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Overview of Bidirectional DC DC Converter for Energy Storage System in Renewable Energy Power Generation

***Tyas Kartika Sari**
Department of Electrical Engineering
Universitas Trisakti
Jl. Kyai Tapa No. 1, Jakarta
*tyas.kartika@trisakti.ac.id

Dianing Novita Nurmala P
Department of Electrical Engineering
Universitas Trisakti
Jl. Kyai Tapa No. 1, Jakarta
dianingnovita@trisakti.ac.id

Maulasukma Widjaja
Department of Electrical Engineering
Universitas Trisakti
Jl. Kyai Tapa No. 1, Jakarta
maula@trisakti.ac.id

Chairul G Irianto
Department of Electrical Engineering
Universitas Trisakti
Jl. Kyai Tapa No. 1, Jakarta
chairul@trisakti.ac.id

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Abstract **– The integration of renewable energy sources (RES), such as wind and solar energy, has become increasingly growth in power generation systems. However, the intermittent and variable nature of these sources poses challenges, especially in maintaining the stability of the power grid. The address this chalange, energy storage systems (ESS) have emerged as a critical component in renewable energy power generation, enhancing grid stability, improving systems resilience and improving the reliability of the electrical grid. Bidirectional DC-DC converters play a crucial role in integrating RES with the energy storage system and the grid. In this study, a comparative is conducted through literature review, design and calculation of buck-boost bidirectional DC-DC converter for battery charging application in renewable energy power generation. This research paper provides an overview of the various bidirectional DC-DC converter topologies which are suitable for energy storage system applications in renewable energy power generation. The paper dicusses the topologies of bidirectional DC-DC converters, advantages and limitations of different converter topologis including isolated and non-isolated configurations. The result indicate that isolated topologies offer better galvanic isolation and flexibility in voltage conversion, whereas non-isolated converters provide higher efficiency and simpler design, making them more suitable for compact ESS application.**

Keywords: Renewable energy sources, Power generation, Intermittent, Energy storage systems, Bidirectional DC-DC converter.

I. INTRODUCTION

The growth in the integration of RES, such as wind and solar energy, has led to increased need for energy storage systems to enhance the reliability of the electrical grid [1]. Bidirectional DC-DC converter plays a crucial role in integrating these energy storage systems with RES and the grid. Bidirectional DC-DC converters are being used in a wide range of applications which need power flow in both forward and reverse directions. These applications include various fields such as energy storage systems, uninterruptible power supplies, electric vehicles and renewable energy systems etc [2]. Unlike conventional converters, bidirectional DC-DC converters allow power to flow in both directions. Thus, this flexibility makes them widely used in various applications. Since the function of bidirectional DC-DC converter as an interface between power sources and energy storage systems, it makes not only reduce the size but also enhance its efficiency and performance by eliminating the necessity for separate converters to manage power flow in both forward and reverse directions [1], [2].

In addition, the general block diagram of bidirectional DC-DC converters is as shown in Fig.1 below. Depending on whether it uses current-mode or voltage-mode control, the control system adjusts the system's voltage or current. A DC-DC converter, as a power-switching device in power electronics, takes a DC input of a specific voltage and converts it into a DC output at a different voltage. Although the voltage levels differ between the input and output, the power remains unchanged on both sides. DC-DC converters are commonly utilized in applications such as battery charging and discharging, where maintaining constant voltage and current helps extend battery life [3], [4].

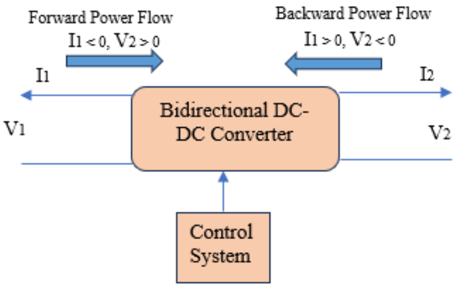

Figure 1. The general structure of bidirectional DC-DC converters

Energy storage systems, such as battery energy storage systems, allow for leveling the load, shaving peak demands and facilitating power transactions with the utility grid [5]. The combination of RES and energy storage devices can enhance the stability of the power grid and ensure the resilience of the electrical grid with improve power system stability [6]. Moreover, bidirectional DC-DC converters could find in smart grid applications and plug-in hybrid electric vehicle (PHEV) charge stations, as shown in Fig. 2 below. This figure describes the vehicle to grid (V2G) architecture which uses bidirectionasl DC-DC converter application, where the charging occurs the power flow from grid side to vehicle and the discharging the power flow to grid from PHEV. It can be concluded that a bidirectional DC-DC converter is not only used in electric vehicles but also in renewable power generation.

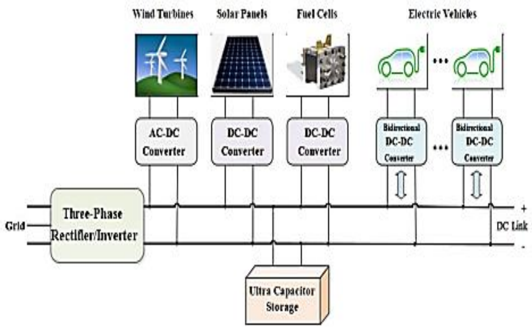

Figure 2. The bidirectional DC-DC converter in vehicle to grid (V2G) architecture

Therefore, due to the widespread harnessing of bidirectional DC-DC converters in electrical systems, the study and development of bidirectional DC-DC converters is necessary conducted. Previous study method's was review based on literature review of bidirectional DC-DC converters which is found in smart grids and plug-in hybrid electric vehicle (PHEV) charge stations. It is worth nothing that the application of bidirectional power converters is not limited to electric vehicle. Furthermore, it uses in another applications of these converters within the broad domain of renewable energy systems. This paper aims to review a comprehensive bidirectional DC-DC converter especially in renewable energy power generation including the topologies of bidirectional DC-DC converter, advantages and limitations of different converter topologis including isolated and non-isolated configurations. The methodology for this paper encompasses review of the existing literature on bidirectional DC-DC converters topologies particularly in renewable energy power generation application. The literature sources were selected to provide a comprehensive understanding of the topic.

II. Topologies of Bidirectional DC-DC Converters

Bidirectional DC-DC converters are essential for interfacing energy storage systems, such as batteries, with RES and the grid. This converter has to support bidirectional power flow to enable for both charging and discharging the energy storage devices. Several topologies have been developed in the literature for bidirectional DC-DC converters, which can be classified as isolated and non-isolated converters [7]. Fig. 3 shows the classification of bidirectional DC-DC converters.

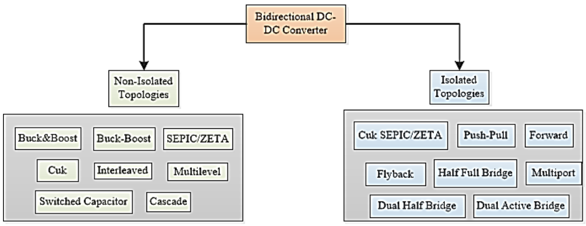

Figure 3. The classification of bidirectional DC-DC converters

In isolated topologies, the power can be transferred in both directions with a magnetic isolation. This topology employs a transformer to provide galvanic isolation between the input and output sides. Hence with this isolation, there are several benefits, such as voltage transformation, enhanced safety and the ability to handle high power applications. One such example is the center-tapped transformer-based single-stage single-phase full-bridge bidirectional AC-DC converter, which links and galvanically isolates the converters and the grid, providing the necessary inductor for current control through its leakage inductance [8].

Non-isolated topologies do not use any transformer or coupled inductor, which make them less complex and more compact compared to isolated topologies. One example of a non-isolated bidirectional DC-DC converter is the dual active bridge converter, which includes two full-bridge inverters connected by a high-frequency isolation transformer.

III. Non-Isolated Bidirectional DC-DC Converters

The non-isolated bidirectional DC-DC converters change one level of DC voltage to another level of DC voltage and they don't consist of transformers. Therefore, these topologies lack the advantages like high-up voltage gain ratio and isolation between source and load. However their weights are reduced because no transformer is utilized and the system will be compact without a transformer [9], [10].

While the transformers are harnessed in the converter, it generates reactive power in the supply line thus more compensation is needed. As the transformer is used with high frequency, the size of the coil reduces and hence the size of the transformer reduces, therefore it can't deal with high current. Also the converters empowering with the transformer can cause sore loss and skin effect with the conductor. Due to this effect, non-isolated converters are utilized in high-power applications also [3].

The non-isolated bidirectional DC-DC converters are classified into eight groups as explained below.

The converter is the basic converter in the bidirectional DC-DC converter family. Specifically, its transformer-less bidirectional DC-DC converter as shown in Fig. 4 below.

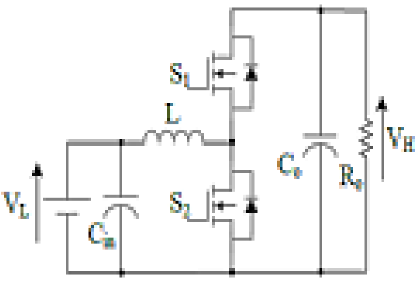

Figure 4. Buck and boost derived bidirectional DC-DC converter

The converter consists of two switches and operates in buck mode and boost mode. While the converter operates in buck mode, power flows from VH to VL and conversely. The switch mode is an automatic process by the controller. This controller can be found in renewable energy applications to automotive system applications.

The converter is developed by adding one more switch to the basic design of unidirectional step-up/step down converter and it is as shown in Fig. 5 below. There are many applications where negative voltage is needed in electronic systems.

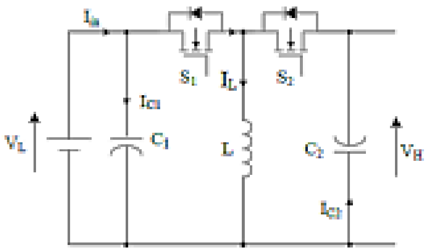

Figure 5. Buck-boost derived bidirectional DC-DC converter

The topology of the converter is as shown in Fig. 6, where the L-C type filter is empowered in this converter. in order to minimize the ripple current obtained by the inductor. Cuk converter delivers the power in both states of switch, i.e both off and on of the states of switch. Meanwhile, buck converter delivers the power when the switch is in on state and boost converter delivers the power when the switch is in off state.

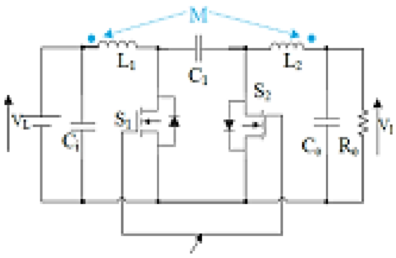

Figure 6. Cuk derived bidirectional DC-DC converter

The topology of such a converter is as shown in Fig. 7, where the sepic is an acronym for single-ended primary-inductor converter. Boost converter is integrated with buck-boost converter back to back form a sepic converter. Because the capacitor is unified at any side of the converter, it is capable of causing true shutdown. Because of this characteristic, it ensures the system gets the required voltage. For example, the SEPIC is particularly effective when the load demands a constant voltage of 3.3 V, while the battery voltage fluctuates between 5 and 2 V.

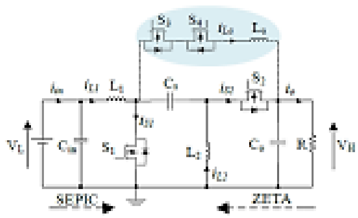

Figure 7. Sepic and zeta derived bidirectional DC-DC converter

The topology of such a converter is built up of two buck-boost converters cascaded back to back as shown in Fig. 8 below. It is usually used in electric vehicle system applications. This converter obtains output voltage which is much better than the input voltage with the certain duty cycle.

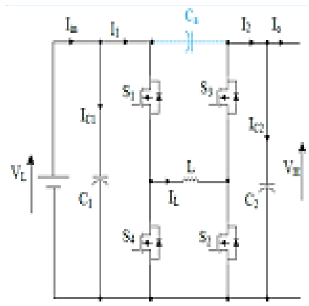

Figure 8. Cascade bidirectional DC-DC converter

The voltage boosting capability of the converter is enhanced by the cell built up of the switched capacitor. The topology of such a converter is as shown in Fig. 9 below. In this topology, there is no magnetic usage and high weight of the converter because there is no inductor utilized.

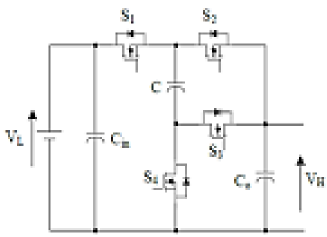

Figure 9. Switched-capacitor bidirectional DC-DC converter

The smaller electromagnetic interference (EMI) because of high speed working devices could be prevented with interleaving techniques used in this converter [11]. The topology of the converter is as shown in Fig. 10 below.

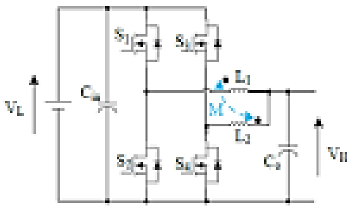

Figure 10. Interleaved bidirectional DC-DC converter

With this topology high gain voltage will be obtained by switching modules linked in repeating patterns in each level. This topology will be found in electric vehicles where two voltage bridges are needed to get regenerative processes and to store the energy in battery energy storage systems. This topology is as shown in Fig. 11.

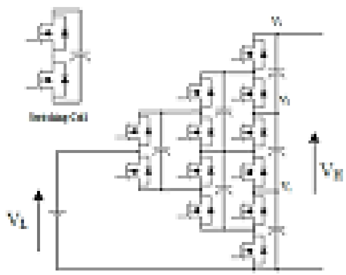

Figure 11. Multilevel bidirectional DC-DC converter

IV. Isolated Bidirectional DC-DC Converters

An isolated bidirectional DC-DC converter is a converter which can transfer power bidirectionally between two DC voltage sources empowering with electrical isolation between them. The isolation guarantees that there is no direct electrical connection between the input and output circuits, offering safety and enabling separate ground potentials between the input and output sides. The isolated bidirectional DC-DC converter is classified into eight groups.

The topology of such a converter is as shown in Fig. 12 below. These isolated bidirectional converters are obtained by introducing high-frequency transformers in the existing bidirectional DC-DC converters. The voltage gain ratio is achieved by incorporating a transformer into the basic bidirectional buck-boost converter, referred to as a flyback converter, which operates without an inductor.

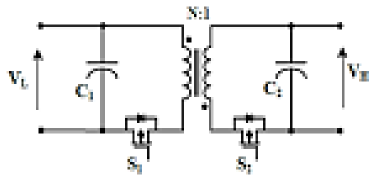

Figure 12. Isolated flyback bidirectional DC-DC converter

The topology of such a converter is as shown in Fig. 13 below. This converter has two different grounds for input and output side with use of transformer on non-solated bidirectional cuck converter. This topology is highly recommended to use in the application of non-conventional energy systems.

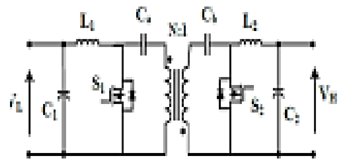

Figure 13. Isolated cuk and sepic/zeta bidirectional DC-DC converter

The topology of such a converter is as shown in Fig. 14 below. It is based on a unidirectional push-pull converter to enable power flow in both directions. This converter uses a transformer to reach it in terms of power. The circuit of the push-pull converter consists of two semiconductor switches connected in between input and the transformer specifically at the primary side of the transformer.

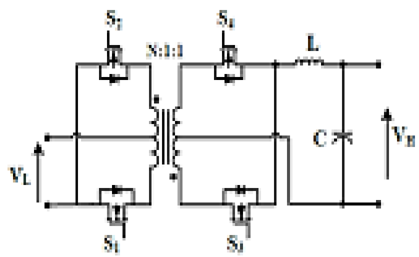

Figure 14. Flyback bidirectional DC-DC converter

The topology of such a converter is as shown in Fig. 15 below. A zero voltage switching is achieved in this converter by integrating a clamped circuit. In-depth research was conducted regarding the bidirectional forward DC-DC converter.

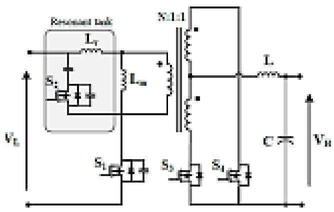

Figure 15. Forward bidirectional DC-DC converter

The topology of such a converter is as shown in Fig. 16 below. This topology is built up of existing circuits like full-bridge circuit or half-bridge circuit and these circuits are powered by voltage or current.

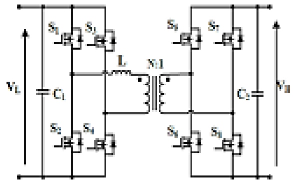

Figure 16. Dual active bidirectional DC-DC converter

The topology of such a converter is as shown in Fig. 17 below. This topology can be found in applications with low power requirements are needed. Advanced research has been conducted on interleaved dual half-bridge topology which increases the voltage.

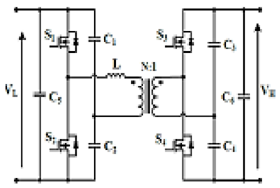

Figure 17. Dual half bridge bidirectional DC-DC converter

The combination of two topologies are integrated back to back with a transformer which can work at high frequency, hence it can reduce the size of the system. It uses less number of switches thus the control requirement goes easy than dual active bidirectiona DC-DC converter. The topology of such a converter is as shown in Fig. 18 below.

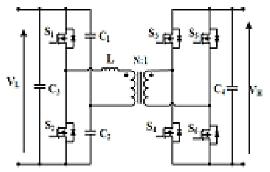

Figure 18. Half bridge and full bridge bidirectional DC-DC converter

The architecture of this converter was proposed incorporating the multi-winding transformer with isolated bidirectional applications which have multiple inputs. The topology of such a converter is as shown in Fig. 19 below.

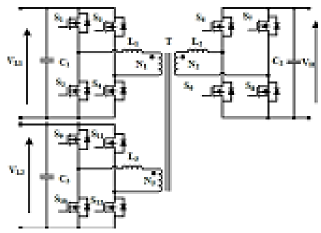

Figure 19. Multiport dual active bus bidirectional DC-DC converter

V. Buck-Boost Bidirectional DC-DC Converter Design in Renewable Energy Power Generation for Battery Charging

One of the bidirectional DC-DC converters which is usually implemented in battery charging applications for solar PV system is buck-boost converter [12], [13]. This section will explain more detail about the design and circuit of buck-boost converter. Fig. 20 shows buck-boost converter circuit.

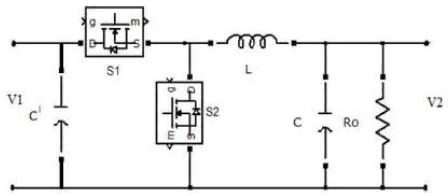

Figure 20. Buck-boost converter circuit for battery charging application in solar PV systems

There are two operation modes in this circuit, forward operation (buck mode) and backward operation (boost mode). For buck mode, switch S1 is activated and for boost mode, switch S2 is activated [14]. For example we design a converter with LV side 24 V and HV side 48 V. V1 indicates HV side and V2 represents LV side. The converter operation and design is released as follows, where V_{in} indicates input voltage and V_{out} denotes output voltage, and η signifies converter efficiency.

A. Buck mode (Step down operation)

The output voltage of buck mode is lower than input voltage as is shown in Fig. 21. The input current increases and flows via switches S1 and inductor L when S1 is on. The IL decreases until the next cycle when S1 is off. The battery is charged harnessing the energy restored in inductor L [15].

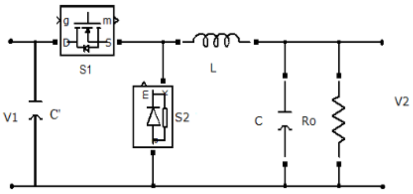

Figure 21. Buck-boost converter in buck mode

B. Design-buck mode

Duty cycle : regarding to expectations, the switch's efficiency ranges from 90% to 95%, the duty cycle can be calculated using this equation.

$$D = \frac{V_{out}}{V_{in}\ x\ \eta} \quad (1)$$

Inductor selection : the output current is assumed to be10 - 20% of the inductor ripple current. The ripple in “inductor current” is calculated by equation 2.

$$\Delta IL = (0.1\ to\ 0.2) x\ I_{out} \quad (2)$$

Where Iout is output current needed by the circuit.Because off less output current ripple, the maximum output current rises as the inductor value increases. Equation 3 is used to calculated the inductor value.

$$L = \frac{DT_S\ x\ (V_d - V_o)}{\Delta IL} \quad (3)$$

Output capacitor selection : applying capacitors with a low ESR is the best way to reduce output voltage ripple. The output voltage ripple is calculated to 10% of the output voltage. Capacitor output value is calculated for a desired output voltage ripple.

$$C_{out} \frac{(1-D) x\ V_{out}\ x\ Ts^2}{8L\ X\ \Delta V_{out}} \quad (4)$$

C. Boost mode (Step up operation)

The output voltage of boost mode is higher than input voltage as is shown in Fig. 22. Battery discharges while switch S2 is on and switch S1 is off.

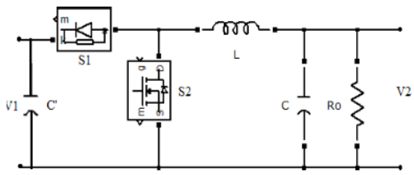

Figure 22. Buck-boost converter in boost mode

The inductor (L) and switch S2 face a rise in input current when switch S2 is turned ON. When S2 is turned OFF, the inductor current decreases until the next cycle, and the energy stored in L is directed through the load

D. Design-boost mode

Duty cycle : The assumed efficiency of the switch is 90 - 95%, and the duty cycle is calculated by equation 5 below.

$$D = 1 - \frac{V_{in}\ x\ \eta}{V_{out}} \quad (5)$$

Selection of inductor : it is assumed that the inductor will have a ripple current of 10 - 20 %. The value of the inductor is calculated with equation 6.

$$L = \frac{DT_s\ x\ V_d}{\Delta IL} \quad (6)$$

$$L = \frac{DT_s\ x\ V_d}{10\%\ of\ Iin}$$

Output capacitor selection : the output capacitor is selected with 10% ripple in output voltage. The output capacitor can be calculated by equation 7 below.

$$C_{out} = \frac{I_O\ x\ D}{f\ x\ \Delta w} \quad (7)$$

VI. Conclusion

In conclusion, this paper has provided an overview of the various bidirectional DC-DC converter topologies which are suitable for energy storage system for both renewable energy applications and electric vehicle applications. The topologies can be widely classified as isolated and non-isolated converters, each with its own advantages and disadvantages. The result indicate that isolated topologies offer better galvanic isolation and flexibility in voltage conversion, whereas non-isolated converters provide higher efficiency and simpler design, making them more suitable for compact ESS application. The growth adoption of renewable energy sources and the increasing demand for efficient and reliable power management systems have encouraged the development of multiport converters, which provide a compact and versatile solution for integrating RES.

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