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A Review on Bidirectional DC-DC Converter for Energy Storage System

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Abstract: *As energy requirement increases daily in every field of application, battery energy storage systems are becoming increasingly important for grid stability and reliability to fulfil the demand. A bidirectional DC-DC converter can connect the source and load to the battery. This research examines and compares a variety of non-isolated bidirectional DC to DC converter topologies. From features to the applications are used to classify and describe each of the types offered. This review study is aimed to facilitate a useful suggestion for users of non-isolated converters in the future. One of the most prospective converters will be selected based on their ease of use, versatility, and high efficiency.*

Keywords: *Battery, Non-isolated, Buck-Boost converter, Bidirectional DC-DC converter.*

1. Introduction

A bidirectional DC-DC converter can step up and down the voltage level while allowing power to flow in both directions [1], [2]. Bidirectional DC-DC converters are presently employed in various applications, including electric vehicle energy storage systems, renewable energy, fuel cells and uninterruptible power supplies. They were formerly only utilized for motor drive speed regulation and regenerative braking [3], [4]. The primary goal of a bidirectional DC-DC converter is to control DC bus voltage while allowing power to flow in both directions [5]. Power generated by wind and solar power plants has big ups and downs due to the unpredictability of energy flow from the primary source to the conversion unit (PV panels and wind turbines) [6]. With such significant ups and downs, it cannot be treated as a sole power source. It must always be supplied by secondary sources such as rechargeable batteries or supercapacitors. When there is an energy shortage, these secondary sources provide electricity and charge themselves when there is a power surplus in the system.

Consequently, the bidirectional DC-DC converter is suited to allow power to flow in both directions. As depicted in Fig 1, a bidirectional DC-DC converter (BDC) is utilized in EVs [7] to connect the energy storage system (fuel cell with supercapacitor or battery) to the DC bus. They're utilized to control the power supply to the motor drive basedon the traction power requirement.

In the electric car application shown in Fig. 1(a), an additional battery is used to capture the power pumped back by the electric machine through motor braking. Furthermore, BDC is necessary for additional battery power supply whenever a substantial quantity of power is needed on motor initiation or acceleration; it increases the voltage of high voltage side bus [9], [10]. Additionally, BDC can be put to use in engineering machinery. Because this machinery regularly begins & stops, so the energy that can be recovered rather being losses. Environment friendly energy resources, like wind turbines and solar photovoltaic technologies, have recently been increasingly utilized in the development of renewable energy producing systems [11], [12]. Owing to oscillations in generating power due to variations in weather patterns and occasionally large demands in power output, Renewable Energy Sources are completely irrelevant forinner operation as a single input [13].

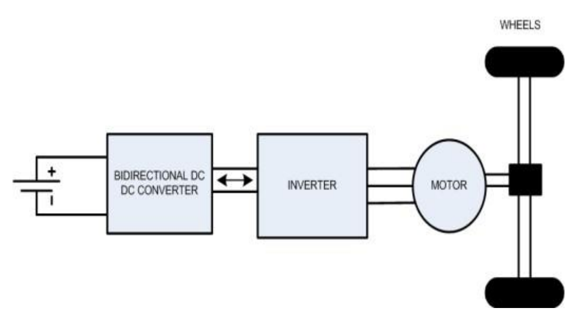

Fig. 1(a). BDC in electric vehicle application.

This study suggests a generic categorization of Non-isolated BDCs, as well as a short description of the distinguishing characteristics of each class.

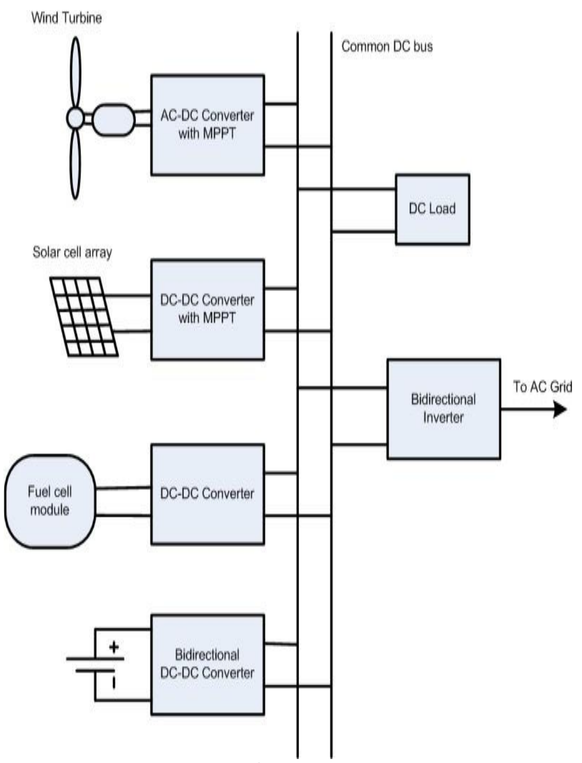

Fig.1(b). Application of BDC in renewable energy sources.

2. Bidirectional DC-DC Converter

The majority of existing BDCs have one side, either current or voltage supplied [14], [15]. BDCs are classified as buck or boost depending on where the additional energy storage is located. The buck type stores energy on the high voltage side, while the boost type stores it on the low voltage side [16], [17]. To achieve bidirectional power in BDCs, the switching cell must conduct current for both directions. Because a dual-side power flow switch is not accessible, a unidirectional power switch such as an IGBT in addition to a diode or a MOSFET is usually used [18]. Depending on the application, several dc to dc converters govern the input side voltage level. Isolated and non-isolated BDCs are the two most common forms of BDCs (Fig. 2). The non-isolated converters will be the subject of this paper. The buck type and boost type dc-dc converters are extensively used in transformer non-isolated power conversion systems. The use of a high-frequency transformer-based system to achieve separation of the load and source sides is a viable option. Whenever an extremely high ratio of step-ups to step-downs is desired, isolation is mandatory. However, non-isolated variety is far more desirable in size, efficiency, cost, and weight. As a result, the non-transformer type is preferred in high-power or spaceship power system applications where size and weight are the primary concerns [19], [20].

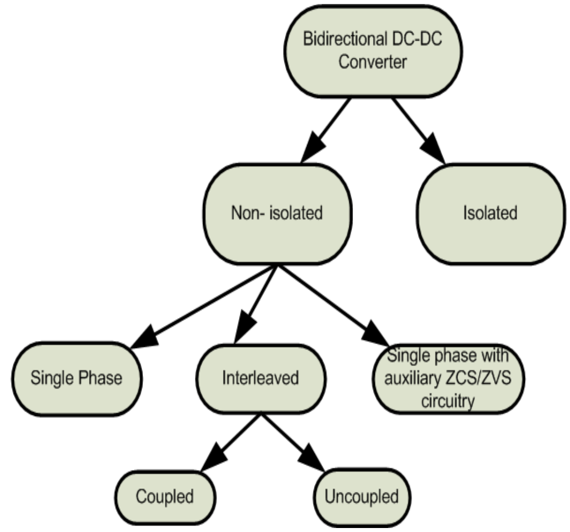

Fig.2. Classification of BDC.

3. Basic Non-Isolated DC-DC Converters

The different types of non-isolated DC-DC converter's performance and the basic circuits for each type of the dc-dc converter are discussed in this section.

3.1Non-Isolated Bidirectional DC-DC Converter (NIBDC)

The NIBDC results from a unidirectional DC-DC converter with bidirectional conducting switches. The basic buck & boost converter circuit (Fig 3) diode prevents bidirectional power flow. The problem will be solved when a MOSFET or combination of an anti-parallel diode with IGBT makes a bidirectional switch that allows conduction in bidirectional nature [21], [22].

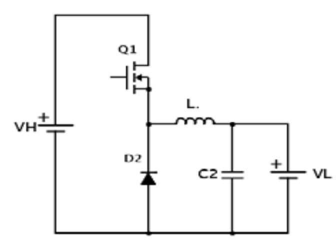

Fig.3(a). Buck converter

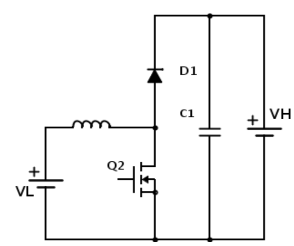

Fig.3(b). Boost converter

3.2 Buck Boost Converter

The first topology, as shown in Figure 4, is developed from a normal buck boost topology with the addition of bidirectional conducting switches [22]. During step-up operation, Q2 is always switched off, whereas Q1 is turned on at the required duty cycle. Accordingly, Q1 is always turned off and Q2 is turned on at the required duty cycle during step-down operation. Small dead time is imposed during transition mode to keep away from cross conduction across switches & converter output capacitance.

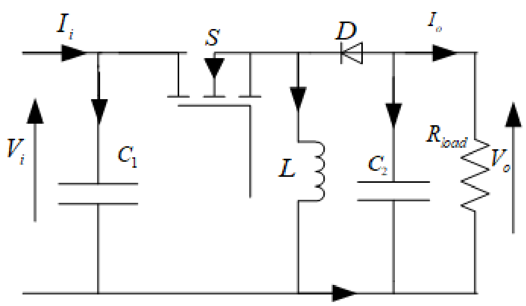

Fig.4. Buck Boost Converter

3.3 Buck Boost Cascade Converter

As shown in Fig 5, by cascading bidirectional boost converters with bidirectional buck converters we can form buck boost cascade converter [23], [24]. Due to switch combination and the direction of current, this layout permits the output voltage can be lower or more than the input voltage.

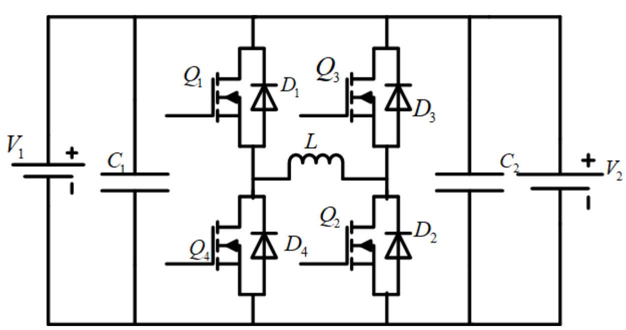

Fig.5. Buck-Boost Cascade Converter

Switches S2 and S4 are always off, and S1 is always on during forward step-up operation, although S2 conducts depending on-duty time. In forward step-down operation, switches S2, S3, and S4 are always off, whilst switch S1 is operated according to the requisite duty period. While Diode D3 is always forward-biased, D2 and D3 diodes are always reverse-biased. A freewheeling diode D4 is shown. S4 is operated with the appropriate duty cycle during backward step-up operation, while S3 is constantly on, with diode D1 acting as a freewheeling diode [25].

3.4 Cuk Converter

In a traditional cuk converter, unidirectional switches are converted to bidirectional switches. As indicated in Fig 6, coupling capacitors C1 and C2 are energy storage elements, whereas capacitor C is a coupling capacitor [26], [27]. Like a buck-boost converter, it can step down or up the input voltage but with the opposite polarity.

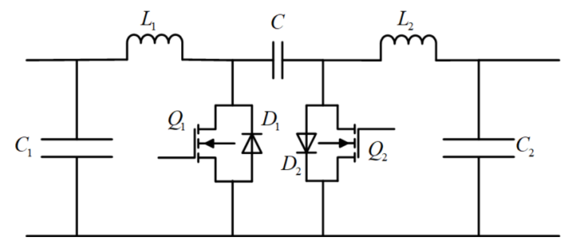

Fig.6. Cuk Converter

3.5 Half Bridge Converter

By coupling in anti-parallel with buck and boost converter, the resultant circuit has the same configuration as the basic Buck & boost circuit, but by addition of bidirectional flow of power, as shown in figure 7. The circuit will function in buck or boost mode depending on the MOSFET Q1 and Q2 switching. The voltage between the switches Q1 and Q2 is stepped up or down depending on the combination of diode D1 and freewheeling diode D2. The circuit's bidirectional operation is described below.

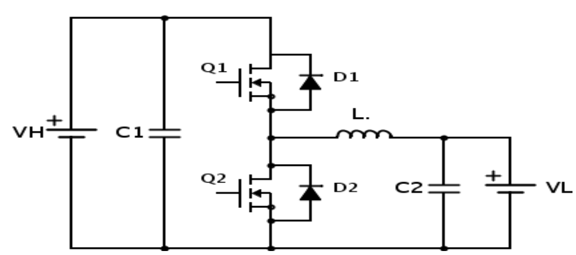

Fig.7. Half-Bridge Converter

Mode 1 (Buck Mode)

Diode D1 and switch Q2 are always off in the buck mode, while switching Q1 and diode D2 conduct according to the duty cycle. Based on the conduction of diode D1 and switch Q2 this mode is separated into two intervals.

1st Interval - Because switch Q1 is active and Q2 is off during this time, the battery charges the inductor and the output capacitor.

2nd Interval - The freewheeling diode D2 discharges the current through the inductor since switches Q1 and Q2 are turned off at this time, resulting in voltage decreasing acrossthe load.

Mode 2 (Boost Mode)

Diode D2 and switch Q1 are always off in the boost mode, while diode D1 and switch Q2 conduct according

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to the duty cycle. This mode is separated into two intervals based on the conduction of switch Q1 and diode D2.

1st Interval - Switch Q2 is on throughout this time, so the lower-sided battery charges the inductor, and the current continues to rise until the gate pulse from Q2 is removed. Switch Q1 is also off because diode D1 is reverse-biased. Thus no current flows through switch Q1.

2nd Interval - Because the current flowing through the inductor cannot change instantly in this mode, the voltage polarity is inverted, and from this stage, it begins to function with the input circuit in series combination. Because forward biasing of diode D1, the output capacitance charged by the inductor current, resulting in an increase in output voltage.

3.6 Switched Capacitor Bidirectional Converter

It's primarily employed when using integrated circuit technology a dc-dc converter needs to be realized. In those converters, no magnetic components are required. IC manufacturing is a viable option. Many ways of operating switches and switching patterns have been proposed for power conversion, starting with using basic SC cells in filter designs. Each capacitor in the converter is being charged from the supply or with another capacitor [28], [29]. On the other hand, switching capacitor converters have low regulation capabilities; by the circuit topology, their voltage conversion ratio is defined, and their input current has a large ripple that causes Electromagnetic Interference. Most of these issues can be overcome by incorporating a voltage control method and a current control system to regulate the capacitor's charging direction [30], [31]. However, the cost and complexity of converters increase as a result.

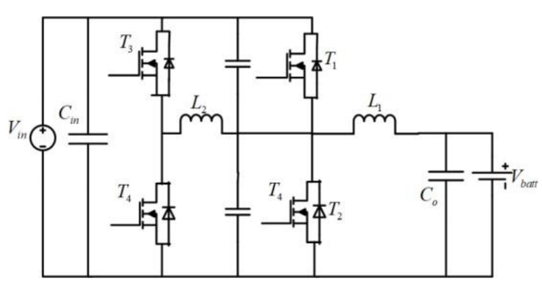

Fig.8. Switched Capacitor BDC

3.7 Single-Phase with Additional ZVS/ZCS Circuitry

A simple control mechanism, high efficiency and consistency, and are the most important factors in all converter. By gaining popularity soft-switching approaches are being applied to NIBDCs due to the limiting effectiveness of switching converters. By decreasing switching losses, compactness, and light weight, the soft- switching technology allows for great efficiency. However, it increases the complexity of schematics, making them more difficult to regulate and tune [32], [33]. The primary forms of half bridge single phase bidirectional converters with additional ZCS/ZVS circuit are depicted in Figure 9. Other types of converters using resonant circuits and active clamps include the switched capacitor converter, Cuk converter and SEPIC/Zeta converter[34].

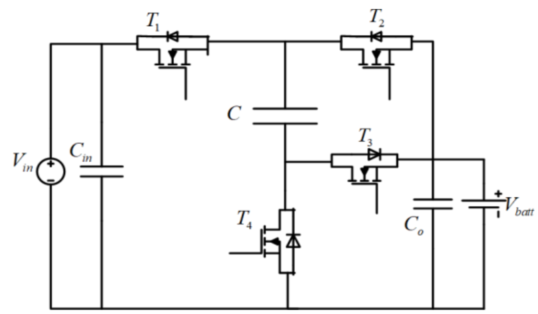

Fig.9. BDC with additional ZCS/ZVS circuit

3.8 Interleaved Converters

It has been observed in recent years that an interleaving approach having relative phase difference (360o / n), is useful. The most well-known application, Voltage Regulator Module, is for powering microprocessors. On the other hand, the interleaving technique is well suited to bidirectional converters. Increased efficiency, Current splitting (Io / n), high power density, current ripple cancellation and improved thermal management are all advantages of power converter paralleling design [35], [36]. Providing excellent efficiency throughout a huge power range is one of the most exciting features of interleaved topologies. Conduction losses (I 2 R) can also be decreased by splitting the current into various channels [37].

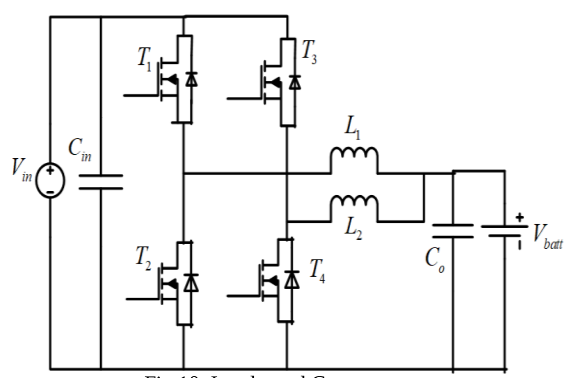

Fig.10. Interleaved Converter

This arrangement provides high efficiency, low input current ripple, and high voltage gain while using less capacitor and inductor space, making this system cost effective than traditional BDCs [38]. An interleaved converter's power inductors can be linked directly or inversely. Inverse coupling improves transient response by reducing phase current ripple [39], [40].

Table I Characteristic Comparison of NBDCS

Topology	Ratio of voltage conversion in buck mode V_{batt}/V_{in}	Ratio of voltage conversion in boost mode V_{in}/V_{batt}	No. of switch	No. of passive component	Required Magnetic element
Inverting BDC	$-\frac{D}{1-D}$	$-\frac{D}{1-D}$	2	3	One inductor
Half bridge BDC	D	$\frac{D}{1-D}$	2	3	One inductor
Cascaded BDC	D	$\frac{D}{1-D}$	4	3	One inductor
Cuk Converter	$-\frac{D}{1-D}$	$-\frac{D}{1-D}$	2	5	Two inductor or coupled
Switched capacitor BDC	0.5	2	4	3	No
Interleaved converter	D	$\frac{D}{1-D}$	2n	2+ n	'n' inductor with/ without coupling

4. Features of the Non-Isolated Bidirectional Converter (NIBC) Topologies

1) Switches in a buck-boost bidirectional converter and the RMS value of inductor current grows by an equal amount to output current is compared to a buck-boost cascade converter, and the RMS value of current through the capacitor increases by 1/3rd of output current. As a result, the power switches capacitor and inductor in a buck-boost bidirectional converter work under thermal stress, resulting in saturation of the inductor core and more power loss than in a buck-boost cascade converter. Because of the higher stress on the diode and MOSFET in a buck-boost cascade converter, high RMS current leads to significant conduction losses and lowers overall efficiency, therefore, power components with bigger ratings are required.

2) In a buck-boost cascade converter, the number of devices required is double that of a buck boost bidirectional converter; however, this difficulty can be avoided by a Half- Bridge Bidirectional DC-DC Converter. It can be used in scenarios where a boost in one direction and a buck in the other is necessary.

3) Above a cuk converter, the fundamental advantage of a half-bridge bidirectional converter is that it only employs single inductor rather than double, and the power device used in a half-bridge bidirectional converter has a far lower rating than a cuk converter. In addition, half-bridge bidirectional converters have higher efficiency and lower conduction losses than cuk converters.

5. Isolated Bidirectional Dc-Dc Converter

This converter can regulate power ranging from a few watts to hundreds of kilowatts. Voltage matching and galvanic isolation are both required in some systems, necessitating the usage of a transformer, which is primarily utilized for this purpose. For energy transfer, the use of a transformer necessitates the use of an AC link. The system becomes complicated and bulky as a result of including all of these features. The most common isolated bidirectional DC-DC converter construction is depicted below.

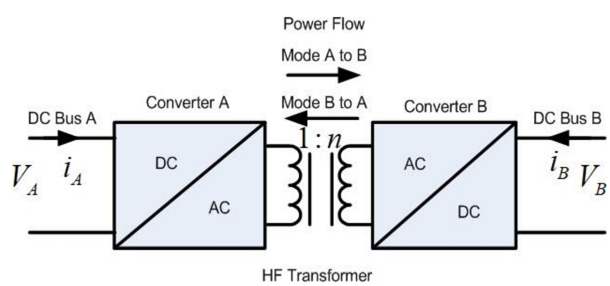

Fig.11. Isolated BDC.

To convert dc input to ac quantity, the system uses two switching DC to AC converters. Transformer provides galvanic isolation and voltage matching; however, because transformers can only function with ac amounts, a dc to ac converter is necessary on both the source and load sides. The converter must accommodate the bidirectional power flow because the system is bidirectional.

Based on the design, isolated bidirectional DC-DC converters can be classified into two categories:

1. In the same way that a typical boost converter has an inductor at its input terminal, a current-fed isolated bidirectional DC-DC converter has an

inductor that acts as a current source at its terminal.

2. Voltage-fed isolated bidirectional DC-DC converters, like ordinary buck converters, feature a capacitor at their input terminal that acts as a voltage source.

6. Conclusion

Because of the growth of electric vehicles and renewable energy sources, BDCs are gaining more interest. They connect the energy storage system to the dc bus and exchange electricity. Even with their diversity, NBDCs can be classified into some basic groups. Isolated and non-isolated converters are the two main types. The non-isolated kind is the topic of this research. Each NBDC topology was given an overview and major operating features. All configuration's benefits and drawbacks were highlighted. Table I summarizes the basic bidirectional converter topologies that have been reviewed. This half-bridge topology and its interleaving versions with linked inductors are the most feasible, stable solutions and highly efficient for future research work, according to the analysis presented.

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