A REVIEW OF TOPOLOGY OPTIMIZATION AND EFFICIENCY ENHANCEMENT OF A BIDIRECTIONAL NON-ISOLATED DC–DC CONVERTER FOR DC-COUPLED RENEWABLE SYSTEMS

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Abstract -*The rapid growth of renewable energy systems and energy storage technologies has significantly increased the demand for efficient power conversion interfaces. In DC-coupled renewable energy systems, bidirectional DC–DC converters play a critical role in enabling controlled power exchange between energy sources, storage units, and DC buses. Among various converter configurations, non-isolated bidirectional DC–DC converters have gained considerable attention due to their simple structure, compact size, lower cost, and high efficiency. However, challenges such as switching losses, voltage stress, limited voltage gain, and control complexity still affect their performance in renewable energy applications. This review paper presents a comprehensive analysis of topology optimization and efficiency enhancement techniques for bidirectional non-isolated DC–DC converters used in DC-coupled renewable systems. The study first discusses the operational principles and fundamental characteristics of bidirectional converters in renewable energy architectures. Subsequently, various converter topologies reported in the literature—including conventional buck–boost, interleaved converters, coupled-inductor based converters, switched-capacitor converters, and multi-port configurations—are systematically reviewed and compared. In addition, recent approaches for improving converter efficiency, such as soft-switching techniques, advanced modulation strategies, and the use of wide bandgap semiconductor devices, are critically examined. The paper also highlights key design challenges and identifies existing research gaps. Finally, future research directions are presented to guide the development of high-efficiency, compact, and reliable bidirectional converters for next-generation renewable energy systems.*

Key Words: Bidirectional DC–DC converter; Non-isolated converter; Renewable energy systems; DC-coupled microgrid; Topology optimization; Efficiency enhancement.

1. INTRODUCTION

1.1 Background

1.1.1 Increasing Penetration of Renewable Energy Sources

The global transition toward sustainable energy systems has led to a rapid increase in the integration of renewable energy sources such as photovoltaic (PV) systems, wind turbines, and energy storage technologies into modern electrical power networks. Concerns regarding climate change, depletion of fossil fuels, and environmental sustainability have accelerated the adoption of clean energy solutions worldwide. As a result, modern power systems are evolving from conventional centralized generation toward distributed and renewable-based architectures. Renewable sources, particularly solar PV and wind energy, are inherently variable and intermittent, which creates challenges in maintaining grid stability and reliable power supply. To address these issues, energy storage systems such as batteries and supercapacitors are increasingly incorporated into renewable energy systems to balance generation and load demand (Luo et al., 2015).

1.1.2 Importance of DC-Coupled Renewable Energy Systems

In recent years, DC-coupled renewable energy systems have gained significant attention due to their improved efficiency and simplified power conversion structure. In these systems, renewable energy sources and storage devices are directly connected to a common DC bus, reducing the number of conversion stages compared with conventional AC-coupled configurations. This architecture minimizes conversion losses, enhances overall system efficiency, and allows easier integration of distributed energy resources. Moreover, DC-coupled systems are particularly suitable for applications such as photovoltaic generation, battery storage integration, electric vehicle charging stations, and DC microgrids. Efficient energy transfer and power regulation in these systems depend heavily on the performance of power electronic converters that manage voltage levels and control energy flow between system components (Dragicevic et al., 2016).

1.1.3 Role of Power Electronic Converters in Renewable Energy Systems

Power electronic converters serve as the core interface between renewable energy sources, energy storage devices, and electrical loads in modern energy systems. These converters regulate voltage levels, control power flow, and ensure stable operation under varying generation and load conditions. In DC-coupled renewable systems, DC–DC converters are commonly employed to adapt voltage levels and enable bidirectional energy transfer between storage devices and the DC bus. Their performance directly influences system efficiency, reliability, and dynamic response. As renewable energy penetration increases, the demand for high-efficiency and flexible converter topologies has become increasingly important for achieving optimal system performance (Erickson and Maksimovic, 2001).

1.2 Role of Bidirectional DC–DC Converters in DC-Coupled Renewable Systems

1.2.1 Energy Storage Charging and Discharging Operation

Bidirectional DC–DC converters play a fundamental role in enabling controlled energy exchange between energy storage devices and DC distribution networks. These converters allow power to flow in two directions, enabling batteries or supercapacitors to both store excess energy and supply power when renewable generation is insufficient. During periods of high renewable generation, the converter operates in buck mode to charge the storage device by reducing the DC bus voltage to a suitable charging level. Conversely, during periods of low generation or high demand, the converter operates in boost mode to discharge stored energy back to the DC bus. This bidirectional capability ensures efficient utilization of renewable resources while maintaining energy balance within the system (Zhang et al., 2014).

1.2.2 Voltage Regulation and DC-Link Stability

Maintaining a stable DC-link voltage is critical for the reliable operation of DC-coupled renewable energy systems. Bidirectional converters contribute to this objective by dynamically adjusting power flow between storage devices and the DC bus. When sudden fluctuations occur in renewable generation or load demand, the converter rapidly responds by either absorbing or supplying power, thereby stabilizing the DC-link voltage. This capability enhances system resilience and prevents voltage instability that could otherwise affect connected loads or downstream converters. Effective control strategies for bidirectional converters therefore play an essential role in ensuring stable operation of renewable-based power systems (Tan et al., 2015).

1.2.3 Applications in Renewable and Electric Power Systems

Bidirectional DC–DC converters are widely used in several emerging energy applications. In photovoltaic-battery hybrid systems, these converters manage energy flow between PV arrays, battery storage, and DC loads. Similarly, in DC microgrids they enable energy sharing among distributed sources and storage units while maintaining system stability. Another major application is in electric vehicles, where bidirectional converters facilitate energy transfer between vehicle batteries and onboard power systems. In vehicle-to-grid (V2G) systems, these converters even allow electric vehicles to return stored energy to the grid when required. Due to their flexibility and high efficiency, bidirectional converters have become a key enabling technology for modern renewable energy infrastructures (Khaligh and Onar, 2017).

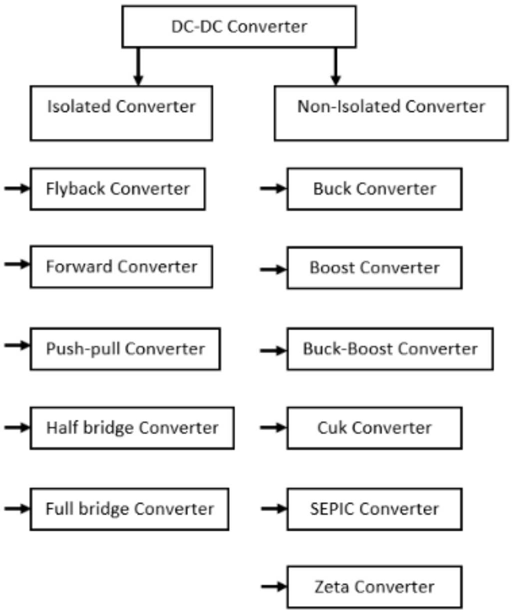

Figure-1: Classification of DC–DC Converter Topologies

1.3 Importance of Non-Isolated Converter Topologies

1.3.1 Structural Advantages of Non-Isolated Converters

Non-isolated DC–DC converters are widely adopted in renewable energy systems because of their relatively simple structure and high efficiency. Unlike isolated converters, they do not require a high-frequency transformer for galvanic isolation, which significantly reduces circuit complexity and component count. The absence of magnetic isolation components also leads to lower conduction and core losses, resulting in improved power conversion efficiency. Furthermore, the simpler architecture allows easier control implementation and reduces overall system cost, making non-isolated converters particularly attractive for many practical applications (Mohan, Undeland and Robbins, 2003).

1.3.2 Benefits in Size, Cost, and Power Density

Another important advantage of non-isolated converters is their compact size and high power density. Since they avoid bulky transformer components, these converters occupy less physical space and require fewer passive elements. This feature is particularly beneficial in applications where space and weight are critical design considerations, such as electric vehicles, portable energy systems, and distributed renewable installations. Additionally, the reduced number of components lowers manufacturing costs and simplifies system integration. As a result, non-isolated bidirectional converters are widely used in low- and medium-power renewable energy applications where isolation is not mandatory (Hart, 2011).

1.3.3 Suitability for Renewable Energy Integration

Due to their high efficiency, compact design, and cost-effectiveness, non-isolated bidirectional converters are well suited for renewable energy integration. These converters enable efficient energy exchange between renewable generation sources and energy storage systems while maintaining stable system operation. They are commonly employed in PV-battery hybrid systems, DC microgrids, and electric vehicle energy management systems. However, challenges such as voltage gain limitations, switching losses, and component stress still remain in conventional topologies. Consequently, ongoing research focuses on optimizing converter topologies and improving efficiency to meet the performance requirements of modern renewable energy systems (Emadi, Khaligh and Rivetta, 2006).

2. ARCHITECTURE OF DC-COUPLED RENEWABLE ENERGY SYSTEMS

2.1 Structure of DC-Coupled Renewable Energy Systems

2.1.1 Configuration of Renewable Sources and Power Conversion Interfaces

DC-coupled renewable energy systems are designed to integrate multiple energy sources and storage units through a common DC distribution network. In such architectures, renewable generation units such as photovoltaic (PV) arrays and wind energy systems are connected to a central DC bus through dedicated DC–DC converters that regulate voltage levels and ensure efficient power transfer. The DC bus acts as an intermediate platform where generated power, stored energy, and load demand are coordinated. An inverter is typically connected to the DC bus to supply AC loads or to interface with the utility grid. Compared with conventional AC-coupled systems, DC-coupled configurations reduce the number of conversion stages because many renewable sources inherently produce DC power. This reduction minimizes conversion losses and improves overall system efficiency while simplifying system control and integration (Guerrero et al., 2013).

2.1.2 Integration of Photovoltaic Systems and Energy Storage

In DC-coupled systems, photovoltaic arrays are usually connected through DC–DC converters that perform maximum power point tracking (MPPT) to extract the maximum available solar energy under varying irradiance conditions. The energy produced by PV modules is then supplied to the DC bus, where it can be used to power loads, charge energy storage devices, or be exported to the grid through an inverter interface. Energy storage systems such as batteries are integrated with the DC bus using bidirectional DC–DC converters that regulate charging and discharging processes. This configuration allows flexible power management and ensures that excess renewable energy can be stored for later use. Consequently, DC-coupled architectures are increasingly used in applications such as microgrids, renewable charging stations, and distributed power systems due to their high efficiency and adaptability (Justo et al., 2013).

2.1.3 Importance of Efficient Power Conversion in Energy Management

Efficient power conversion plays a crucial role in the performance of DC-coupled renewable systems. Since renewable sources often operate under fluctuating environmental conditions, power converters must efficiently regulate voltage levels and manage energy flow between different system components. High-efficiency converters reduce energy losses, improve system reliability, and increase the overall utilization of renewable resources. Additionally, advanced converter control strategies help maintain DC bus voltage stability while accommodating dynamic load and generation conditions. Therefore, the design and optimization of power electronic converters remain a key aspect in improving the performance and scalability of DC-coupled renewable energy architectures (Liserre, Sauter and Hung, 2010).

2.2 Role of Energy Storage Systems in DC Networks

2.2.1 Integration of Battery Energy Storage Systems

Energy storage systems are essential components in renewable energy networks because they help mitigate the intermittency associated with renewable generation. Battery energy storage systems are commonly integrated into DC-coupled architectures to store excess energy during periods of high renewable generation and supply power during periods of low generation or high demand. Lithium-ion batteries, in particular, are widely used due to their high energy density, long cycle life, and relatively high efficiency. In DC networks, batteries are connected through bidirectional DC–DC converters that regulate charging currents and ensure safe operation under varying load conditions. This integration improves system reliability and allows more effective utilization of renewable energy resources (Divya and Østergaard, 2009).

2.2.2 Use of Supercapacitors for Dynamic Energy Support

In addition to batteries, supercapacitors are increasingly used in renewable energy systems to provide rapid energy buffering and improve dynamic performance. Supercapacitors possess high power density and can respond quickly to sudden power fluctuations, making them suitable for applications that require fast transient response. When integrated into DC networks, supercapacitors can absorb short-term power surges and stabilize voltage variations caused by sudden load changes or renewable generation fluctuations. They are often used in hybrid energy storage systems together with batteries, where batteries provide long-term energy storage while supercapacitors handle high-power transient events (Burke, 2000).

2.2.3 Role of Bidirectional Converters in Energy Exchange

The integration of energy storage devices within DC networks requires efficient bidirectional power converters to regulate energy exchange between storage units and the DC bus. These converters enable controlled charging and discharging processes while maintaining stable system voltage levels. During charging operation, excess renewable energy is directed toward storage devices, whereas during discharging operation stored energy is supplied back to the DC network to support loads. Proper control of these converters ensures optimal utilization of storage capacity and enhances the flexibility of renewable energy systems. Consequently, bidirectional DC–DC converters are considered essential components in modern DC microgrid architectures (Bidram and Davoudi, 2012).

2.3 Power Flow Control in DC-Coupled Systems

2.3.1 Charging Mode Operation (Buck Mode)

In DC-coupled renewable systems, charging mode occurs when excess energy from renewable sources is available and needs to be stored in energy storage devices. During this mode, the bidirectional DC–DC converter operates in buck configuration to step down the DC bus voltage to a suitable level required for battery charging. The converter regulates the charging current to ensure safe and efficient energy storage while preventing battery overcharging. Proper control strategies are necessary to maintain stable charging conditions and to optimize battery life. Charging operation typically occurs during periods of high solar irradiation or low load demand when surplus renewable energy is available (Chen et al., 2012).

2.3.2 Discharging Mode Operation (Boost Mode)

Discharging mode takes place when renewable generation is insufficient to meet load demand or when additional power is required to stabilize the DC bus voltage. In this situation, the bidirectional converter operates in boost mode, increasing the storage device voltage to match the DC bus voltage level. Stored energy from batteries or other storage devices is therefore transferred to the DC network to supply loads or support system stability. The boost operation ensures continuous power availability and enhances system reliability during fluctuations in renewable generation (Kjaer, Pedersen and Blaabjerg, 2005).

2.3.3 Dynamic Energy Management in Renewable Systems

The combination of charging and discharging modes allows DC-coupled renewable systems to achieve dynamic energy management. By continuously monitoring generation conditions, load demand, and storage levels, the control system determines the appropriate operating mode of the bidirectional converter. This dynamic control strategy enables optimal utilization of renewable resources, reduces power fluctuations, and improves the stability of the DC bus. As renewable penetration increases, effective power flow control becomes increasingly important for ensuring reliable and efficient operation of DC-based power systems (Lasseter and Paigi, 2004).

3. FUNDAMENTALS OF BIDIRECTIONAL NON-ISOLATED DC–DC CONVERTERS

3.1 Operating Principles of Bidirectional Converters

3.1.1 Concept of Bidirectional Power Flow

Bidirectional DC–DC converters are power electronic interfaces that enable energy transfer in two directions between two DC sources or between a DC source and an energy storage system. Unlike conventional unidirectional converters, which allow power flow only from the input to the output, bidirectional converters are designed to support both charging and discharging operations. This capability is essential in applications where energy storage devices such as batteries or supercapacitors must both absorb and supply energy depending on system conditions. The fundamental concept of bidirectional operation is based on controlling semiconductor switches so that the converter can reverse the direction of current flow while maintaining regulated voltage levels. As a result, these converters are widely used in renewable energy systems, electric vehicles, and DC microgrids where flexible energy management is required (Kazimierczuk, 2016).

3.1.2 Switching Operation and Control Mechanism

The operation of bidirectional converters relies on high-frequency switching of semiconductor devices such as MOSFETs or IGBTs to regulate voltage and current. By appropriately controlling the duty cycle of switching signals, the converter can operate either in step-down or step-up mode depending on the direction of power flow. During switching operation, energy is temporarily stored in passive components such as inductors and capacitors before being transferred to the output side. Advanced control techniques are often implemented to ensure stable operation under varying load conditions and input voltage fluctuations. Effective switching control not only determines the direction of power flow but also influences converter efficiency, switching losses, and dynamic response characteristics (Rashid, 2014).

3.1.3 Importance in Energy Storage and Renewable Systems

Bidirectional converters are particularly important in renewable energy systems where energy storage devices must interact dynamically with generation sources and loads. For example, when renewable generation exceeds demand, the converter enables energy storage by directing power toward batteries or other storage devices. Conversely, when generation is insufficient, the stored energy can be supplied back to the system. This flexible energy exchange improves system stability, increases renewable energy utilization, and enhances overall power management. Consequently, bidirectional converters are considered fundamental components in modern DC-based energy infrastructures (Blaabjerg, Yang and Yang, 2017).

3.2 Basic Bidirectional Buck–Boost Converter

3.2.1 Structure of the Conventional Buck–Boost Converter

The bidirectional buck–boost converter represents one of the most commonly used non-isolated converter topologies due to its simple structure and flexible operation. The basic configuration typically consists of two active switches, an inductor, and filtering capacitors that facilitate energy transfer between two DC sources. In this topology, both switches are controlled in such a way that the converter can operate either as a buck converter or as a boost converter depending on the direction of power flow. The simplicity of this structure results in reduced component count, lower cost, and relatively straightforward control implementation, making it suitable for a wide range of low- and medium-power applications (Mohan, Undeland and Robbins, 2003).

3.2.2 Buck Mode Operation

When the converter operates in buck mode, power flows from the higher-voltage DC bus to the lower-voltage energy storage device. In this mode, the converter reduces the input voltage by controlling the duty cycle of the switching device. Energy is stored temporarily in the inductor during the switch-on interval and then transferred to the output during the switch-off interval. This operating mode is commonly used when charging batteries or other storage systems from a higher voltage DC bus, such as in photovoltaic energy storage applications (Erickson and Maksimovic, 2001).

3.2.3 Boost Mode Operation

In boost mode, the direction of power flow is reversed and energy is transferred from the lower-voltage storage device to the higher-voltage DC bus. During this operation, the inductor stores energy when the switch is turned on and releases it to the DC bus when the switch is turned off, thereby increasing the output voltage level. This mode is typically used when stored energy is required to support system loads or maintain DC bus voltage stability. Despite its advantages, the conventional bidirectional buck–boost converter may experience limitations such as high switching stress, increased conduction losses, and restricted voltage gain when operating under high power conditions (Zhang et al., 2014).

3.3 Key Performance Parameters

3.3.1 Voltage Conversion Ratio

The voltage conversion ratio is one of the most important parameters used to evaluate the performance of DC–DC converters. It represents the relationship between the output voltage and input voltage of the converter and determines the capability of the converter to adapt voltage levels within the system. A higher voltage conversion ratio allows the converter to support a wider range of operating conditions, which is particularly important in renewable energy applications where source voltages may vary significantly due to environmental conditions (Hart, 2011).

3.3.2 Efficiency and Power Losses

Efficiency is a critical factor in power converter design because it determines how effectively electrical energy is transferred from the input to the output. Converter efficiency is affected by various loss mechanisms including conduction losses in semiconductor devices, switching losses during transistor transitions, and losses in passive components such as inductors and capacitors. High-efficiency converters are essential in renewable energy systems because they minimize energy wastage and improve overall system performance (Krein, 1998).

3.3.3 Switching Loss and Power Density

Switching losses occur when semiconductor devices transition between on and off states during high-frequency operation. These losses increase with switching frequency and can significantly affect converter efficiency and thermal performance. Power density, defined as the amount of power delivered per unit volume, is another important performance metric. Increasing power density requires compact design and efficient thermal management, which are key considerations in modern power electronic converter development (Luo et al., 2015).

3.3.4 Voltage Stress and Dynamic Response

Voltage stress refers to the maximum voltage experienced by semiconductor devices during converter operation. Excessive voltage stress can reduce device reliability and increase the risk of component failure. Therefore, converter topologies are often designed to minimize voltage stress on switches and passive components. Dynamic response is another important parameter that describes how quickly the converter can respond to changes in load or input conditions. A fast dynamic response is particularly important in renewable energy systems where generation and load levels may fluctuate rapidly (Emadi, Khaligh and Rivetta, 2006).

4. LITERATURE REVIEW OF NON-ISOLATED BIDIRECTIONAL DC–DC CONVERTER TOPOLOGIES

The development of bidirectional non-isolated DC–DC converters has received significant attention in recent years due to the growing demand for efficient energy conversion in renewable energy systems, electric vehicles, and DC microgrids. Researchers have proposed numerous converter topologies to improve voltage gain, reduce switching losses, and enhance overall system efficiency. This section reviews the most widely studied converter structures reported in the literature, including conventional topologies, interleaved converters, coupled-inductor converters, switched-capacitor converters, multi-port converters, and soft-switching configurations.

4.1 Conventional Bidirectional Converter Topologies

4.1.1 Bidirectional Buck–Boost Converter

The bidirectional buck–boost converter is one of the most widely used non-isolated converter topologies for energy storage applications. This converter allows bidirectional power transfer between two DC sources and can operate either in buck mode or boost mode depending on the direction of power flow. The topology generally consists of two active switches, an inductor, and capacitors for energy storage and filtering. In buck mode, the converter steps down the input voltage to charge the battery or storage device, while in boost mode it increases the storage voltage to support the DC bus. Due to its simple structure and ease of control, the bidirectional buck–boost converter is commonly used in renewable energy systems and electric vehicle applications. However, it suffers from several limitations including limited voltage gain, high switching stress on semiconductor devices, and increased conduction losses at higher power levels (Erickson and Maksimovic, 2001).

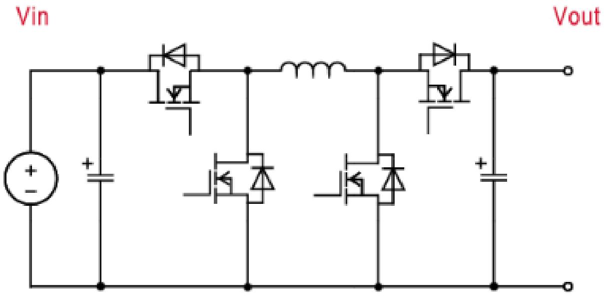

Figure-2: Bidirectional Buck–Boost Converter Topology

4.1.2 Bidirectional Cuk Converter

The Cuk converter is another conventional topology used for bidirectional power conversion. Unlike the buck–boost converter, the Cuk converter employs two inductors and a coupling capacitor to transfer energy between input and output stages. This structure provides continuous current at both input and output sides, which significantly reduces current ripple and improves power quality. The Cuk converter also exhibits improved electromagnetic interference performance compared with simpler converter structures. Nevertheless, the topology requires additional passive components and results in higher circuit complexity and increased cost. Furthermore, the presence of multiple inductors increases the physical size of the converter, which may reduce its suitability for compact power electronic systems (Middlebrook and Cuk, 1976).

4.1.3 Bidirectional SEPIC Converter

The Single-Ended Primary Inductor Converter (SEPIC) is another non-isolated topology capable of providing bidirectional energy transfer with flexible voltage conversion capability. The SEPIC converter utilizes two inductors and a series coupling capacitor to regulate voltage levels while maintaining non-inverted output polarity. One key advantage of this topology is its ability to operate across a wide input voltage range while maintaining stable output voltage. As a result, SEPIC converters are particularly suitable for renewable energy applications where input voltages vary significantly due to environmental conditions. However, the topology requires multiple passive components and experiences higher conduction losses due to additional current paths, which may limit its efficiency in high-power applications (Mohan, Undeland and Robbins, 2003).

4.2 Interleaved Bidirectional Converter Topologies

4.2.1 Principle of Interleaving Technique

Interleaved bidirectional converters have been proposed to improve the performance of conventional converter topologies by distributing the power flow across multiple parallel converter phases. In this approach, several converter modules operate simultaneously with phase-shifted switching signals. The interleaving technique significantly reduces input and output current ripple because the ripple components generated by each phase partially cancel each other. This reduction in current ripple allows the use of smaller passive components and improves overall system efficiency. Additionally, current sharing among multiple phases reduces thermal stress on individual components, enhancing converter reliability and power handling capability (Krein, 1998).

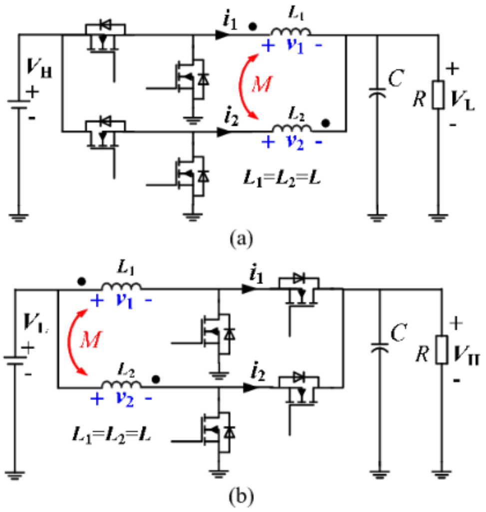

Figure-3: Interleaved Bidirectional DC–DC Converter

4.2.2 Performance Advantages of Interleaved Converters

Interleaved converter structures are particularly beneficial in high-power renewable energy systems and electric vehicle powertrains. By distributing current across multiple phases, interleaved converters reduce conduction losses and improve dynamic performance during transient conditions. Furthermore, the modular nature of interleaved converters provides flexibility in system design and scalability for higher power levels. Despite these advantages, the increased number of switching devices and control complexity may increase system cost and design difficulty (Zhang et al., 2014).

4.3 Coupled-Inductor Based Converter Topologies

4.3.1 Concept of Coupled Inductors in DC–DC Converters

Coupled-inductor based converters have been widely investigated as an effective method for achieving higher voltage conversion ratios without significantly increasing the duty cycle of the switching devices. In these converters, magnetic coupling between inductors allows energy to be transferred more efficiently between input and output stages. The use of coupled inductors also enables improved voltage gain and better energy utilization compared with traditional single-inductor topologies. Additionally, the leakage inductance of coupled inductors can be used to reduce switching stress and improve converter efficiency (Blaabjerg, Yang and Yang, 2017).

4.3.2 Advantages and Design Challenges

Converters employing coupled inductors offer several advantages including high voltage gain, reduced switch stress, and improved efficiency in high step-up or step-down applications. These characteristics make them attractive for renewable energy systems where wide voltage conversion ranges are required. However, the design of coupled inductors requires careful consideration of magnetic coupling coefficients, leakage inductance, and core material characteristics. Improper design may lead to increased electromagnetic interference or efficiency losses (Kazimierczuk, 2016).

4.4 Switched-Capacitor and Voltage Multiplier Converters

4.4.1 Switched-Capacitor Converter Principle

Switched-capacitor converters utilize capacitors as the primary energy transfer elements instead of inductors. In these converters, capacitors are periodically charged and discharged through controlled switching sequences to achieve voltage conversion. The absence of magnetic components makes switched-capacitor converters lightweight and compact, which is beneficial for applications requiring high power density. These converters can also achieve high voltage conversion ratios without requiring large duty cycles (Fang et al., 2017).

4.4.2 Voltage Multiplier Techniques

Voltage multiplier circuits extend the concept of switched-capacitor converters by connecting multiple capacitors and diodes in cascaded arrangements to increase output voltage levels. Such configurations are commonly used to achieve high step-up voltage gain in renewable energy systems with low-voltage sources such as photovoltaic panels. By increasing the voltage through capacitor multiplication stages, these converters can operate efficiently without placing excessive stress on switching devices. However, capacitor voltage balancing and increased conduction losses may present design challenges (Hart, 2011).

4.5 Multi-Port and Multi-Input Converter Topologies

4.5.1 Integration of Multiple Energy Sources

Multi-port DC–DC converters have emerged as an effective solution for integrating multiple energy sources within a single converter structure. In renewable energy systems, these converters allow simultaneous connection of photovoltaic arrays, batteries, and supercapacitors to a common DC bus. This architecture reduces the number of required converters and simplifies system control by enabling coordinated energy management within a unified topology (Khaligh and Onar, 2017).

4.5.2 Application in Hybrid Renewable Energy Systems

Multi-input converters are particularly suitable for hybrid renewable systems where different energy sources operate under varying conditions. For example, photovoltaic generation may fluctuate due to changes in solar irradiance, while battery storage provides stable energy supply. Multi-port converters enable efficient coordination between these sources by dynamically controlling power flow according to system demand and resource availability.

5.1.1 Soft-Switching Techniques for Loss Reduction

Switching losses are one of the primary sources of efficiency degradation in high-frequency DC–DC converters. Conventional hard-switching converters experience significant energy loss during the transition of semiconductor devices between the on and off states. To address this limitation, advanced switching techniques known as soft-switching methods have been developed. Soft-switching techniques reduce switching losses by ensuring that either the voltage or current across the switching device becomes zero before the switching transition occurs. This reduces energy dissipation and improves overall converter efficiency. Common soft-switching methods include resonant switching, quasi-resonant converters, and active clamp circuits, which are widely applied in high-performance power electronic converters (Erickson and Maksimovic, 2001).

5.1.2 Zero-Voltage and Zero-Current Switching

Two widely used soft-switching approaches are zero-voltage switching (ZVS) and zero-current switching (ZCS). In ZVS operation, the switching device turns on when the voltage across it is nearly zero, thereby minimizing switching losses and reducing electromagnetic interference. ZCS, on the other hand, ensures that the current through the switching device becomes zero before the switching transition occurs, which significantly reduces switching stress and power loss. These techniques are particularly beneficial in bidirectional converters operating at high switching frequencies, as they improve efficiency while also enhancing device reliability and thermal performance (Kazimierczuk, 2016).

5.1.3 Reliability Improvement through Soft Switching

In addition to improving efficiency, soft-switching techniques also contribute to improved reliability of power electronic systems. By reducing voltage and current stress on semiconductor devices, soft-switching converters experience lower thermal stress and reduced switching-related degradation. This improvement in device reliability is particularly important in renewable energy systems, where converters are expected to operate continuously for long periods under varying environmental conditions. Consequently, many modern converter topologies incorporate soft-switching mechanisms to achieve both high efficiency and long-term operational stability (Rashid, 2014).

5.2 Wide Bandgap Semiconductor Devices

5.2.1 Limitations of Conventional Silicon Devices

Traditional silicon-based semiconductor devices such as MOSFETs and IGBTs have been widely used in power electronic converters for several decades. Although these devices provide reliable performance, they suffer from limitations related to switching speed, conduction losses, and thermal performance when operating at high frequencies and high power levels. As renewable energy systems demand higher efficiency and power density, the limitations of conventional silicon devices become more evident, motivating the development of advanced semiconductor technologies (Mohan, Undeland and Robbins, 2003).

5.2.2 Silicon Carbide (SiC) Power Devices

Silicon carbide (SiC) devices have emerged as one of the most promising wide bandgap semiconductor technologies for high-efficiency power conversion. SiC devices exhibit superior electrical characteristics such as higher breakdown voltage, lower switching losses, and better thermal conductivity compared with conventional silicon devices. These properties enable converters to operate at higher switching frequencies while maintaining lower power losses. As a result, the use of SiC MOSFETs in bidirectional DC–DC converters significantly improves efficiency and reduces the size of passive components such as inductors and capacitors (Blaabjerg, Yang and Yang, 2017).

5.2.3 Gallium Nitride (GaN) Devices

Gallium nitride (GaN) is another wide bandgap semiconductor material that offers excellent performance in high-frequency power electronics applications. GaN devices have extremely fast switching capabilities and low gate charge, which allows converters to operate at very high switching frequencies with minimal switching losses. This characteristic leads to higher power density and improved converter efficiency. Due to these advantages, GaN-based converters are increasingly used in renewable energy systems, electric vehicles, and high-performance DC power distribution networks (Millán et al., 2014).

5.3 Improved Modulation and Control Strategies

5.3.1 Importance of Advanced Control in DC–DC Converters

Control strategies play a crucial role in determining the performance, efficiency, and stability of bidirectional DC–DC converters. In renewable energy systems, converters must operate under varying input voltages, fluctuating load conditions, and dynamic environmental factors. Conventional control methods such as proportional–integral (PI) control may not provide sufficient performance under such conditions. Therefore, advanced modulation and control techniques have been developed to improve dynamic response, reduce steady-state errors, and enhance overall system efficiency (Krein, 1998).

5.3.2 Model Predictive Control (MPC)

Model Predictive Control has gained significant attention in recent years due to its ability to handle nonlinear system dynamics and multiple control objectives simultaneously. MPC predicts future system behavior using a mathematical model of the converter and selects optimal control actions that minimize a predefined cost function. This predictive capability allows the converter to respond quickly to disturbances and maintain stable operation under rapidly changing conditions. Consequently, MPC is increasingly applied in renewable energy systems and DC microgrids for efficient power management (Camacho and Bordons, 2007).

5.3.3 Sliding Mode Control (SMC)

Sliding Mode Control is a robust nonlinear control method widely used in power electronic converters due to its strong disturbance rejection capability and fast dynamic response. In SMC, the system states are forced to follow a predefined sliding surface, ensuring stable operation even under parameter variations and external disturbances. This property makes sliding mode control particularly suitable for renewable energy systems where operating conditions frequently change. Additionally, SMC offers improved robustness compared with conventional linear control techniques (Utkin, Guldner and Shi, 2009).

5.3.4 Artificial Intelligence-Based Control Techniques

Artificial intelligence and machine learning techniques are increasingly being explored for advanced control of power electronic converters. AI-based controllers, including neural networks, fuzzy logic systems, and reinforcement learning algorithms, can adapt to complex system dynamics and learn optimal control strategies through training or real-time data analysis. These intelligent control approaches enable improved efficiency, better fault tolerance, and enhanced adaptability in renewable energy systems. As computational capabilities continue to improve, AI-based control methods are expected to play an increasingly important role in next-generation power electronic converter systems (Dragicevic et al., 2019).

6. COMPARATIVE ANALYSIS OF EXISTING CONVERTER TOPOLOGIES

The performance of bidirectional non-isolated DC–DC converters depends strongly on their topology, switching strategy, and component configuration. Over the past decade, numerous converter structures have been proposed to improve efficiency, voltage gain capability, and power density for renewable energy applications. However, each topology presents different trade-offs in terms of complexity, cost, and performance characteristics. Therefore, a comparative analysis of these converter structures is essential to identify their suitability for specific applications such as photovoltaic energy systems, DC microgrids, and electric vehicle power management. This section analyzes key performance indicators of various converter topologies and provides a summary comparison of their advantages and limitations.

6.1 Performance Comparison

6.1.1 Efficiency Characteristics of Converter Topologies

Efficiency is one of the most critical parameters when evaluating DC–DC converter performance because it directly determines how effectively electrical energy is transferred between sources and loads. Conventional bidirectional buck–boost converters generally provide high efficiency under moderate load conditions due to their simple structure and low component count. However, efficiency may decrease under high power conditions due to switching losses and conduction losses in semiconductor devices. Advanced converter topologies such as interleaved converters and soft-switching converters have demonstrated improved efficiency by reducing switching losses and distributing current among multiple phases (Erickson and Maksimovic, 2001).

6.1.2 Voltage Gain Capability

Voltage conversion ratio is another important factor in determining converter performance. Renewable energy sources such as photovoltaic panels often produce relatively low output voltages that must be increased to match the DC bus voltage of the system. Conventional buck–boost converters provide moderate voltage gain but may require high duty cycles to achieve large voltage step-up ratios. In contrast, coupled-inductor and switched-capacitor converters can achieve significantly higher voltage gains without excessive duty cycles. These topologies therefore provide improved voltage conversion capability for applications where large voltage differences exist between source and load (Kazimierczuk, 2016).

6.1.3 Component Count and Circuit Complexity

The number of components used in a converter topology significantly affects its circuit complexity, reliability, and manufacturing cost. Simple converter structures such as the buck–boost topology typically require fewer components, which simplifies control implementation and improves system reliability. However, advanced topologies such as multi-port converters and switched-capacitor converters often require additional switches, inductors, and capacitors to achieve improved performance characteristics. While these designs may enhance voltage gain and efficiency, the increased component count can also complicate circuit design and control strategies (Mohan, Undeland and Robbins, 2003).

6.1.4 Cost and Power Density Considerations

Cost and power density are important design considerations for practical power electronic systems. Converters with fewer passive components and simpler control circuits generally offer lower manufacturing costs and higher reliability. However, high-performance applications may require advanced converter topologies that provide improved efficiency and voltage gain at the expense of additional components. Power density, defined as the amount of power delivered per unit volume, is also an important parameter in modern converter design. High power density converters are particularly desirable in applications such as electric vehicles and portable renewable energy systems where space and weight constraints are critical (Krein, 1998).

7. CONCLUSION

The rapid expansion of renewable energy systems and energy storage technologies has significantly increased the importance of efficient bidirectional DC–DC power conversion in modern electrical networks. This review has comprehensively analyzed the topology optimization and efficiency enhancement techniques of bidirectional non-isolated DC–DC converters used in DC-coupled renewable energy systems. Various converter structures, including conventional buck–boost, Cuk, and SEPIC converters, have been discussed along with their operating principles, advantages, and inherent limitations. In addition, advanced topologies such as interleaved converters, coupled-inductor converters, switched-capacitor converters, and multi-port converter configurations were examined to highlight their potential for improving voltage gain, power density, and operational flexibility.

The review also emphasized the significance of efficiency enhancement techniques such as soft-switching methods, wide bandgap semiconductor devices, and advanced control strategies. Techniques including zero-voltage switching and zero-current switching have been shown to reduce switching losses and improve converter reliability. Furthermore, the integration of SiC and GaN semiconductor devices enables high-frequency operation with reduced conduction losses, leading to improved overall system efficiency. Advanced control approaches such as model predictive control, sliding mode control, and AI-based algorithms further enhance dynamic response and system stability.

Overall, bidirectional non-isolated DC–DC converters remain a key enabling technology for efficient renewable energy integration, energy storage management, and DC microgrid operation. Continued research in topology innovation, high-efficiency switching techniques, and intelligent control methods will further improve the performance and reliability of future renewable energy power conversion systems.

7.1. Limitations of the Review

Although this review provides a comprehensive overview of bidirectional non-isolated DC–DC converter topologies and efficiency enhancement techniques, several limitations should be acknowledged. The review primarily focuses on widely studied converter structures reported in the literature and may not cover all emerging or highly specialized converter configurations. Additionally, the comparative analysis is mainly based on reported performance characteristics rather than experimental evaluation under identical operating conditions. Variations in design parameters, operating environments, and implementation methods may therefore influence the reported performance of different converter topologies. Furthermore, the review emphasizes non-isolated converter architectures, while isolated converters with high-frequency transformers are also widely used in many renewable energy systems. Future studies may expand the scope by incorporating detailed experimental comparisons and hybrid converter structures.

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