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Bi-Directional Power Converters for Electric Mobility

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Abstract: *Bi-Directional Power Converters (BDPC) are essential for electric mobility, enabling efficient energy transfer between batteries, electric motors, and the grid while supporting key functions such as regenerative braking, Grid-to-Vehicle (G2V), and Vehicle-to-Grid (V2G) operations. These converters optimize power management in electric vehicles by enhancing energy efficiency, reliability, and system performance. This paper presents a detailed analysis of their design, operational principles, and integration into electric mobility systems, addressing challenges such as thermal management, power losses, and electromagnetic interference through advanced circuit topologies and control strategies. Their role in grid stability, particularly with renewable energy integration, is explored, highlighting their contribution to sustainability and carbon footprint reduction. Additionally, emerging advancements in power density and adaptive control mechanisms are discussed, further improving performance and functionality. By facilitating dynamic energy interactions and supporting the transition to sustainable transportation, BDPC play a pivotal role in shaping the future of electric mobility and achieving global energy sustainability objectives.*

Keywords: *Bi-directional power converters, Pulse Width Modulation, Energy Storage Systems, Dual-Active-Bridge.*

1. INTRODUCTION

In electric vehicle production, bidirectional converters are essential as they make it easier for engines and battery modules to transfer power. These converters also allow charging and discharging of the battery, as seen in regenerative braking systems. This study looked at a number of predictive model control systems made for fuelled-cell-based dynamic power systems, including hydrogen fuel cells. Their cost-effectiveness, environmental friendliness, lack of pollutants, and capacity to manage high power loads were also taken into consideration when evaluating their appropriateness for automotive applications. The various kinds of non-isolated DC to DC converters and discuss the possible applications of fuel cell technology and point out the challenges it faces [1]. Moreover, it offers an extensive classification of DC-DC converters. Different types of Bidirectional DC Converters (BDCs), including boost converters, buck-boost, and single-ended main inductors, are commonly used in Electric Vehicles (EVs). An output voltage that is noticeably greater than the input voltage is produced by a particular type of DC converter called a boost converter. Traditionally, the boost converter is controlled using Pulse Width Modulation (PWM), which allows for strong output voltage and efficient operation. It is critical to acknowledge the necessity of effective energy utilisation in light of the growing demand for energy and technological advancements. There is significant environmental damage as a result of an over-reliance on non-Renewable Energy Sources (RES). Globally, the growth of RES has been propelled by a greater understanding of safeguarding the environment. DC micro grids with Energy Storage Systems (ESSs) and DC power systems play a crucial role in improving the quality of power, efficiency in conversion, and electrical power resilience as the use of renewable energy sources rises. Thus, one of the main concerns in this industry is energy conservation. One of the main goals to accomplish this is to increase power converter efficiency. ESSs usually include a battery that runs at a voltage lower than that of the DC bus. An ESS's battery set is charged and discharged via a bidirectional DC/DC converter. To enable domestic energy storage systems, bidirectional DC/DC converters must be made more efficient and have a higher power density. To ensure converter protection, galvanic isolation is also required. This is typically accomplished by implementing a separated converter topology, which includes CLLC, Dual-

Active-Bridge (DAB) and LLC converters. In order to increase power density with minimal control demands, the DAB converters utilise the high-voltage transformer's leakage inductance as the power transfer component [2, 3]. The broad voltage fluctuations of DC sources, like ESS, Li-Ion batteries, or RES, however, result in a restricted no-voltage switching range and a high circulation current, particularly at low loads. It was suggested that sophisticated modulation incorporating three or more control parameters would ensure smooth switching throughout the whole load range. This method requires an offline optimisation to choose the best amalgamation of factors, but it also makes the controller implementation more difficult [4]. An apparatus that effectively transfers electrical energy between two voltages levels by either raising (boost mode) or lowering (buck mode) the voltage as required is known as a BDCs converter. It is essential for applications like energy storage, EVs, and RES as it regulates the bidirectional flow of energy using electrically controlled switches and a control system. In applications like battery storage, RES, and EVs, this flexibility is crucial for energy management, grid integration, and improved system efficiency. Bidirectional converters are essential components of contemporary energy systems as they provide bidirectional control and power transfer. The efficiency, energy densities, and cost characteristics of several BDC kinds were assessed in this thorough evaluation and comparative analysis. Additionally, a number of control strategies are examined to evaluate how well they regulate the converter's resultant voltage and current, including PWM and hysteresis control. Through an analysis of the BDC types utilised in EVs and an assessment of their performance, this study seeks to determine the best converter system for EV usage. It also emphasises how important control measures are. Figure 1 shows the structure of BDC.

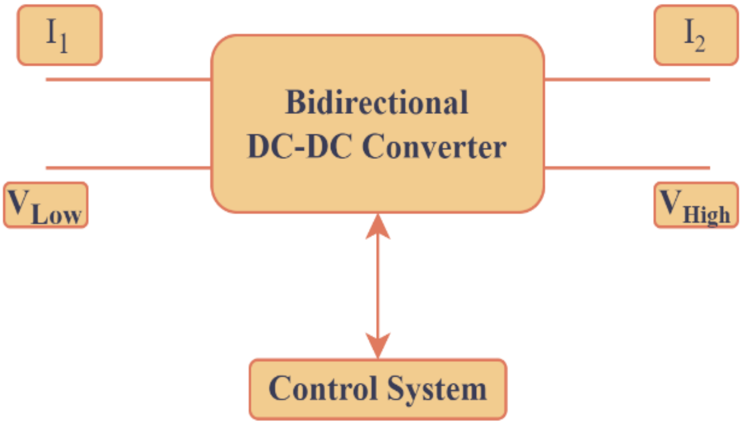

FIGURE 1. Structure of BDC

The CLLC resonant DC/DC converters [5] and the isolated bidirectional LLC [6, 7] are made up of resonant tanks and two bridges. Higher efficiency is achieved by resonant converters due to their greater Zero Voltage Switching (ZVS) load range compared to the DAB converter. Nevertheless, when the switching frequency is different from the resonance frequency, resonant converters may experience decreased efficiency. Consequently, if a resonant converter is constructed as a single-stage device, it could not function at its best across the whole load range.

2. LITERATURE REVIEW

Chen et al., have stated that the LLC converter is operating at its resonance rate, the suggested topology can solve the issue of circulating current. A pair of LLC resonant tanks are included in this design, though, which adds more switches and might lower the converter's total efficiency. For battery charging, it provides a thorough design process for a CLLC-type resonant converter that permits high-frequency performance and guarantees soft-switching in all switches. Computing the transformer turns ratio, designing the magnetising inductance, and figuring out the resonant inductance and capacitance are all part of the design process [8]. Tang et al., have proposed a hybrid control approach. This novel control approach achieves high efficiency and steady operation by combining Phase-Shift Modulation (PSM) and Pulse Frequency Modulation (PFM). For power electronics programs, the suggested control is a workable approach as it is simple to implement employing a digital signal processor. Soft switching, broad voltage gains, and reduced circulating currents are just a few benefits of these circuit designs. However, the strong output ripple of CLLC converters may shorten the battery's duration [9]. Liu and Cao et al., have described a two-stage circuit that modifies the output voltage in the following phase was used to address the output ripple problem. This work presents a digital adaptive control scheme for a bidirectional DC/DC charger/discharger. This technique does not require an additional Zero-Crossing Detection (ZCD) circuit to achieve ZVS. Soft switching is possible across a broad range of input and output voltages as it uses digital calculation to calculate the proper switching frequency in order to meet ZVS requirements. Expanding the output voltage range and reducing output ripple are made possible by the use of a two-stage circuit, despite the fact that it uses more components, which can almost reduce the total efficiency [10, 11]. Wang and Parvez et al., have proposed a high switching frequencies are required to achieve higher power densities and cheaper costs when passive components in the converter, including capacitors and inductors, are larger and more expensive as the switching frequency drop. However, as the frequency rises, switching losses also rise, resulting in decreased efficiency. To address this, soft switching strategies like ZVS and Zero Current Switching (ZCS) have been developed; however, they come at the expense of more complex circuits. Additionally, WBG semiconductors like Gallium Nitride (GaN) and silicon carbide (SiC) offer an alternative to conventional silicon (Si) power switches. SiC and GaN devices provide better electrical performance and greater frequency of operation than standard IGBT and MOSFET devices, which lower switch losses and allow for smaller passive components. WBG materials combination and design are still in their infancy, which leads to more costly products. In contrast, Si power electronics is an advanced technology that is capable of integrating both power and control components in one silicon chip [12, 13].

3. RESEARCH METHODOLOGY

The research adopts an analytical approach to examine the design, operational principles, and integration of BDPC in electric mobility systems. It involves evaluating circuit topologies and control strategies to address challenges such as thermal management, power losses, and electromagnetic interference. The study assesses the efficiency, reliability, and impact of these converters on power management in electric vehicles. Their role in grid stability and renewable energy integration is analyzed, emphasizing contributions to sustainability. Advancements in power density and adaptive control mechanisms are explored to enhance system performance. A comparative assessment of converter designs identifies optimal configurations for electric mobility applications. The research focuses on performance evaluation based on key operational parameters, considering energy transfer efficiency and system stability. The findings contribute to the advancement of energy-efficient and sustainable transportation solutions.

Working Principle

One sort of isolated bidirectional converter that uses galvanic isolation to transmit energy across two DC power sources (such as batteries or capacitors) is the DC-DC converter. It operates on the basis of two active bridges, one on the main side along with another on the secondary side. High-frequency transformers are usually used for isolation. Transformers and inductors are linked to the AC terminals of two full-bridge converters in order for them to function. The high frequency square wave is produced by the use of square wave modulation, and both the direction and magnitude of the power flow can be altered by varying the difference in phase among the two AC sources. The level of adaptability and power density can be significantly increased by the high-frequency isolation transformer, while the dual active bridge converter can achieve electrical isolation of the DC transformer and bi-directional power flow. Forward and backward power transfer are made possible by the use of twin DC-DC converters, and the power density of the circuit is greatly increased by regular application of isolation transformers. Figure 2 displays the schematic of the BDC converter.

Primary Side Bridge (Input Side): There are four switches (usually MOSFETs or IGBTs) that make up the primary bridge. The transformer is driven by a high-frequency AC voltage produced by these switches alternating between on and off states.

High-Frequency Transformer: Galvanic isolation between both ends of the circuit is provided by the high-frequency transformer, which transfers the AC signal produced on the primary side. In accordance with the turn's ratio, the transformer either increases or decreases the voltage.

Secondary Side Bridge (Output Side): The secondary side likewise features a bridge with four active switches, exactly like the primary side. These switches supply power to the output load by converting the AC voltage that comes from the transformer into DC.

Phase-Shift Control: Phase shift between both primary and secondary sources of bridges is a DAB converter's primary control method. The step-up and step-down operations are possible and the energy transfer is regulated by varying the phase shift between the two bridges. Maximum energy transmission occurs at a phase shift of 0°, however power transfer diminishes as the phase shift increases.

Bidirectional Power Flow: The DAB converter's capacity to transfer power in both directions is one of its key characteristics. The converter may step up or step down voltage and transmit power in both directions by adjusting the phase shift in both directions. This is helpful for applications such as battery charging and systems for energy storage.

Power Stage Configuration: Two full-bridge inverter circuits—one on the transformer's main side and one on its secondary—are joined by a high-frequency transformer to form the DAB converter. The input DC voltage is linked to the primary bridge, while the output DC voltage is linked to the secondary bridge.

Switching Operation: Controlled switching, usually with MOSFETs or IGBTs, powers both the primary and secondary bridges. In order to regulate the power transmission from the input to the output, the switching pattern is made to produce a phase shift between the two bridges. ESS Bidirectional power converters play a crucial role in electric mobility by enabling efficient energy exchange between the ESS (typically a battery or super capacitor) and the drivetrain or grid. These converters operate in two primary modes: boost mode, where energy is supplied from the battery to the drivetrain, and buck mode, where energy from regenerative braking or external sources is used to recharge the battery. The mathematical formulation of these converters provides insights into their operational principles, control requirements, and efficiency considerations.

1. System Representation and Power Flow

A bidirectional DC-DC converter consists of an inductor (L), a capacitor (C), power switches (MOSFETs or IGBTs), and a battery or energy storage unit. The two operating modes are as follows:

1. **Boost Mode (Step-Up Operation - Discharge Mode):** The battery voltage is stepped up to meet the required DC-link voltage of the motor.
2. **Buck Mode (Step-Down Operation - Charging Mode):** Regenerative energy from the motor is stepped down to charge the battery efficiently.

For an ideal bidirectional converter, the fundamental voltage and current relationships are derived below.

2. Boost Mode (Step-Up Operation - Discharge Mode)

In boost mode, the converter transfers power from a lower voltage source (V_{in}, typically the battery) to a higher voltage (V_{out}, required by the motor). The circuit operation is governed by the inductor voltage balance principle.

2.1 Voltage and Current Relationships

Applying Kirchhoff’s Voltage Law (KVL) for the inductor during the switching states:

- **Switch ON State (S_1 Closed, S_2Open):**
The inductor stores energy from the input voltage, and the voltage across it is

$$V_L = V_{in} = L\frac{di_L}{dt}$$

- **Switch OFF State (S_1 Open, S_1 Closed):**
The inductor releases stored energy to the output, and the voltage equation becomes

$$V_{out} = V_{in} + V_L$$

Using the inductor volt-second balance principle in steady-state:

$$DV_{in} = (1 - D) (V_{out} - V_{in})$$

Solving for V_{out}: $V_{out} = \frac{V_{in}}{1- D}$

Where D is the duty cycle of the switch.

- **Current Relationship:**
  From power balance (assuming ideal components with negligible losses),

$$P_{in} = P_{out}$$
$$V_{in}\, I_{in} = V_{out} + I_{out}$$

Solving for output current:

$$I_{out} = I_{in}\, (1 - D)$$

These equations describe how voltage is boosted and how the current is adjusted accordingly.

3. Buck Mode (Step-Down Operation - Charging Mode)

In buck mode, the converter steps down a higher voltage (V_{in}, such as the regenerative braking voltage) to charge the battery at a lower voltage (V_{out}).

3.1 Voltage and Current Relationships

- **Switch ON State (S_1 Closed, S_2Open):**
  The input voltage is applied across the inductor, and the inductor equation is

$$V_L = V_{in} - V_{out} = L\frac{di_L}{dt}$$

- **Switch OFF State (S_1 Open, S_2Closed):**
  The inductor releases stored energy to the output, and the voltage equation is

$$V_L = - V_{out}$$

Applying the inductor volt-second balance principle:

$$D\, (V_{in} - V_{out}) = (1 - D)\, (-V_{out})$$

Solving for V_{out}: $V_{out} = DV_{in}$

- **Current Relationship:**
  From power balance:

$$I_{in}V_{in} = I_{out}V_{out}$$

Solving forI_{out}: $I_{out} = \frac{I_{in}}{D}$

These equations define how energy is transferred efficiently during regenerative braking or external charging.

4. Efficiency Considerations

In practical applications, bidirectional converters experience losses due to resistance in inductors (R_L), switch conduction losses, and switching losses. Considering these losses, the overall efficiency (η) can be expressed as:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out}\, I_{out}}{V_{in}\, I_{in}}$$

For a non-ideal converter including conduction and switching losses,

$$\eta = (\frac{V_{out}}{V_{in}}) * (\frac{I_{in}}{I_{out}}) * (1 - P_{Loss})$$

Where P_{Loss} includes conduction, switching, and core losses.

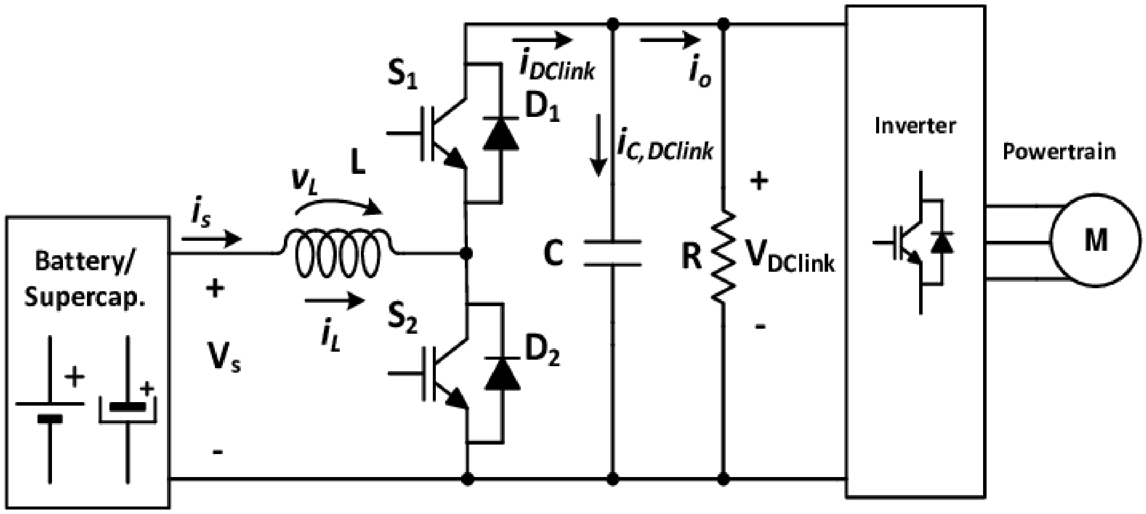

FIGURE 2. Schematic of the bidirectional DC-DC converter

Analysing the operation mode of bi-directional DC-DC converter

An essential power electronics component that permits energy to flow in both ways while adjusting to the demands of the system is a DC-DC bidirectional converter. Managing power transmission between two voltage levels is the converter's main task; depending on its operating mode, it can either step up or step down the voltage. In buck mode, the converter steps down the voltage from a higher input level to a lower output level. This operation is commonly used when the energy stored in a battery or power source is at a higher voltage than what is required by the load or device. The converter uses an inductor, capacitor, and switch (like a transistor) to control the energy flow. Energy is stored in the inductor's magnetic field as current passes through it when the switch is activated. The inductor lowers the voltage to the appropriate level by releasing the energy it has stored to the load when the switch is switched off. Changing the duty cycle of the switch and calculating the input-to-output voltage ratio controls the conversion. Conversely, when the converter is in boost mode, the voltage is increased. This mode is necessary when energy must be transmitted from a lower to a higher voltage load when the input voltage is less than the desired output voltage. In this instance, when the switch is closed, the inductor stores energy, which it then releases to raise the voltage when the switch opens. The duty cycle is modified by the converter's control system to guarantee that the output voltage is raised to the necessary level. The bidirectional nature of the converter means it can alternate between these two modes based on the direction of power flow. For instance, during charging, the converter typically operates in boost mode to step up the voltage from a lower-voltage source (like solar panels or a power supply) to charge a higher-voltage battery. During discharging, it switches to buck mode to step down the battery's voltage to power a lower-voltage load. This flexibility in switching between buck and boost modes makes the converter highly efficient for applications that require dynamic voltage adjustment, such as in energy storage systems, electric vehicles, and battery management systems. The converter automatically adapts to whether it needs to charge or discharge energy, ensuring the system operates optimally. By precisely controlling the voltage and current, the bidirectional DC-DC converter minimizes energy losses and allows for efficient power transfer in both directions, making it an essential component in various renewable energy and power management systems.

Control Strategies for Bidirectional Converters

Bidirectional converters require effective control strategies to regulate power flow between energy sources and loads while ensuring stable and efficient operation. These control strategies play a crucial role in applications such as ESS, EVs, and renewable energy integration. The primary objective of control techniques is to maintain voltage and current stability, improve dynamic response, and enhance overall system efficiency. Various control approaches, including linear, nonlinear, predictive, and intelligent methods, are employed to achieve optimal performance. The selection of an appropriate control strategy depends on system constraints, load variations, and performance requirements. The key control strategies are discussed below.

1. Voltage and Current Control

Voltage and current control methods are fundamental techniques used to maintain the desired operating conditions of bidirectional converters. Voltage mode control (VMC) regulates the output voltage by adjusting the duty cycle based on a feedback loop, ensuring voltage stability under varying load conditions. On the other hand, current mode control (CMC) enhances system stability by incorporating an inner current control loop along with an outer voltage loop. CMC improves transient response and provides better protection against overcurrent conditions, making it suitable for high-power applications. Additionally, hysteresis control, which operates by maintaining the current within a predefined band, offers a fast response but results in variable switching frequency.

2. Linear Control Techniques

The simplicity and efficacy of linear control strategies in attaining stable system operation make them popular. Examples of these strategies are state feedback control and proportional-integral-derivative (PID) control. PID control, which consists of proportional, integral, and derivative components, ensures accurate voltage and current regulation by minimizing steady-state errors and improving dynamic response. However, its performance is sensitive to parameter variations, requiring proper tuning. State feedback control, an alternative linear method, utilizes system state variables to optimize performance and enhance system stability, making it beneficial for high-speed applications.

3. Nonlinear Control Techniques

To address the limitations of linear control methods, nonlinear control techniques such as sliding mode control (SMC) and fuzzy logic control (FLC) have been developed. SMC is a robust control approach that ensures system stability by forcing the system states to follow a predefined sliding surface, making it highly resistant to disturbances and parameter variations. However, it may introduce chattering, which can affect the reliability of power electronics components. FLC, on the other hand, is an intelligent control technique that does not require a precise mathematical model of the system. Instead, it relies on rule-based decision-making to adaptively regulate converter performance, making it suitable for applications with high uncertainty and nonlinear behaviour.

4. Model Predictive Control (MPC)

MPC is a highly advanced control technique that uses a dynamic model to estimate future system performance and optimises switching choices in accordance with that prediction. This approach improves transient response, minimizes losses, and enhances overall efficiency by dynamically adjusting control inputs based on system constraints and operating conditions.

5. Artificial Intelligence-Based Control

Modern bidirectional converters benefit from artificial intelligence techniques, including neural networks and genetic algorithms, which enable adaptive learning and real-time optimization. Neural networks facilitate self-learning control adjustments, while genetic algorithms optimize control parameters for improved performance, particularly in dynamic and uncertain environments.

6. Droop Control for Power Sharing

In applications involving multiple converters, droop control is employed to regulate power sharing without requiring direct communication between converters. By adjusting voltage and frequency based on load conditions, droop control ensures stable and efficient operation in distributed energy systems.

7. Selection of Control Strategies

The choice of an appropriate control strategy depends on specific application requirements, including response time, efficiency, robustness, and computational complexity. While linear control methods provide simplicity and ease of implementation, nonlinear and predictive control techniques offer enhanced adaptability and precision for advanced energy management systems.

4. CONCLUSION

BDPC plays a significant role in electric mobility by enabling efficient energy transfer between batteries, motors, and the grid, supporting key functions such as regenerative braking and vehicle-to-grid (V2G) operations. This study analysed various converter topologies and control strategies, highlighting advancements in power density, switching efficiency, and stability through techniques like model predictive control and wide-bandgap semiconductor integration. While these innovations have improved performance, challenges such as thermal management, electromagnetic interference, and efficiency optimization remain. Additionally, the integration of BDPC with renewable energy sources and microgrids enhances grid stability and sustainability. Their ability to regulate bidirectional power flow makes them essential for the transition toward cleaner energy systems. Future research should focus on optimizing designs to improve efficiency, reduce costs, and enhance adaptability to diverse operating conditions. Advancements in digital control, adaptive modulation, and hybrid power conversion can further refine their performance. As electric mobility evolves, continued innovation in BDPC will be key to enhancing energy efficiency and supporting sustainable transportation solutions.

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