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Bidirectional DC–DC Converters for Energy Storage and Electric Vehicle Applications

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Abstract

Bidirectional DC–DC converters plays an important role in modern power electronic systems where energy flow must be controlled in two directions. These converters are widely used in energy storage systems, electric vehicles (EVs), renewable energy integration, and smart grids. In EVs, they interface the battery with the DC bus and support regenerative braking, while in energy storage systems they helps in charging and discharging operations with high efficiency. This paper presents a detailed review of bidirectional DC–DC converter topologies, control strategies, design challenges, and their applications in EV and energy storage systems. Various isolated and non-isolated configurations are discussed with comparison. Modulation and control techniques are also explained for efficient energy transfer. Tables and figures are provided for better understanding of working and performance parameters.

Keywords: *Bidirectional converters, EV powertrain, energy storage, DC bus, regenerative braking, isolated converters, battery interface.*

INTRODUCTION

With increasing demand of electric vehicles and renewable energy sources, bidirectional power flow is becoming very necessary. Traditional DC–DC converters are unidirectional, meaning energy can move only from source to load. But in EV and battery storage, energy must flow in both directions. For example, during regenerative braking, energy from motor goes back to battery.

Bidirectional DC–DC converters (BDCs) allows this two-way transfer of energy efficiently. They connect batteries, supercapacitors, fuel cells, and DC buses. These converters also improves system flexibility, reduce component size, and increases energy utilization.

In EV applications, BDCs are used between battery pack and DC link. In energy storage, they are used between storage element and grid-connected converter. Because of these advantages, research in BDCs is growing very fast.

2. NEED OF BIDIRECTIONAL DC–DC CONVERTERS (ELABORATED)

The rapid growth of electric vehicles, renewable energy systems, and DC microgrids has created a strong requirement for converters that can transfer energy in both directions with high efficiency and reliability. Conventional DC–DC converters are designed only for one-way power flow, which is not sufficient for modern systems where energy must be stored, recovered, and redistributed dynamically. Bidirectional DC–DC converters (BDCs) fulfill this requirement by allowing controlled power transfer from source to load and from load back to source using the same hardware structure.

The major practical needs that make BDCs very important are explained below.

2.1 Regenerative Braking in Electric Vehicles

In electric vehicles, when the vehicle slows down or brakes, the motor operates as a generator. The kinetic energy of the vehicle is converted back into electrical energy. If a unidirectional converter is used, this energy is wasted as heat in braking resistors.

With a bidirectional converter, this generated electrical energy is routed back to the battery pack for storage. This process is known as regenerative braking.

Importance:

- Improves overall vehicle efficiency
- Extends driving range
- Reduces heating and mechanical wear of brakes
- Enhances battery utilization

During acceleration, the converter works in boost mode (battery to DC link). During braking, it automatically shifts to buck mode (DC link to battery).

2.2 Charging and Discharging of Battery Storage

Battery energy storage systems require frequent charging and discharging depending on load demand and source availability. For example, in solar systems, the battery charges during daytime and discharges at night.

A BDC allows:

- Controlled charging of battery with proper current and voltage profile
- Safe discharging when load requires energy
- Protection of battery from overcharge and deep discharge
- Integration with battery management system (BMS)

This bidirectional capability is very essential for lithium-ion and other advanced batteries which requires precise control.

2.3 Integration of Renewable Energy with Storage

Renewable sources like solar PV and wind are intermittent. Their output power fluctuates based on weather conditions. To maintain stable power supply, energy storage systems are connected to DC bus.

Here BDC performs two functions:

Condition	Converter Action
Excess solar/wind power	Charges battery
Low generation	Discharges battery to DC bus

Thus, BDC helps in smooth power flow between renewable source, storage, and load without disturbance.

2.4 Power Balancing in DC Microgrids

Modern DC microgrids contain multiple sources and loads such as:

- Solar panels
- Fuel cells
- Batteries
- EV chargers
- DC loads

Power demand and supply are constantly changing. Bidirectional converters helps in maintaining DC bus voltage by balancing power among these elements.

For example:

- If load demand increases, battery discharges through BDC
- If generation is high, battery charges through BDC

This makes the microgrid stable and reliable.

2.5 Reduction of Converter Count

Without bidirectional capability, two separate converters are needed:

1. One for charging battery
2. One for discharging battery

This increases:

- Component count
- Cost
- Losses
- Control complexity
- Size of system

A single BDC replaces both converters, reducing hardware requirement and making system compact.

2.6 Improved Efficiency and Compact Size

Using one converter for two operations reduces conduction losses, switching losses, and magnetic component size. Also, modern BDCs use high frequency switching and advanced semiconductor devices (SiC, GaN), which further reduces size.

Benefits include:

- High power density
- Reduced heat generation
- Smaller inductors and capacitors
- Lightweight EV powertrain

3. Classification of Bidirectional DC–DC Converters (Elaborated)

Bidirectional DC–DC converters (BDCs) are broadly classified based on the presence or absence of galvanic isolation between input and output. This isolation is usually provided by a high-frequency transformer. Depending on application voltage level, safety requirement, and power rating, designers select either **non-isolated** or **isolated** topology.

The two main classes are:

1. **Non-Isolated Bidirectional Converters**
2. **Isolated Bidirectional Converters**

This section focuses first on non-isolated types which are widely used in low and medium voltage battery systems, EV auxiliary units, and energy storage modules.

3.1 Non-Isolated Bidirectional Converters

Non-isolated BDCs do not use any transformer between source and load. The input and output share a common ground. Because of absence of transformer, these converters are:

- Simple in structure
- Low in cost
- Compact in size
- Highly efficient due to less components
- Suitable for low voltage applications (typically below 100–150 V)

They are commonly used in:

- EV scooters and e-bikes
- Battery–supercapacitor interface
- Portable energy storage
- DC microgrid low voltage bus

The common non-isolated bidirectional topologies are discussed below.

3.1.1 Bidirectional Buck–Boost Converter

This is the most basic and popular non-isolated BDC topology. It consists of one inductor and two active switches placed in such a way that power can flow in both directions.

Operation:

- In **boost mode**, power flows from battery (low voltage side) to DC bus (high voltage side).
- In **buck mode**, power flows from DC bus to battery for charging.

Features:

- Minimum component count
- Simple PWM control
- High efficiency
- Easy implementation

Limitations:

- No electrical isolation
- High current ripple if single phase is used
- Limited voltage conversion ratio

This converter is widely used in small EV battery packs and low power storage.

3.1.2 Bidirectional Ćuk Converter

The Ćuk converter uses two inductors and a coupling capacitor for energy transfer. In bidirectional form, the switches are arranged to reverse current direction.

Characteristics:

- Continuous input and output current (very low ripple)
- Better EMI performance
- Suitable for battery applications where ripple must be minimized

Drawbacks:

- More components than buck–boost
- Slightly complex control
- Capacitor stress is high

Because of smooth current waveform, it is useful in sensitive battery systems.

3.1.3 SEPIC / Zeta Based Bidirectional Converter

SEPIC (Single Ended Primary Inductor Converter) and Zeta converters are also modified into bidirectional form.

Advantages:

- Ability to step-up and step-down voltage
- Non-inverting output voltage
- Low ripple characteristics
- Better voltage gain flexibility than buck–boost

Applications:

- Battery to DC bus interface
- Hybrid energy storage (battery + supercapacitor)

These topologies provide improved performance but require more passive components.

3.1.4 Interleaved Bidirectional Converter

In this topology, two or more bidirectional buck–boost phases are connected in parallel and operated with phase shift.

Benefits of Interleaving:

- Reduced input and output current ripple
- Smaller inductor size
- Better thermal distribution
- High current handling capability
- Improved efficiency at high power

This topology is highly preferred in EV battery modules where current rating is very high (tens to hundreds of amperes).

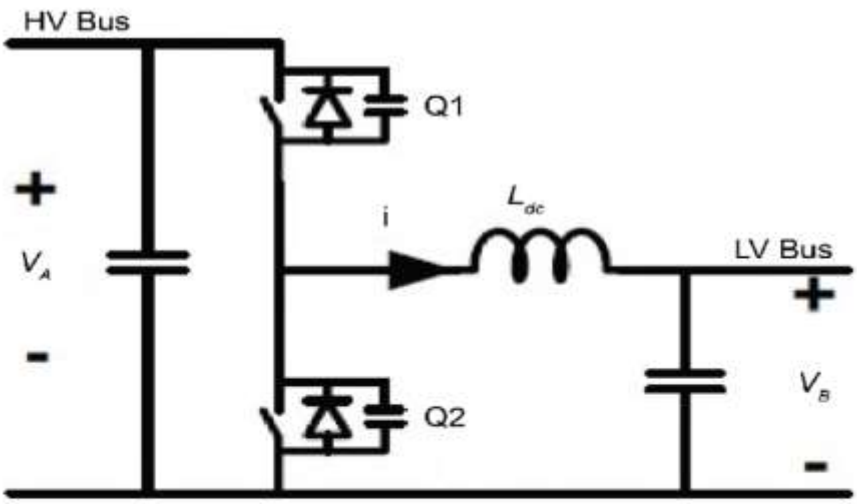

Figure 1: Basic Bidirectional Buck–Boost Converter

3.2 Isolated Bidirectional Converters (Elaborated)

Isolated bidirectional DC–DC converters use a **high-frequency transformer** between input and output sides. This transformer provides two important functions:

1. **Galvanic isolation** for safety
2. **Voltage scaling** using transformer turns ratio

Because EV battery packs and fast charging systems operate at high voltages (200 V to 800 V or even higher), isolation becomes mandatory for user safety and system protection. Also, large difference between battery voltage and DC bus voltage can be easily managed using transformer turns ratio.

These converters are widely used in:

- Electric vehicle main battery interface
- Fast DC charging stations
- Vehicle-to-Grid (V2G) systems
- High power energy storage units
- Aerospace and marine DC systems

The main isolated bidirectional topologies are discussed below.

3.2.1 Dual Active Bridge (DAB) Converter

The Dual Active Bridge is the most popular isolated bidirectional topology for EV and storage applications.

Structure:

- Two full bridges (one on each side of transformer)
- High frequency transformer in between
- Power flow controlled by phase shift between bridges

Working Principle:

Both bridges generate square wave voltages. The phase difference between these voltages causes power to transfer through the transformer leakage inductance.

- If phase shift is positive → power flows from battery to DC bus
- If phase shift is negative → power flows from DC bus to battery

Advantages:

- Soft switching (ZVS) possible → very high efficiency
- Suitable for high power (kW to hundreds of kW)

- Easy bidirectional control using phase shift
- High power density
- Isolation and voltage matching

Applications:

- EV main battery interface
- Fast chargers
- V2G systems

3.2.2 Bidirectional Flyback Converter

The flyback converter is simple isolated topology. In bidirectional form, active switches are placed on both primary and secondary.

Operation:

- Energy is stored in transformer magnetizing inductance during ON period
- Energy is transferred to other side during OFF period
- Direction is controlled by switching sequence

Advantages:

- Very simple circuit
- Low component count
- Suitable for low power isolated storage

Disadvantages:

- High ripple current
- Lower efficiency at high power
- Transformer stress is high

Applications:

- Small energy storage modules
- Auxiliary EV power supplies

3.2.3 Push–Pull Bidirectional Converter

This topology uses a center-tapped transformer and two switches on primary side.

Features:

- Better transformer utilization than flyback
- Moderate efficiency
- Isolation provided

- Suitable for medium power range

Limitations:

- Transformer core saturation issues
- Control complexity in bidirectional mode

Used in medium power battery interfaces.

3.2.4 Full Bridge Bidirectional Converter

In this topology, full bridge converters are used with transformer for isolation. It is similar to DAB but may use PWM instead of phase shift control.

Advantages:

- High power handling capability
- Good voltage control
- Isolation
- Suitable for high voltage battery packs

Disadvantages:

- More switches
- Complex gate driving
- Higher cost

4. WORKING PRINCIPLE

A bidirectional converter operates in two modes:

Mode	Power Flow	Operation
Forward Mode	Battery → DC Bus	Boost mode
Reverse Mode	DC Bus → Battery	Buck mode

Switches are controlled in such a way that current direction is reversed without changing hardware.

5. POPULAR TOPOLOGIES FOR EV AND STORAGE

5.1 Bidirectional Buck–Boost Converter

Most simple topology used in low power EV scooters and battery packs.

Advantages:

- Less components

- Simple control
- High efficiency

Disadvantages:

- No isolation
- Limited voltage gain

5.2 Interleaved Bidirectional Converter

Two or more phases are connected in parallel to reduce ripple.

Benefits:

- Reduced current ripple
- Better thermal performance
- Suitable for high current EV batteries

5.3 Dual Active Bridge (DAB) Converter

Most popular isolated topology for EVs.

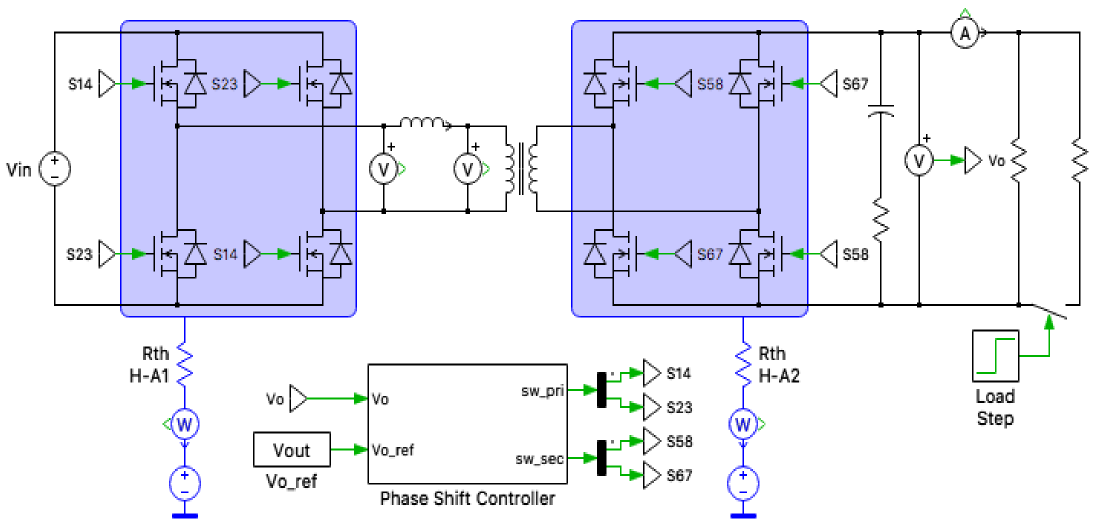

Figure 2: Dual Active Bridge

Power transfer depends on phase shift between two bridges.

Advantages:

- Soft switching possible
- High power density
- Isolation

5.4 Flyback Bidirectional Converter

Used in low power storage systems. Simple but less efficient for high power.

6. Control Techniques for Bidirectional Converters

Proper control is necessary for smooth energy transfer.

6.1 PWM Control

Duty cycle is changed to control direction and magnitude of power.

6.2 Phase Shift Control (for DAB)

Power flow is controlled by phase angle between two bridges.

6.3 Current Mode Control

Used to protect battery and manage charging current.

6.4 Voltage Mode Control

Maintains DC bus voltage stable.

APPLICATION IN ELECTRIC VEHICLES

In EV, BDC is placed between battery and inverter DC link.

Functions:

- Supply power to motor
- Absorb energy during braking
- Manage battery charging from DC charger
- Maintain DC link voltage

EV Condition	Converter Mode
Acceleration	Boost mode
Braking	Buck mode
Charging	Buck mode
Idle	Standby

APPLICATION IN ENERGY STORAGE SYSTEMS

In solar and wind systems, BDC connects battery to DC bus.

- Stores excess energy

- Supplies during deficit
- Stabilizes microgrid voltage

DESIGN CHALLENGES

Some issues in designing BDC:

- High current stress
- Switching losses
- Thermal management
- Control complexity
- EMI issues

COMPARISON OF TOPOLOGIES

Topology	Isolation	Efficiency	Complexity	Application
Buck–Boost	No	High	Low	Low power EV
Interleaved	No	Very High	Medium	High current battery
Flyback	Yes	Medium	Low	Storage
DAB	Yes	Very High	High	EV, Fast charging

ADVANTAGES OF BIDIRECTIONAL CONVERTERS

- Energy recovery
- Reduced hardware
- High efficiency
- Compact design
- Flexible control

FUTURE TRENDS

- Use of SiC and GaN devices
- High frequency operation
- Digital control with DSP
- Integration with BMS
- Modular converter design

CONCLUSION

Bidirectional DC–DC converters are essential part of modern EV and energy storage systems. They allows two way power transfer with high efficiency and reliability. Different topologies are available depending on power level and isolation requirement. Among them, Dual Active Bridge is most promising for high power EV systems, while buck–boost and interleaved converters are useful for battery modules. Proper control techniques improves performance and battery life. Future research is moving towards wide bandgap devices and smart digital control to improve power density and efficiency.

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