stands as a cornerstone configuration within power electronic systems, purpose-built to step down elevated input voltages to a lower, regulated output while achieving commendable efficiency levels. As a member of the non-isolated DC-DC converter family, this topology maintains a direct electrical linkage between source and load, inherently ensuring that the output voltage consistently remains below the input potential [60], [61]. Due to its inherent simplicity and favorable dynamic characteristics, namely its uniform structure and minimum phase behavior, the buck DC-DC converter has seen widespread adoption across various industrial applications. Often designated as a step-down regulator, this configuration is extensively employed across a broad array of electronic architectures due to its simplicity, reliability, and effective voltage reduction capability [62]. The compact structure of buck DC-DC converters is particularly advantageous in miniaturized electronic applications, as it reduces the reliance on bulky passive elements. This topology plays a crucial role in contemporary power electronics, significantly contributing to efficient voltage regulation and power conversion. Its versatility, compactness, and cost-effectiveness have made it a widely adopted solution across various sectors. Despite these advantages, the buck converter's reliance on hard switching mechanisms and reduced efficiency at elevated switching frequencies can result in increased electromagnetic interference, posing challenges for high-frequency applications [63].

Fig. 13 depicts the internal arrangement of a conventional buck-type DC-DC converter. This schematic is adapted from the circuit diagrams in the referenced studies shown below the figure. Upon the activation of the switching element, electrical power is routed from the input source toward the output terminal. Initially, the inductor absorbs energy, resulting in a delayed rise in load current; nevertheless, this is followed by a gradual build-up in both the voltage across the output capacitor

and the current delivered to the load. Throughout this interval, the diode remains in a reverse-bias state, as the voltage at its cathode exceeds that at the anode, thereby inhibiting current conduction.

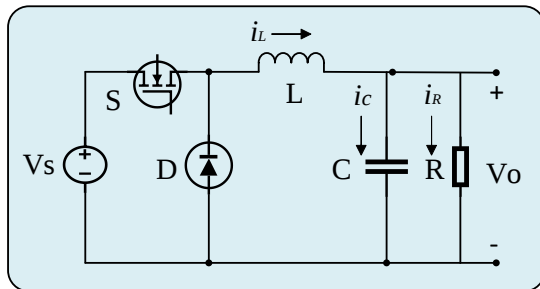


Fig.13. Conventional DC-DC buck converter design [64]–[66].

When the switching device is deactivated, the inductor, having previously accumulated magnetic energy, undergoes a polarity inversion that facilitates sustained current flow despite the switch being in its open state. This energy discharge drives current through the forward-bias diode and continues to energize the load. As the magnetic field within the inductor collapses, the diminishing energy gradually reduces the current until it is depleted. At this point, the output capacitor takes over the responsibility for maintaining voltage regulation by supplying current to the load. This sequence of magnetically and capacitively sustained conduction recurs with each switching interval, thereby ensuring a stable and continuous DC output.

In summary, the buck converter's ease of use, dependability, and effective step-down voltage control make it one of the most basic and popular non-isolated topologies. It is ideal for portable applications and embedded systems due to its compact size and low component count. Its scalability for sophisticated power systems is limited by its hard-switching nature, which increases EMI and reduces efficiency at high frequencies. Future developments should prioritize EMI suppression strategies, soft-switching approaches, and integration with digital control systems to improve their suitability for high-performance and noise-sensitive settings.

2) Boost DC-DC converter architecture

A boost-type DC-DC converter is an advanced energy conversion configuration engineered to elevate a lower direct current input voltage to a significantly higher output level. This topology is widely used in modern electronic and electrical systems, where stringent requirements for voltage amplification and efficient power conditioning exist. Distinguished by its step-up functionality and absence of galvanic isolation, the boost converter operates through controlled energy accumulation in inductive elements during the switch-on period, followed by energy release during the switch-off phase. Its compact form factor, combined with high operational efficiency, renders it indispensable in space-constrained and performance-critical environments, such as portable electronics, electric vehicles, and renewable energy interfaces. By regulating the switching duty cycle through the coordinated operation of passive elements and semiconductor switching devices, the boost converter effectively ensures the desired

voltage elevation [67], [68]. Fig. 14 depicts the prototypical topology of a boost DC-DC converter, which relies on the intricate orchestration of switching elements and inductive energy storage to facilitate voltage elevation. This schematic is adapted from the circuit diagrams in the referenced studies shown below the figure. The operational sequence can be delineated into distinct yet interrelated phases: the inductor's energy accumulation during the conduction interval, the subsequent energy delivery to the load when the switch transitions to the off state, and the precise voltage regulation achieved via output filtering and control circuitry. Upon closing the power switch, current flows through the inductor, generating a growing magnetic field that stores energy. When the switch is disengaged, this stored magnetic flux propels current continuity, thereby sustaining power flow to the load and effectuating an output voltage exceeding that of the source. The converter's output voltage magnitude is governed by modulating the duty cycle of the PWM signal applied to the switch; augmenting this duty cycle proportionally raises the output voltage, while reducing it produces the inverse effect.

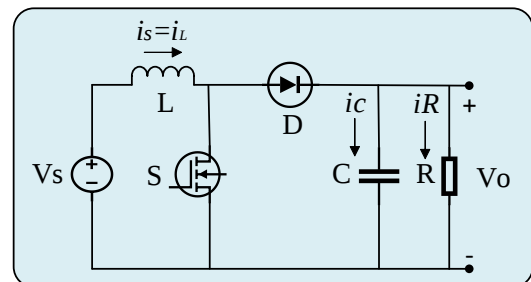


Fig.14. Traditional architectures for DC-DC boost converter [10], [69]

Boost DC-DC converters are critical elements within modern power management frameworks, due to their high efficiency and compact form factors, which effectively address the diverse energy demands of contemporary technologies. As advancements in electrical power systems and electronic devices continue to accelerate, these converter topologies are expected to exhibit enhanced performance metrics and expanded applicability, thereby maintaining their pivotal role in the continually advancing domain of electrical and electronic engineering.

Overall, the boost converter is a highly effective topology for stepping up low input voltages, offering a compact and efficient solution widely used in electric vehicles, battery systems, and renewable energy platforms. Its straightforward control and minimal component requirements enhance design simplicity. Nevertheless, drawbacks such as high output voltage ripple, increased switch stress, and limited efficiency at low load conditions constrain its performance in high-power and precision-demanding applications. Future research should address these limitations by incorporating interleaved structures, digital predictive control, and advanced wide-bandgap devices to improve efficiency, dynamic response, and thermal stability.

3) Buck-Boost DC-DC converter architecture

Buck-boost converter topologies hold a pivotal position within power electronics due to their inherent capability to seamlessly regulate output voltage levels both above and below

the input supply. This dual-mode operation facilitates dynamic voltage adaptation, enhancing overall system flexibility and conversion efficacy. In non-isolated buck-boost implementations, the converter operates in boost mode when the output voltage exceeds the input voltage and switches to buck mode when the output falls below the input level. The transition between these operating states is determined by the modulation index of the PWM control signal that governs the switching device. As a result, precise voltage regulation is achievable, enabling the output to be adjusted responsively with respect to the input voltage magnitude [70], [71]. Buck-boost converter configurations are highly regarded across various industrial sectors for their exceptional versatility, enabling precise modulation of voltage levels that either step up or step down the input voltage while maintaining circuit simplicity through a reduced component count [72], [73]. Fig. 10 depicts the fundamental structural layout of a buck-boost DC-DC converter. This schematic is adapted from the circuit diagrams in the referenced studies shown below the figure.

Similar to other DC-DC converter frameworks, the buck-boost converter's operation is divided into two primary intervals, governed by the switching device's conduction status: the energy accumulation interval and the energy delivery interval. The interplay between these phases underpins the converter's functional dynamics. The core elements of this topology include a semiconductor switch, an inductive coil, a diode, and an energy storage capacitor. The converter toggles between buck and boost modes depending on the switch position. When the switch is engaged, the current flows through the inductor, resulting in the storage of magnetic energy within its core, while the diode remains reverse-biased, preventing current passage. Under steady-state conditions, with a zero average voltage across the inductor and zero net current through the capacitor, the opening of the switch reverses the polarity of the inductor voltage. Consequently, the diode transitions to a forward-bias state, enabling the inductor to discharge its stored magnetic energy into the capacitor and the load. The capacitor replenishes its charge while simultaneously supplying the load. This cyclical process of switching on and off repeats continuously, with the power switch regulated by PWM to control output voltage and current.

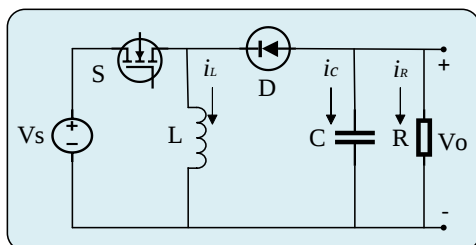


Fig.15. A buck-boost DC-DC converter's basic configuration [74]–[76].

Buck-boost converters offer notable advantages, including operational versatility across extensive voltage ranges and high adaptability to varying application requirements. Their compatibility with diverse input and output voltage levels facilitates integration into a wide range of systems, such as energy management networks, battery storage units, renewable energy platforms, and electric vehicle infrastructures.

Furthermore, these converters are favored for their compact form factors and superior energy conversion efficiencies. Anticipated advancements in these topologies, along with integration with emerging technologies, are expected to drive significant enhancements in the functional effectiveness and efficiency of modern power transformation mechanisms.

The buck-boost topology stands out due to its bidirectional voltage handling capability, enabling it to function efficiently under both step-up and step-down scenarios. Despite its widespread applicability and structural simplicity, it tends to suffer from performance degradation at extreme duty ratios, particularly in terms of efficiency and output ripple. To address these shortcomings, novel control strategies and the incorporation of low-loss passive elements are being actively explored. Enhancing transient response and minimizing ripple noise remain key focal points for future development.

4) Cuk and SEPIC DC-DC converter architectures

Within the broad spectrum of DC-DC converter architectures, the Cuk and SEPIC topologies stand out due to their versatile operational capabilities. The non-isolated Cuk converter notably produces an output voltage with polarity inverse to the input, while offering the flexibility to generate output voltages either higher or lower than the input magnitude [77]. The Cuk converter topology is uniquely recognized for its dual capability to both elevate and reduce voltage levels. Key features include a wide conversion ratio, capacitive energy transfer that inherently isolates the input from the output, seamless buck-boost functionality, continuous current conduction on both input and output circuits, the use of low-side switching devices, and the predominant use of capacitive elements for power transmission [78], [79]. A distinguishing attribute of the Cuk converter is its ability to maintain stable output voltage regulation regardless of fluctuations in the input voltage. Furthermore, this topology naturally excels in scenarios that demand a negative polarity output, offering this characteristic inherently without the need for additional circuitry.

Illustrated in Fig. 16(a) is the elementary topology of the Cuk converter. The SEPIC converter, devoid of galvanic isolation, achieves voltage transformation by rapidly toggling its semiconductor switching element. This schematic is adapted from the circuit diagrams in the referenced studies shown below the figure. This arrangement allows for the adjustment of the output voltage to levels either above or below the input voltage, while maintaining the same polarity throughout the process [77]. The SEPIC converter architecture employs an integrated buck-boost approach, distinguished by maintaining a nearly steady input current and producing an output voltage that preserves the input's polarity, in contrast to the polarity-inverting behavior of the Cuk converter. Compared to many conventional DC-DC converter designs, the SEPIC converter typically offers superior efficiency [80]. Fig.16(b) illustrates a relatively simple configuration of a SEPIC DC-DC converter. The switching actions of power semiconductors in these converter topologies are precisely regulated by PWM techniques to maximize operational efficiency. The Cuk converter's behavior is divided into two distinct intervals determined by the status of the switching device. As shown in Fig. 16(a), during the ON interval, current flows through inductor L1, while the diode is reverse-blocked, preventing

current passage. When the switch toggles to the OFF state, the diode becomes conductive, enabling capacitor C1 to charge with a voltage polarity identical to the input, thanks to the closed loop on the diode's left side. Simultaneously, the energy stored in L1 during the ON phase is transferred to the load through inductor L2 and capacitor C2 via the diode.

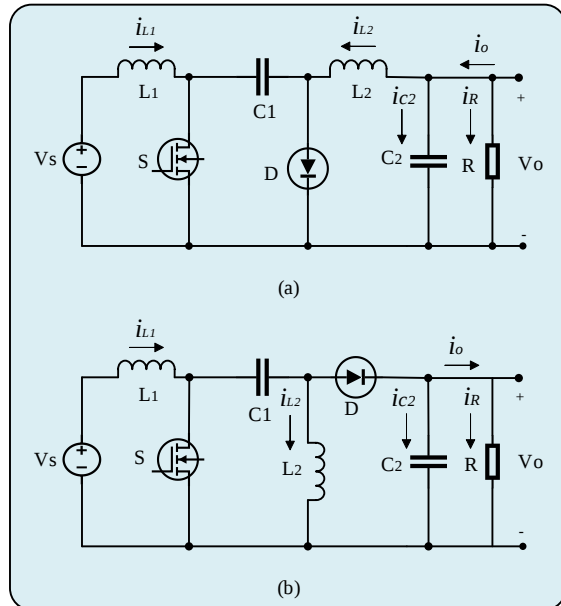


Fig.16. The fundamental Cuk and SEPIC DC-DC converter schemes: (a) Cuk converter topology, (b) SEPIC converter topology [81]–[84].

Conversely, the SEPIC converter, illustrated in Fig. 16(b), shares a comparable operational concept but with nuanced differences. With the switch closed, the input voltage causes current to flow through L1, while capacitor C1, charged in the previous cycle, supplies current to the adjacent circuit segment. The current flowing through L2 induces a voltage that opposes the polarity of the input source. When the switch opens, L1's stored energy reverses polarity and injects power into the circuit, ensuring continuous energy delivery. The combined current from the input source and L1 charges capacitor C2, which subsequently discharges during the next switching cycle. Similarly, inductor L2 changes polarity, contributing to the total load current. Capacitor C2 delivers power to the load, preserving an output voltage polarity consistent with that of the input source. In both converter topologies, the input and output voltages share identical polarity at the load terminals. Control is continuously maintained via PWM signals that switch the power device on and off, thereby regulating energy transfer cyclically.

Renowned for their adaptability and efficiency, the Cuk and SEPIC converter architectures serve as pivotal elements in power electronics, delivering robust and dependable operation across diverse domains, including renewable energy systems, DC microgrid management, electric vehicle charging platforms, and advanced power supply networks. Their ability to handle fluctuating input and output conditions underscores their value in both consumer-grade electronics and industrial-scale operations. Amid the growing worldwide focus on

optimizing energy use, these converter configurations are anticipated to serve as fundamental components driving the progression of advanced and highly efficient power management frameworks. The rapid advancement of semiconductor technology presents an opportunity to further refine these topologies in terms of operational efficiency, compactness, and ease of integration. Consequently, future research should aim to improve their functional adaptability, minimize their physical footprint, and enhance their maintainability. With ongoing innovation, Cuk and SEPIC converters are likely to remain fundamental components in shaping the upcoming generation of sustainable and adaptive power structures.

Both the Cuk and SEPIC converter designs offer enhanced input-output continuity and polarity-specific control, making them suitable for a range of power conditioning applications. However, the increased complexity arising from the addition of inductors and capacitors introduces trade-offs in terms of cost, size, and control difficulty. While these architectures offer smoother input currents and stable output profiles, practical deployment often demands refined component selection and efficient layout strategies. Ongoing efforts in miniaturization and digital control optimization may facilitate broader adoption in compact electronic systems.

5) Zeta DC-DC converter architecture

The fundamental role of DC-DC converter architectures lies in their ability to modulate and convert DC voltage levels to desired magnitudes. Among the spectrum of available topologies, the Zeta converter is distinguished by its unique configuration and multifaceted operational capabilities. As a fourth-order, nonlinear, and non-isolated power electronic system, the Zeta converter adeptly facilitates both voltage step-up and step-down functions, adapting seamlessly to varying application demands [85], [86]. Analogous to the Cuk and SEPIC converter families, the Zeta DC-DC converter preserves a unipolar voltage orientation at its input and output nodes. This intrinsic characteristic enables seamless functionality in both voltage elevation (boost) and reduction (buck) modes. Fundamentally, the Zeta topology guarantees congruent polarity between its input and output voltages, thereby broadening its utility across diverse power management applications [87], [88]. Zeta DC-DC converter architectures outperform SEPIC converters due to their integrated continuous feedback control, which facilitates improved voltage stability, enhanced load transient response, reduced output voltage ripple, and simplified rectification processes [89]. Fig.17 depicts the circuit schematic of a conventional Zeta DC-DC converter topology. This schematic is adapted from the circuit diagrams in the referenced studies shown below the figure.

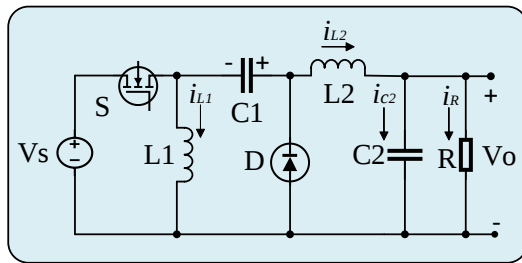


Fig.17. Traditional Zeta DC-DC converter structure [88], [90]–[93]

A conventional Zeta DC-DC converter configuration comprises a power switch, a diode, a pair of inductors, and a capacitor. This configuration enables both energy transfer and voltage regulation to be effectively managed. By incorporating two inductive components, the Zeta converter structure enables dual-mode operation, allowing for both boosting and bucking, making it highly adaptable for various applications. Output voltage regulation is achieved by dynamically adjusting the switching device's operation, enabling seamless toggling between voltage increase and decrease modes. When the switch is engaged, the diode is blocked from conducting, permitting both inductors L1 and L2 to accumulate magnetic energy in alignment with the polarity of the input supply. During this phase, the source voltage V_s is directly imposed across these inductors. Upon deactivation of the switch, the voltage polarity across L1 and L2 inverts, activating the diode to enter conduction mode and allowing continuous power transfer to the output load [90]. In the off state of the switching component, the semiconductor diode governs the current pathway, ensuring effective energy delivery throughout the system. The Zeta converter topology incorporates a pair of inductors that are pivotal for energy retention, enabling the converter to function seamlessly in both voltage elevation and reduction regimes. Additionally, the inclusion of a capacitor enhances the voltage stability by smoothing output voltage fluctuations and mitigating transient oscillations, ensuring a more consistent and regulated output.

The Zeta converter represents a refined solution for applications that demand stable voltage levels under dynamic load and input conditions. Its capability to perform both buck and boost actions with maintained polarity makes it favorable in regulated supply systems. Nevertheless, its relatively complex control characteristics and dependence on dual inductors can limit its attractiveness in cost-sensitive scenarios. Advancements in integrated magnetics and control circuitry may help simplify implementation and expand their utility across more compact and efficient designs.

C. Multi-level DC-DC Converter Architectures

Multi-level DC-DC converters represent a significant advancement in modern power conversion technologies and have emerged as transformative solutions within semiconductor-based power electronic systems. These advanced converter structures are designed to minimize harmonic distortion, improve energy efficiency, and enable the generation of higher output voltage levels. The fundamental concept behind multi-level converter technology involves intentionally combining several distinct voltage steps to achieve the targeted output, thereby reducing voltage stress on switching devices and enhancing the overall system efficiency.

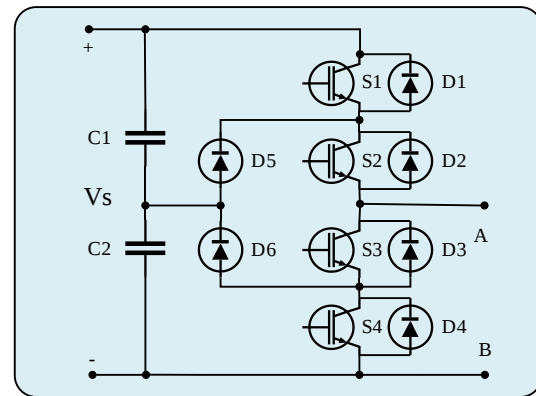


Fig.18. Multi-level DC-DC converter with diode-based voltage clamping [94]

Multi-level DC-DC converters are available in both isolated and non-isolated variants. Within the realm of non-isolated designs, notable configurations encompass diode-clamped, flying-capacitor, and cascaded H-bridge topologies. The diode-clamped approach is widely appreciated for its straightforward architecture and economic feasibility. Nevertheless, its applicability at higher voltage ranges is constrained due to the increasing number of clamping diodes required, which adds complexity and poses challenges for scalability in practical deployments. While flying capacitor converter topologies have demonstrated acceptable performance within certain operating conditions, their efficiency remains constrained. Moreover, the utilization of this architecture at medium voltage levels presents challenges, primarily due to the excessive number of flying capacitors required, which increases system complexity and physical footprint [95]. Historically, flying capacitor converter topologies have been predominantly utilized in applications involving high-voltage, high-power DC-to-AC conversion. These multi-level converter topologies offer significant benefits in efficiency and power handling capabilities when compared to many traditional converter designs [96], [97].

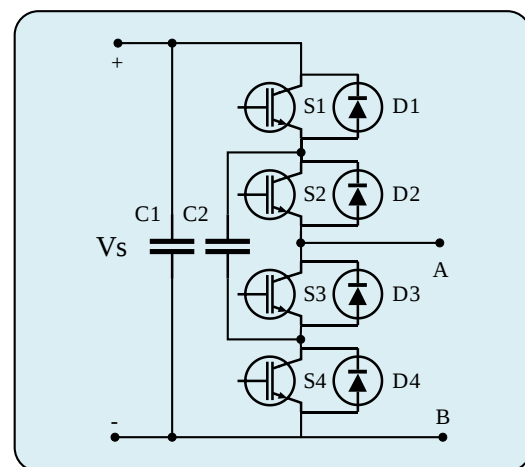


Fig.19. Flying capacitor-based multi-level DC-DC converter architecture [94]

Among multi-level converter methodologies, the cascaded H-bridge configuration stands out as one of the most extensively adopted architectures in practical applications. This configuration is formed by connecting multiple identical H-

bridge units in series. Cascaded H-bridge DC-DC converters offer the benefit of achieving elevated output voltage levels while maintaining high power quality. These results are obtained by integrating several discrete converter cells within the overall structure. Additionally, the inherent modularity of cascaded H-bridge designs provides excellent fault tolerance, enhancing their suitability for various practical applications [98]. Due to its ability to generate high-level output voltages and maintain superior waveform fidelity, the cascaded H-bridge architecture is particularly advantageous for medium- to high-power applications [99]–[101]. Fig. 18, Fig. 19, and Fig. 20, respectively, depict the circuit configurations of the diode-clamped, flying capacitor, and cascaded multi-level DC-DC converter topologies.

In multi-level DC-DC converter designs, an array of capacitors arranged on the secondary side partitions the primary voltage into multiple discrete stepped levels. The series connection of these capacitors establishes defined voltage increments. As illustrated in Fig. 18, the diode-clamped multi-level DC-DC converter employs interconnected capacitors to divide the input voltage into three separate levels. This schematic is adapted from the circuit diagrams in the referenced studies shown below the figure. Within this topology, diodes function as voltage clamps, maintaining the output voltage at specific set points. The architecture comprises power semiconductor switches, such as MOSFETs or IGBTs, alongside diodes and capacitors, with the switching devices orchestrating the current flow to precisely regulate the output voltage. High-speed switching components are essential for optimal operation. Diodes play a crucial role by limiting the voltage at each level, enabling precise regulation of the output voltage steps. Capacitors attached to each voltage level serve to stabilize the voltage, minimizing fluctuations and improving overall system efficiency.

Diode-clamped multi-level converters offer several key benefits, including minimized harmonic distortion, improved operational efficiency, robust handling of high voltage and power demands, and reduced thermal loading. These attributes render them especially well-suited for use in electric vehicle drives, energy storage solutions, renewable energy systems, and power distribution networks. However, challenges remain, including their complex circuit topology, higher manufacturing costs, and difficulties in maintaining voltage balance across capacitor levels. Advancements in semiconductor components and sophisticated control techniques are poised to resolve current obstacles, enabling substantial enhancements in the efficacy and broader implementation of diode-clamped multi-level DC-DC converters within forthcoming power electronic frameworks.

As demonstrated in Figure 19, the flying capacitor multi-level DC-DC converter topology achieves its secondary-side output voltage levels by allocating the voltage across a series-connected capacitor network. This schematic is adapted from the circuit diagrams in the referenced studies shown below the figure. This architecture's distinct advantage lies in its ability to generate multiple voltage levels without relying on additional voltage clamping devices, such as diodes. Rather than relying solely on passive components, this topology incorporates flying capacitors that are dynamically engaged and disengaged within the circuit, allowing for accurate construction of discrete

voltage steps. Although flying capacitor multi-level converters present challenges in capacitor voltage balancing and operational complexity, their performance benefits make them highly suitable for applications demanding high voltage, high power, and improved efficiency. These topologies effectively minimize harmonic distortion, rendering them attractive for integration into industrial power systems, electric vehicle powertrains, energy storage solutions, and renewable energy installations. Nonetheless, issues such as maintaining voltage equilibrium across capacitors, increased complexity of the control system, and higher implementation costs remain significant considerations. Progress in semiconductor devices and sophisticated control techniques is projected to improve the feasibility and widespread deployment of flying capacitor multi-level DC-DC converters in next-generation power electronic systems.

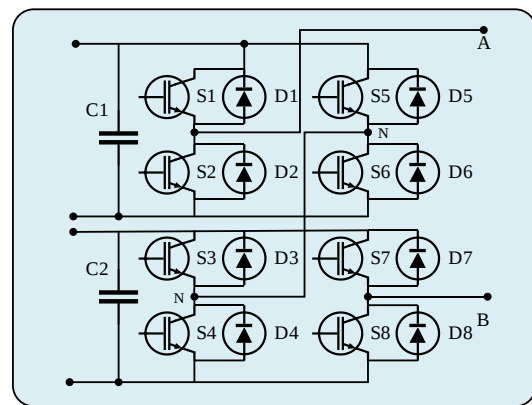


Fig.20. Architecture of cascaded multi-level DC-DC converter system [94]

The cascaded multi-level DC-DC converter topology, depicted in Fig. 20, consists of multiple H-bridge converter units connected in sequence, each supplied by a distinct power source. This schematic is adapted from the circuit diagrams in the referenced studies shown below the figure. This architecture represents an advanced methodology that employs several converter stages in series to achieve elevated output voltage levels while simultaneously reducing harmonic distortion and enhancing overall efficiency. Within cascaded multi-level systems, each converter module contributes a fraction of the total primary voltage by either stepping it up or down. These individual voltage increments are then combined through serial connection to synthesize a high-voltage output. Such converters are well-suited for high-power applications demanding substantial voltage conversion, superior efficiency, reduced harmonic distortion, and operational flexibility. These converter types excel in high-power scenarios requiring significant voltage transformation, enhanced efficiency, minimized harmonic content, and versatile operational capabilities. The modular nature of cascaded converters facilitates the management of high voltages by dividing the voltage transformation across multiple stages, each operating at a lower voltage level. To ensure optimal performance, challenges related to isolation, thermal management, synchronization, and electromagnetic interference mitigation must be effectively addressed during the design process. Progressive breakthroughs in semiconductor manufacturing and advanced control frameworks are anticipated to establish

cascaded multi-level DC-DC converter architectures as integral elements within emerging power conversion technologies, with particular relevance to sectors such as electric transportation, sustainable energy integration, uninterrupted power supply systems, and heavy industrial power infrastructure. Table I presents a comparative analysis of the conventional DC-DC converter topologies discussed in this study, evaluated based on key performance indicators, including efficiency, cost, circuit complexity, application suitability, bidirectional capability, and voltage gain [10], [14], [102], [103].

Multi-level converter systems play a significant role in the advancement of high-voltage and high-efficiency power conversion infrastructure. By layering voltage steps, they successfully reduce switching stress and suppress harmonic content, which are crucial in demanding power applications. Still, their elevated design intricacy, component count, and control synchronization requirements can hinder widespread deployment, especially in cost-critical or space-constrained environments. Future research is expected to center on modularization, reliability, and simplified control logic to unlock their broader potential in sustainable energy platforms.

TABLE I
COMPARATIVE EVALUATION OF DC-DC CONVERTER TOPOLOGIES

Topology	Efficiency	Cost	Complexity	Application Suitability	Bidirectional Capability	Voltage Gain
Buck (Step-Down)	High	Low	Low	Battery chargers, regulated low-voltage loads	Limited	Step-down ($V_{out} < V_{in}$)
Boost (Step-Up)	Medium-High	Low	Low	PV converters, LED drivers	Moderate	Step-up ($V_{out} > V_{in}$)
Buck-Boost	Moderate	Moderate	Moderate	EV powertrains, portable electronics	Yes	Step-up/down
Cuk	Moderate	Moderate	High	Audio systems, power factor correction	Yes	Negative output, flexible gain
SEPIC (Single-Ended Primary Inductor Converter)	Moderate	High	High	Automotive systems, renewable energy integration	Yes	Step-up/down (positive output)
Zeta	Moderate	High	High	LED lighting, constant current applications	Limited	Step-up/down
Forward	High	Moderate	Moderate	Isolated telecom and embedded power supplies	No	Fixed-ratio step-down
Flyback	Moderate	Low	Moderate	Small SMPS, low-power instrumentation	No	Wide gain range
Push-Pull	High	Moderate	High	Medium power supplies, symmetrical loads	Yes	High gain (with center-tap)
Half-Bridge	High	Medium-High	High	Medium-power converters, motor drives	Yes	Medium-to-high gain
Full-Bridge	High	High	Very High	High-voltage inverters, HVDC systems	Yes	High voltage gain
Single Active Bridge	High	High	High	Power transfer, battery management systems	Yes	Isolated, controllable gain
Dual Active Bridge	High	High	Very High	Bidirectional energy storage, fast EV chargers	Strong	Wide gain range
Boost Half-Bridge	High	High	High	High-voltage DC distribution	Yes	Step-up with isolation
Resonant (LLC, Resonant Boost, Hybrid Resonant, etc.)	Very High	High	Very High	Data centers, EV charging stations	Yes	Wide gain (frequency-dependent)

IV. DISCUSSION AND FUTURE DIRECTIONS

Despite the fact that DC-DC converter technologies have been the subject of extensive study, the majority of these studies focus on optimal operating conditions, often overlooking real-world issues such as environmental unpredictability, long-term reliability, and fault tolerance. Furthermore, it is difficult to make meaningful comparisons and occasionally results in contradictory findings in the literature when studies lack defined assessment parameters, such as efficiency, cost, control complexity, EMI levels, and power density. A uniform multi-criteria assessment system should be established to bridge this gap and enable objective, consistent evaluation of various converter types. A novel categorization strategy based on functional modularity, control flexibility, and integration possibilities with digital and AI-assisted control systems may also provide a more comprehensive and modern viewpoint than

the conventional input-output voltage classifications. Future studies should concentrate on intelligent, adaptive control algorithms, modular converter architectures that work with hybrid energy systems, fault-tolerant designs, and ecologically friendly solutions. By moving forward in these areas, it will be easier to get over present obstacles and create converter designs that are more adaptable, dependable, and application-specific.

V. CONCLUSION

This study has provided a comprehensive analysis of DC-DC converter architectures, systematically classifying them into isolated and non-isolated categories. These converters have become indispensable components in modern power electronic systems due to their ability to regulate voltage with high precision and efficiency. The demand for compact, energy-efficient, and adaptable power conversion solutions is growing across various sectors, including industrial automation,

renewable energy integration, and consumer electronics, driven by the pursuit of higher performance and environmental sustainability. DC-DC converters play a pivotal role in minimizing energy dissipation, reducing thermal stress, and improving overall system reliability. Their applications span from smart electrical grids and electric vehicles to portable devices and sustainable energy platforms. In renewable energy systems, for example, they stabilize variable outputs from sources like photovoltaic panels and wind turbines, facilitating smooth and reliable power delivery.

Looking ahead, the evolution of DC-DC converter technologies is expected to be shaped by several key research directions. One significant trend is the adoption of wide-bandgap semiconductor devices, such as Gallium Nitride (GaN) and Silicon Carbide (SiC). These materials offer superior electrical characteristics, including higher switching frequencies, lower conduction losses, and better thermal performance, compared to traditional silicon-based devices, enabling the development of next-generation high-efficiency power converters. Another promising avenue lies in integrating artificial intelligence (AI) and machine learning (ML) techniques into converter control strategies. AI-assisted algorithms have the potential to optimize real-time performance, adapt to dynamic load conditions, improve fault detection, and enhance energy management in complex systems. Moreover, the increasing electrification of transportation systems presents new challenges and opportunities for the development of DC-DC converters. Electric vehicles (EVs) demand high power density, bidirectional operation, and robust thermal management. Future research should focus on designing converters tailored for on-board chargers, traction inverters, and battery management systems. Microgrids and distributed energy systems also present a fertile ground for innovation. The need for reliable, flexible, and intelligent power conversion solutions in these decentralized networks highlights the importance of programmable and interoperable converter architectures that can seamlessly interact with various sources and loads.

In conclusion, future developments in DC-DC converter technology are likely to be driven by the convergence of material science innovations, intelligent control systems, and application-specific demands. By advancing switching techniques, incorporating low-loss components, and leveraging AI-driven adaptability, DC-DC converters will continue to be central to the development of energy-efficient and sustainable power systems. Their role in shaping the future of electric mobility, renewable integration, and smart energy infrastructures remains both foundational and transformative.

ACKNOWLEDGMENT

This study is derived from the doctoral dissertation of Abdurrahim Erat.

REFERENCES

- [1] J. Chen, M.-K. Nguyen, Z. Yao, C. Wang, L. Gao, and G. Hu, "DC-DC Converters for Transportation Electrification: Topologies, Control, and Future Challenges," *IEEE Electr. Mag.*, vol. 9, no. 2, pp. 10–22, 2021, doi: 10.1109/MELE.2021.3070934.
- [2] T. Sutikno, A. S. Samosir, R. A. Aprilianto, H. S. Purnama, W. Arsadiando, and S. Padmanaban, "Advanced DC-DC converter topologies for solar energy harvesting applications: a review," *Clean Energy*, vol. 7, no. 3, pp. 555–570, Jun. 2023, doi: 10.1093/ce/zkad003.
- [3] M. F. Akhtar, S. R. S. Raihan, N. A. Rahim, M. N. Akhtar, and E. Abu Bakar, "Recent Developments in DC-DC Converter Topologies for Light Electric Vehicle Charging: A Critical Review," *Applied Sciences*, vol. 13, no. 3, 2023, doi: 10.3390/app13031676.
- [4] Z. W. Khan, H. Minxiao, C. Kai, L. Yang, and A. u. Rehman, "State of the Art DC-DC Converter Topologies for the Multi-Terminal DC Grid Applications: A Review," in *2020 IEEE International Conference on Power Electronics, Smart Grid and Renewable Energy (PESGRE2020)*, 2020, pp. 1–7, doi: 10.1109/PESGRE45664.2020.9070529.
- [5] J. Wang, B. Wang, L. Zhang, J. Wang, N. I. Shchurov, and B. V. Malozyomov, "Review of bidirectional DC-DC converter topologies for hybrid energy storage system of new energy vehicles," *Green Energy Intell. Transp.*, vol. 1, no. 2, p. 100010, 2022, doi: <https://doi.org/10.1016/j.geits.2022.100010>.
- [6] M. Abolghasemi, I. Soltani, M. Shivaie, and H. Vahedi, "Recent advances of step-up multi-stage DC-DC converters: A review on classifications, structures and grid applications," *Energy Reports*, vol. 13, pp. 3050–3081, 2025, doi: <https://doi.org/10.1016/j.egyr.2025.02.025>.
- [7] A. Tuluhong, Z. Xu, Q. Chang, and T. Song, "Recent Developments in Bidirectional DC-DC Converter Topologies, Control Strategies, and Applications in Photovoltaic Power Generation Systems: A Comparative Review and Analysis," *Electronics*, vol. 14, no. 2, 2025, doi: 10.3390/electronics14020389.
- [8] M. Mezouari, M. Megrini, and A. Gaga, "High efficiency DC-DC converter for renewable energy integration and energy storage applications: A review of topologies and control strategies," *Control Eng. Pract.*, vol. 162, p. 106371, 2025, doi: <https://doi.org/10.1016/j.conengprac.2025.106371>.
- [9] F. Mumtaz, N. Z. Yahaya, S. T. Meraj, B. Singh, R. Kannan, and O. Ibrahim, "Review on non-isolated DC-DC converters and their control techniques for renewable energy applications," *Ain Shams Eng. J.*, vol. 12, no. 4, pp. 3747–3763, 2021.
- [10] A. Amir, A. Amir, H. S. Che, A. Elkhateb, and N. Abd Rahim, "Comparative analysis of high voltage gain DC-DC converter topologies for photovoltaic systems," *Renew. energy*, vol. 136, pp. 1147–1163, 2019.
- [11] S. Dahale, A. Das, N. M. Pindoriya, and S. Rajendran, "An overview of DC-DC converter topologies and controls in DC microgrid," in *2017 7th International Conference on Power Systems (ICPS)*, 2017, pp. 410–415.
- [12] A. Lavanya, J. D. Navamani, K. Vijayakumar, and R. Rakesh, "Multi-input DC-DC converter topologies-a review," in *2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT)*, 2016, pp. 2230–2233.
- [13] M. Parvez, A. T. Pereira, N. Ertugrul, N. H. E. Weste, D. Abbott, and S. F. Al-Sarawi, "Wide bandgap DC-DC converter topologies for power applications," *Proc. IEEE*, vol. 109, no. 7, pp. 1253–1275, 2021.
- [14] S. A. Gorji, H. G. Sahebi, M. Ektesabi, and A. B. Rad, "Topologies and control schemes of bidirectional DC-DC power converters: An overview," *IEEE Access*, vol. 7, pp. 117997–118019, 2019.
- [15] F. L. Luo and H. Ye, *Advanced dc/dc converters*. crc Press, 2016.
- [16] S. Ikeda and F. Kurokawa, "Isolated and wide input ranged boost full bridge DC-DC converter with low loss active snubber," in *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2017, pp. 2213–2218.
- [17] F. Krismer and J. W. Kolar, "Efficiency-optimized high-current dual active bridge converter for automotive applications," *IEEE Trans. Ind. Electron.*, vol. 59, no. 7, pp. 2745–2760, 2011.
- [18] A. Gnanasravanan and M. Rajaram, "Dynamic response analysis and output voltage control of asymmetric half bridge DC-DC converter for low voltage applications," *Int. J. Electr. Power Energy Syst.*, vol. 43, no. 1, pp. 774–778, 2012.
- [19] A. G. Saravanan and M. Rajaram, "Fuzzy controller for dynamic performance improvement of a half-bridge isolated DC-DC converter," *Neurocomputing*, vol. 140, pp. 283–290, 2014.
- [20] R. W. A. A. De Doncker, D. M. Divan, and M. H. Kheraluwala, "A three-phase soft-switched high-power-density DC/DC converter for high-power applications," *IEEE Trans. Ind. Appl.*, vol. 27, no. 1, pp. 63–73, 1991.
- [21] S. Shao, H. Chen, X. Wu, J. Zhang, and K. Sheng, "Circulating current and ZVS-on of a dual active bridge DC-DC converter: A review," *Ieee Access*, vol. 7, pp. 50561–50572, 2019.
- [22] A. Kumar, A. H. Bhat, and P. Agarwal, "Review and comparative

- analysis of dual active bridge isolated DC to DC converter with different control techniques," *Int. J. Ind. Electron. Drives*, vol. 4, no. 2, pp. 69–84, 2018.
- [23] Q. Bu, H. Wen, J. Wen, Y. Hu, and Y. Du, "Transient DC bias elimination of dual-active-bridge DC–DC converter with improved triple-phase-shift control," *IEEE Trans. Ind. Electron.*, vol. 67, no. 10, pp. 8587–8598, 2019.
- [24] J.-Y. Lee, H.-S. Kim, and J.-H. Jung, "Enhanced dual-active-bridge DC–DC converter for balancing bipolar voltage level of DC distribution system," *IEEE Trans. Ind. Electron.*, vol. 67, no. 12, pp. 10399–10409, 2019.
- [25] L. Chen, S. Shao, Q. Xiao, L. Tarisciotti, P. W. Wheeler, and T. Dragičević, "Model predictive control for dual-active-bridge converters supplying pulsed power loads in naval DC micro-grids," *IEEE Trans. Power Electron.*, vol. 35, no. 2, pp. 1957–1966, 2019.
- [26] S. Zengin and M. Boztepe, "A novel current modulation method to eliminate low-frequency harmonics in single-stage dual active bridge AC–DC converter," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1048–1058, 2019.
- [27] H. Qin and J. W. Kimball, "Generalized Average Modeling of Dual Active Bridge DC–DC Converter," *IEEE Trans. Power Electron.*, vol. 27, no. 4, pp. 2078–2084, 2012, doi: 10.1109/TPEL.2011.2165734.
- [28] R. Jha, M. Forato, S. Prakash, H. Dashora, and G. Buja, "An analysis-supported design of a single active bridge (SAB) converter," *Energies*, vol. 15, no. 2, p. 666, 2022.
- [29] D. Vinnikov, A. Chub, E. Liivik, F. Blaabjerg, and Y. Siwakoti, "Boost half-bridge DC-DC converter with reconfigurable rectifier for ultra-wide input voltage range applications," in *2018 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2018, pp. 1528–1532.
- [30] H.-S. Lee, B. Kang, W.-S. Kim, and S.-J. Yoon, "Reduction of input voltage/current ripples of boost half-bridge DC-DC converter for photovoltaic micro-inverter," *Sol. Energy*, vol. 188, pp. 1084–1101, 2019.
- [31] C.-E. Kim, G.-W. Moon, and S.-K. Han, "Voltage Doubler Rectified Boost-Integrated Half Bridge (VDRBHB) Converter for Digital Car Audio Amplifiers," *IEEE Trans. Power Electron.*, vol. 22, no. 6, pp. 2321–2330, 2007, doi: 10.1109/TPEL.2007.904222.
- [32] H.-S. Lee, H.-J. Choe, and J.-J. Yun, "Improved Boost Half-Bridge DC–DC Converter for DC Distribution Networks," *J. Electr. Eng. Technol.*, vol. 17, no. 5, pp. 2889–2898, 2022, doi: 10.1007/s42835-022-01107-1.
- [33] C. Yoon, J. Kim, and S. Choi, "Multiphase DC–DC Converters Using a Boost-Half-Bridge Cell for High-Voltage and High-Power Applications," *IEEE Trans. Power Electron.*, vol. 26, no. 2, pp. 381–388, 2011, doi: 10.1109/TPEL.2010.2060498.
- [34] H.-S. Lee and J.-J. Yun, "Quasi-Resonant Voltage Doubler With Snubber Capacitor for Boost Half-Bridge DC–DC Converter in Photovoltaic Micro-Inverter," *IEEE Trans. Power Electron.*, vol. 34, no. 9, pp. 8377–8388, 2019, doi: 10.1109/TPEL.2018.2883535.
- [35] K. Fathy, H. W. Lee, T. Mishima, and M. Nakaoka, "Boost-half bridge single power stage PWM DC-DC converter for small scale fuel cell stack," in *2006 IEEE International Power and Energy Conference*, 2006, pp. 426–431.
- [36] V. A. G. Cunha, A. O. C. Neto, G. B. Lima, and L. C. G. Freitas, "A Bridgeless Boost Half Bridge DC-DC Converter for Electrical and Hybrid Vehicle Applications," in *2019 IEEE PES Innovative Smart Grid Technologies Conference - Latin America (ISGT Latin America)*, 2019, pp. 1–6, doi: 10.1109/ISGT-LA.2019.8895388.
- [37] C. Yoon, J. Kim, and S. Choi, "Multiphase DC–DC converters using a boost-half-bridge cell for high-voltage and high-power applications," *IEEE Trans. Power Electron.*, vol. 26, no. 2, pp. 381–388, 2010.
- [38] B. Su, T. Yang, Z. Lu, and D. Xu, "Soft-switching dual forward DC/DC converters employing secondary side control," in *2009 IEEE Energy Conversion Congress and Exposition*, 2009, pp. 1855–1859.
- [39] K.-H. Cheng, C.-F. Hsu, C.-M. Lin, T.-T. Lee, and C. Li, "Fuzzy-neural sliding-mode control for DC–DC converters using asymmetric Gaussian membership functions," *IEEE Trans. Ind. Electron.*, vol. 54, no. 3, pp. 1528–1536, 2007.
- [40] R. Kanthimathi and J. Kamala, "Analysis of different flyback converter topologies," in *2015 international conference on industrial instrumentation and control (ICIC)*, 2015, pp. 1248–1252.
- [41] M. C. Taneri, N. Genc, and A. Mamizadeh, "Analyzing and comparing of variable and constant switching frequency flyback DC-DC Converter," in *2019 4th International Conference on Power Electronics and their Applications (ICPEA)*, 2019, pp. 1–5.
- [42] J.-W. Yang and H.-L. Do, "Soft-switching dual-flyback DC–DC converter with improved efficiency and reduced output ripple current," *IEEE Trans. Ind. Electron.*, vol. 64, no. 5, pp. 3587–3594, 2017.
- [43] Z. Zhang, M. Liao, D. Jiang, X. Yang, and S. Li, "High step-up isolated forward-flyback DC/DC converter based on resonance with pulse frequency modulation," *J. Power Electron.*, vol. 21, no. 2, pp. 483–493, 2021, doi: 10.1007/s43236-020-00186-5.
- [44] V. Parkash, P. Kumar, P. Sharma, and G. Sapra, "Design and implementation of flyback converter as high voltage power supply for nanofibers production," *Mater. Today Proc.*, vol. 45, pp. 5285–5291, 2021.
- [45] Y. Wu, Y. Huangfu, R. Ma, A. Ravey, and D. Chrenko, "A strong robust DC-DC converter of all-digital high-order sliding mode control for fuel cell power applications," *J. Power Sources*, vol. 413, pp. 222–232, 2019.
- [46] R. W. Erickson, "DC–DC power converters," *Wiley Encycl. Electr. Electron. Eng.*, 2001.
- [47] K.-H. Chen and T.-J. Liang, "Design of Quasi-resonant flyback converter control IC with DCM and CCM operation," in *2014 International Power Electronics Conference (IPEC-Hiroshima 2014-ECCE ASIA)*, 2014, pp. 2750–2753.
- [48] M. Salem *et al.*, "Three-phase series resonant DC-DC boost converter with double LLC resonant tanks and variable frequency control," *IEEE Access*, vol. 8, pp. 22386–22399, 2020.
- [49] M. Salem, A. Jusoh, N. R. N. Idris, H. S. Das, and I. Alhamrouni, "Resonant power converters with respect to passive storage (LC) elements and control techniques—An overview," *Renew. Sustain. Energy Rev.*, vol. 91, pp. 504–520, 2018.
- [50] F. Alaql and I. Batarseh, "Review and comparison of resonant DC-DC converters for wide-output voltage range applications," in *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2020, pp. 1197–1203.
- [51] X. Zhao *et al.*, "A high-efficiency hybrid series resonant DC-DC converter with boost converter as secondary for photovoltaic applications," in *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2015, pp. 5462–5467, doi: 10.1109/ECCE.2015.7310428.
- [52] X. Zhao, L. Zhang, R. Born, and J.-S. Lai, "A High-Efficiency Hybrid Resonant Converter With Wide-Input Regulation for Photovoltaic Applications," *IEEE Trans. Ind. Electron.*, vol. 64, no. 5, pp. 3684–3695, 2017, doi: 10.1109/TIE.2017.2652340.
- [53] G. I. Vacheva, K. Genev, and N. L. Hinov, "Modeling and Simulation of DC-DC Push-Pull Converter," in *2022 57th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST)*, 2022, pp. 1–4, doi: 10.1109/ICEST55168.2022.9828584.
- [54] Q. Wu, Q. Wang, J. Xu, and L. Xiao, "A wide load range ZVS push–pull DC/DC converter with active clamped," *IEEE Trans. Power Electron.*, vol. 32, no. 4, pp. 2865–2875, 2016.
- [55] S. Musumeci and S. Di Mauro, "Low voltage single fuel cell interface by Push-Pull converter: A case of study," in *2017 6th International Conference on Clean Electrical Power (ICCEP)*, 2017, pp. 541–548.
- [56] S. Bal, A. K. Rathore, and D. Srinivasan, "Naturally clamped snubberless soft-switching bidirectional current-fed three-phase push–pull DC/DC converter for DC microgrid application," *IEEE Trans. Ind. Appl.*, vol. 52, no. 2, pp. 1577–1587, 2015.
- [57] R. Kalpana, "Configurations of modular push-pull buck dc-dc converters for 12KW telecom SMPS and its design," in *2016 Biennial International Conference on Power and Energy Systems: Towards Sustainable Energy (PESTSE)*, 2016, pp. 1–7.
- [58] H. Zenk, "Comparison of the Performance of Photovoltaic Power Generation-Consumption System with Push-Pull Converter under the Effect of Five Different Types of Controllers," *Int. J. Photoenergy*, vol. 2019, no. 1, p. 3810970, 2019.
- [59] H. Givi, E. Farjah, and T. Ghanbari, "A comprehensive monitoring system for online fault diagnosis and aging detection of non-isolated DC–DC converters' components," *IEEE Trans. Power Electron.*, vol. 34, no. 7, pp. 6858–6875, 2018.
- [60] S. N. Singh, "Selection of non-isolated DC-DC converters for solar photovoltaic system," *Renew. Sustain. Energy Rev.*, vol. 76, pp. 1230–1247, 2017.
- [61] T. K. Nizami and C. Mahanta, "An intelligent adaptive control of DC–DC buck converters," *J. Franklin Inst.*, vol. 353, no. 12, pp. 2588–2613, 2016.
- [62] B. B. Naik and A. J. Mehta, "Sliding mode controller with modified sliding function for DC-DC Buck Converter," *ISA Trans.*, vol. 70, pp. 279–287, 2017.

- [63] C. Nan, R. Ayyanar, and Y. Xi, "A 2.2-MHz active-clamp buck converter for automotive applications," *IEEE Trans. Power Electron.*, vol. 33, no. 1, pp. 460–472, 2017.
- [64] J. Wang, J. Rong, and L. Yu, "Dynamic prescribed performance sliding mode control for DC–DC buck converter system with mismatched time-varying disturbances," *ISA Trans.*, vol. 129, pp. 546–557, 2022.
- [65] W. Chen, Z. Ge, Y. Cheng, H. Du, Q. Du, and M. Yu, "Current-constrained finite-time control algorithm for DC–DC buck converter," *J. Franklin Inst.*, vol. 358, no. 18, pp. 9467–9482, 2021.
- [66] T. K. Nizami, A. Chakravarty, and C. Mahanta, "Time bound online uncertainty estimation based adaptive control design for DC–DC buck converters with experimental validation," *IFAC J. Syst. Control*, vol. 15, p. 100127, 2021.
- [67] İ. Yazici, "Robust voltage-mode controller for DC–DC boost converter," *IET Power Electron.*, vol. 8, no. 3, pp. 342–349, 2015.
- [68] F. L. Tofoli, D. de C. Pereira, W. Josias de Paula, and D. de S. Oliveira Junior, "Survey on non-isolated high-voltage step-up dc–dc topologies based on the boost converter," *IET power Electron.*, vol. 8, no. 10, pp. 2044–2057, 2015.
- [69] T. K. Nizami and A. Chakravarty, "Neural network integrated adaptive backstepping control of DC–DC boost converter," *IFAC-PapersOnLine*, vol. 53, no. 1, pp. 549–554, 2020.
- [70] S. Vadi, F. B. Gurbuz, S. Sagioglu, and R. Bayindir, "Optimization of pi based buck-boost converter by particle swarm optimization algorithm," in *2021 9th International Conference on Smart Grid (icSmartGrid)*, 2021, pp. 295–301.
- [71] K. Prag, M. Woolway, and T. Celik, "Data-driven model predictive control of DC-to-DC buck-boost converter," *IEEE Access*, vol. 9, pp. 101902–101915, 2021.
- [72] N. Rana and S. Banerjee, "Interleaved tri-state buck-boost converter with fast transient response and lower ripple," in *2019 IEEE Transportation Electrification Conference (ITEC-India)*, 2019, pp. 1–5.
- [73] N. Rana, S. Banerjee, S. K. Giri, A. Trivedi, and S. S. Williamson, "Modeling, analysis and implementation of an improved interleaved buck-boost converter," *IEEE Trans. Circuits Syst. II Express Briefs*, vol. 68, no. 7, pp. 2588–2592, 2021.
- [74] E. Babaei, M. E. S. Mahmoodieh, and H. M. Mahery, "Operational modes and output-voltage-ripple analysis and design considerations of buck–boost DC–DC converters," *IEEE Trans. Ind. Electron.*, vol. 59, no. 1, pp. 381–391, 2011.
- [75] K. Wang, D. Liu, and L. Wang, "The implementation of synergetic control for a DC–DC buck-boost converter," *Procedia Comput. Sci.*, vol. 199, pp. 900–907, 2022.
- [76] M. Martinez-Lopez, J. Moreno-Valenzuela, and W. He, "A robust nonlinear PI-type controller for the DC–DC buck–boost power converter," *ISA Trans.*, vol. 129, pp. 687–700, 2022.
- [77] S. Kumar, R. Kumar, and N. Singh, "Performance of closed loop SEPIC converter with DC–DC converter for solar energy system," in *2017 4th International Conference on Power, Control & Embedded Systems (ICPCES)*, 2017, pp. 1–6.
- [78] L. Kathi, A. Ayachit, D. K. Saini, A. Chadha, and M. K. Kazimierzczuk, "Open-loop small-signal modeling of Cuk DC–DC converter in CCM by circuit-averaging technique," in *2018 IEEE Texas Power and Energy Conference (TPEC)*, 2018, pp. 1–6.
- [79] B. P. Mokal and K. Vadirajacharya, "Extensive modeling of DC–DC Cuk converter operating in continuous conduction mode," in *2017 International Conference on Circuit, Power and Computing Technologies (ICCPCT)*, 2017, pp. 1–5.
- [80] M. Verma and S. S. Kumar, "Hardware design of sepic converter and its analysis," in *2018 International Conference on Current Trends towards Converging Technologies (ICCTCT)*, 2018, pp. 1–4.
- [81] S. Sivakumar, M. J. Sathik, P. S. Manoj, and G. Sundararajan, "An assessment on performance of DC–DC converters for renewable energy applications," *Renew. Sustain. Energy Rev.*, vol. 58, pp. 1475–1485, 2016.
- [82] M. B. Ferrera, S. P. Litran, E. D. Aranda, and J. M. A. Marquez, "A converter for bipolar DC link based on SEPIC–Cuk combination," *IEEE Trans. Power Electron.*, vol. 30, no. 12, pp. 6483–6487, 2015.
- [83] J. Marjani, A. Imani, A. Hekmati, and E. Afjei, "A new dual output DC–DC converter based on SEPIC and Cuk converters," in *2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, 2016, pp. 946–950.
- [84] A. H. R. Rosa, L. M. F. Morais, G. O. Fortes, and S. I. S. Júnior, "Practical considerations of nonlinear control techniques applied to static power converters: A survey and comparative study," *Int. J. Electr. Power Energy Syst.*, vol. 127, p. 106545, 2021.
- [85] R. K. Pachauri and Y. K. Chauhan, "Modeling and simulation analysis of PV fed Cuk, Sepic, Zeta and Luo DC–DC converter," in *2016 IEEE 1st international conference on power electronics, intelligent control and energy systems (ICPEICES)*, 2016, pp. 1–6.
- [86] K. Manikandan, A. Sivabalan, R. Sundar, and P. Surya, "A study of landsman, sepic and zeta converter by particle swarm optimization technique," in *2020 6th international conference on advanced computing and communication systems (ICACCS)*, 2020, pp. 1035–1038.
- [87] M. Kaouane, A. Boukhefifa, and A. Cheriti, "Implementation of incremental-conductance MPPT algorithm in a photovoltaic conversion system based on DC–DC ZETA converter," in *2016 8th International Conference on Modelling, Identification and Control (ICMIC)*, 2016, pp. 612–617.
- [88] J. S. Alagesan, J. Gnanavadeivel, N. S. Kumar, and K. S. K. Veni, "Design and Simulation of Fuzzybased DC–DC Interleaved Zeta Converter for Photovoltaic Applications," in *2018 2nd International Conference on Trends in Electronics and Informatics (ICOEI)*, 2018, pp. 704–709.
- [89] M. M. Nishat, M. R. K. Shagor, H. Akter, S. A. Mim, and F. Faisal, "An optimal design of PID controller for DC–DC zeta converter using particle swarm optimization," in *2020 23rd International Conference on Computer and Information Technology (ICCIT)*, 2020, pp. 1–6.
- [90] A. Raj, S. R. Arya, and J. Gupta, "Solar PV array-based DC–DC converter with MPPT for low power applications," *Renew. Energy Focus*, vol. 34, pp. 109–119, 2020.
- [91] H. Sarkawi, Y. Ohta, and P. Rapisarda, "On the switching control of the DC–DC zeta converter operating in continuous conduction mode," *IET Control Theory Appl.*, vol. 15, no. 9, pp. 1185–1198, 2021.
- [92] N. Vosoughi, M. Abbasi, E. Abbasi, and M. Sabahi, "A Zeta-based switched-capacitor DC–DC converter topology," *Int. J. Circuit Theory Appl.*, vol. 47, no. 8, pp. 1302–1322, 2019.
- [93] R. F. Rajakumari and M. S. Ramkumar, "Design considerations and performance analysis based on ripple factors and switching loss for converter techniques," *Mater. Today Proc.*, vol. 37, pp. 2681–2686, 2021.
- [94] N. Ghasemi, F. Zare, C. Langton, and A. Ghosh, "A new unequal DC link voltage configuration for a single phase multilevel converter to reduce low order harmonics," in *Proceedings of the 2011 14th European Conference on Power Electronics and Applications*, 2011, pp. 1–9.
- [95] S. Du, B. Wu, N. R. Zargari, and Z. Cheng, "A flying-capacitor modular multilevel converter for medium-voltage motor drive," *IEEE Trans. Power Electron.*, vol. 32, no. 3, pp. 2081–2089, 2016.
- [96] S. Qin, Y. Lei, Z. Ye, D. Chou, and R. C. N. Pilawa-Podgurski, "A high-power-density power factor correction front end based on seven-level flying capacitor multilevel converter," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 7, no. 3, pp. 1883–1898, 2018.
- [97] C. B. Barth *et al.*, "Design and control of a GaN-based, 13-level, flying capacitor multilevel inverter," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 8, no. 3, pp. 2179–2191, 2019.
- [98] A. Marquez *et al.*, "Discontinuous-PWM method for multilevel N-cell cascaded H-bridge converters," *IEEE Trans. Ind. Electron.*, vol. 68, no. 9, pp. 7996–8005, 2020.
- [99] A. M. Alcaide *et al.*, "Variable-angle PS-PWM technique for multilevel cascaded H-bridge converters with large number of power cells," *IEEE Trans. Ind. Electron.*, vol. 68, no. 8, pp. 6773–6783, 2020.
- [100] Y. Koyama, Y. Nakazawa, H. Mochikawa, A. Kuzumaki, K. Sano, and N. Okada, "A transformerless 6.6-kV STATCOM based on a hybrid cascade multilevel converter using SiC devices," *IEEE Trans. Power Electron.*, vol. 33, no. 9, pp. 7411–7423, 2017.
- [101] H. D. Tafti, A. I. Maswood, G. Konstantinou, C. D. Townsend, P. Acuna, and J. Pou, "Flexible control of photovoltaic grid-connected cascaded H-bridge converters during unbalanced voltage sags," *IEEE Trans. Ind. Electron.*, vol. 65, no. 8, pp. 6229–6238, 2017.
- [102] F. A. Abbas, T. A. Abdul-Jabbar, A. A. Obed, A. Kersten, M. Kuder, and T. Weyh, "A Comprehensive Review and Analytical Comparison of Non-Isolated DC–DC Converters for Fuel Cell Applications," *Energies*, vol. 16, no. 8, 2023. doi: 10.3390/en16083493.
- [103] S. Pourjafar, H. Afshari, P. Mohseni, O. Husev, O. Matiushkin, and N. Shabbir, "Comprehensive Comparison of Isolated High Step-up DC–DC Converters for Low Power Application," *IEEE Open J. Power Electron.*, vol. 5, pp. 1149–1161, 2024, doi: 10.1109/OJPEL.2024.3433554.

BIOGRAPHIES



Abdurrahim Erat received the B.S. and M.S. degrees in Electrical and Electronics Engineering from the University of Niğde Ömer Halisdemir, Niğde, in 2013 and the University of Necmettin Erbakan, Konya, in 2018, respectively. He is currently in the dissertation phase of the PhD program at Gaziantep University, Department of Electrical and Electronics Engineering.

He has been working as a Lecturer in the Department of Electrical and Energy at Şırnak Vocational School, Şırnak University since 2019.



Ahmet Mete Vural received the B.S. and M.S. degrees in Electrical and Electronics Engineering from Gaziantep University, Gaziantep, in 1999 and 2001, respectively. He also received the Ph.D. degrees in Electrical and Electronics Engineering from the Çukurova University, Adana, in 2012. He works as

a full-time Professor in Electrical and Electronics Engineering Department in Gaziantep University, Gaziantep, Türkiye. He leads the Power Systems Research Group. His research interests include application of power electronics to power systems, multi-level converters, FACTS devices, power quality, microgrid, smartgrid, renewable energy, and energy storage.