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REVIEW ARTICLE

A Review and Comprehensive Study on DC-DC Converters

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Abstract: ***Background***: DC-DC converters are used in various applications based on their required voltage capabilities ranging from milli volts to thousands of volts.

Methods: This review paper discusses various voltage boosting techniques, such as buck-boost, switched inductor, switched capacitors, isolated converters, *etc*., and provides a detailed evaluation of the literature and comparison of different DC-DC converters.

Results: This study reports a number of storage elements included, such as inductors and capacitors as well as switches and diodes. Their features along with methodologies, merits, complexity, efficiency, and voltage gain have been tabulated. A comprehensive study, converter classification based on the characteristics, and a detailed analysis of isolated and non-isolated DC-DC converters have also been provided.

Conclusion: As this study provides a comparison of each isolated and non-isolated converter's comprehensive gain, this research may help in future topology optimization for the choice of the ideal converter for applications. In addition, the examination of each isolated and non-isolated converter's comprehensive gain comparison has also been presented in this paper.

Keywords*:* DC-DC converters, methodology, comparative analysis, isolated converters, non-isolated converters, switched inductor, topology optimization.

1. INTRODUCTION

Due to extreme fuel consumption by automobiles and a rapid increase in electricity consumption causing environmental pollution and global energy shortage in energy resources, such as fossil fuels and natural gases, renewable energy sources, such as photovoltaic (PV), fuel cells, and wind [1], have become recent trends. Most of the energy sources produce power with low voltage ranges. To integrate renewable energy sources with the grid or any other voltage applications [2], many power conversion stages are required. Power electronic technologies play an important role in the conversion of voltage ranges. DC-DC converters have gained importance for use in recent application trends, such as aircraft/air space applications, UPS, renewable energy, medical equipment, utility, industrial applications, lighting, telecom, transportation, military applications, and electric vehicle applications [3]. Converters are designed to support the voltage gain ratios and to reduce the conversion stages. Previously, a number of studies have been conducted on the DC-DC converters and reported in the literature review. Every converter has its own features and demerits depending on the application where converters are used in terms of output power.

DC-DC converters with high gain are widely used in many power converter applications, ranging in power levels from millwatts to Megawatts. High voltage is utilized for a variety of purposes, such as in X-rays, medical equipment, food processing, water treatment, agriculture, industries, and defense applications, such as missile launchers and e-bombs. The high-voltage equipment utilized in these applications has smaller power and voltage ratings, and is portable and lightweight. Typically, lower voltage energy sources, like solar PV, fuel cells, batteries, *etc*., are used to power portable high-voltage devices.

The converter has limited gain due to the presence of parasitic elements, and also voltage stress across the semiconductor devices is high. Therefore, a high-gain DC-DC converter is needed to boost the voltage level. A boost converter is required when a high step-up ratio is required; however, utilizing the boost converter can be disadvantageous due to the low system efficiency [4].

In step-down applications, classical buck converters are used in low-power applications due to their low cost and low maintenance. The demand for DC-DC converters has increased in the case of hybrid electric vehicles (HEV) [5],

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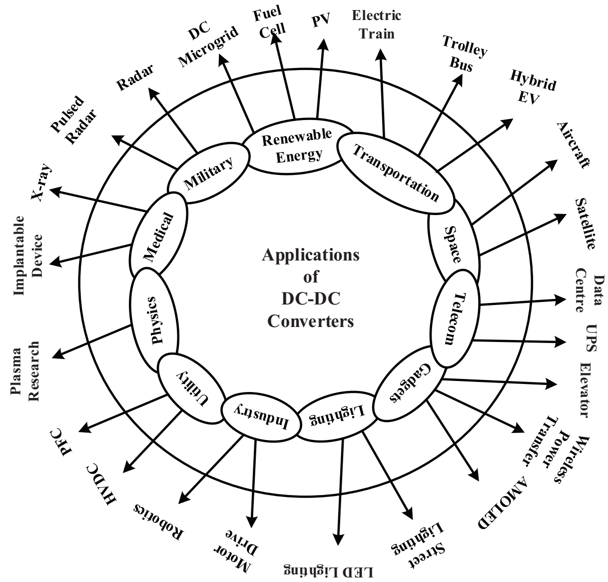

Fig. (1). Applications of DC-DC converters. *(A higher resolution / colour version of this figure is available in the electronic copy of the article).*

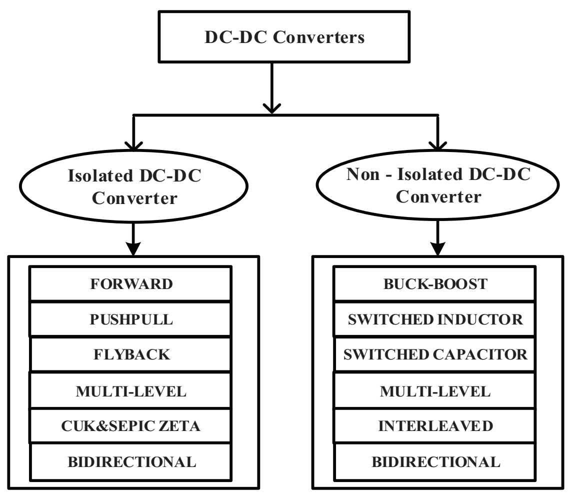

Fig. (2). Classification of DC-DC converters.

micro-grid sources [6], and fuel cell vehicle (FCV) applications [7]. As mentioned earlier, due to the ever-increasing electrical loads, the automotive industry is opting for more power electronic converters [8]. The integration of power electronics and associated motor provides intensive solutions to control the load of HEVs with respect to the consumption of fuel as well as emit fewer pollutants. Based on the demands of the HEVs [9], high voltage levels are required.

Thus, it has become necessary to utilize DC-DC converters to supply excessive load. To meet the demands of such applications, new power converter gain topologies are coming into the limelight [10]. Every power converter has its own merits as well as demerits depending on the number of switches, design, internal voltage stresses, and ripple currents. The performance, as well as the efficiency of the power converter [11], depends on the model and design.

There is a persistent need for dependable, effective, small-sized, and lightweight step-up DC-DC converters for various power applications reviewed in the literature study, as shown in Fig. (**1**). The literature also discusses complex, recent topologies that make use of various voltage-boosting strategies, such as multilevel, interleaved, cascaded topologies, voltage multiplier cells (VMC), switched capacitors (SCs), and coupled inductors. The characteristics of every individual converter along with its features and demerits are explained in the proposed paper, and the detailed configurations and features have been comparatively described.

2. CLASSIFICATION OF DC-DC CONVERTERS

According to the literature review, many of the advanced electric loads require power electronic control techniques [12]. In advanced future vehicles, micro-grids, or renewable energy sources, power electronics plays a major role. The primary function of power converters is to simply turn on or off the loads. Moreover, they serve as a controller in numerous power converter applications, such as traction motors.

Table 1. Isolated forward DC-DC converters.

Forward Converter	N_S	N_C	N_L	Efficiency (%)
[13]	7 or 8	3	2	92
[14]	4	1	2	91
[15]	4	3	1	88

Table 2. Isolated push-pull DC-DC converters.

Push-Pull Converter	N_S	N_C	N_L	Efficiency (%)
[16]	6	1	2	94
[17]	6	2	1	94.1

Mechanical switches handle on/off switching of loads and control the traction motor. The main task of power electronics is to change the voltage levels from one level to another. Power electronics applications are used to convert AC to DC, DC to AC, and DC to DC.

In order to achieve high gain and high efficiency, DC-DC converters are employed. The principal categories for the converters are shown in Fig. (**2**), and once again, each category has been classified according to its characteristics and configurations. The aforementioned topologies' features, drawbacks, complexity, and step-up/step-down gain ratios are summarized based on a wide range of parameters.

2.1. Isolated DC-DC Converters

In many high-voltage applications, isolated DC-DC converters are used due to their advantage of galvanic isolation between the input and output of the circuit whenever a fault occurs. Usually, the transformer offers an extremely high range of voltage gain. These converters are categorized into different types based on the methodology used to operate the circuit. Some of them have been discussed below along with their component count and efficiency.

2.1.1. Forward DC-DC Converter

A forward DC-DC converter is used to convert the voltage from one level to another, either boost or buck. It is a simple structure with a wide range of input and output voltages even if the frequency is limited. It achieves soft switching with ZVS operation. It has minimum current ripples in input current that leads to high voltage gain. Forward DC-DC converters are further classified into basic forward [13], forward-flyback [14], and push-pull forward converters [15], as shown in Table **1**.

2.1.2. Push-pull Converter

Push-pull converter topology differs significantly from that of a traditional, isolated DC-DC converter [16]. The output voltage in this design is controlled by the transformer. Because it stores energy in one cycle and supplies it in the next, it is known as a push-pull system. The main advantage of this converter is that it reduces peak current and extends voltage conversion [17]. The major drawback of these converters is high input ripple current, and to reduce it, a filter circuit is used. At higher ratings, a push-pull converter is more efficient and reduces switching components. The types of push-pull converters [16, 17] are summarized in Table **2**.

2.1.3. Flyback Converter

In flyback converters [18], the inductor adjusts the voltage gain. Flyback converters involve the advantages of galvanic isolation and great dynamic behavior. High switching stress across the switches is the conventional flyback converter's major drawback. To reduce switching losses, a snubber circuit [19] is used. Snubber circuits are used to clamp the voltage or control the rising voltages in a short time. Active clamped circuits recover the energy from leakage inductance and reduce current ripples. Different types of flyback converters [18, 19] are summarized in Table **3**.

2.1.4. CUK and SEPIC Converter

An isolated Cuk converter is used to control the output voltage, and it helps to eliminate current ripples [20]. These converters have additional benefits, such as high power density and low operating frequency. In the SEPIC (single ended primary inductor converter) switch [21], a clamping switch and clamping capacitor are used to minimize leakage inductance. Different types of these converters [20, 21] are summarized in Table **4**.

2.1.5. Multilevel Converter

The voltage jump during each switching operation has an impact on the power converter's switching loss, switching harmonics, and electromagnetic interference (EMI) [22]. A multi-level power converter minimizes each switching operation's voltage jump, and reduces switching loss, switching harmonics, and EMI [23]. Smaller size and reduced cost are benefits of the isolated DC-DC power converter. Applications for an isolated DC-DC power converter include DC microgrids, high voltage direct current power distribution systems for data centers, and electric vehicles. Different types of multilevel converters [22, 23] are summarized in Table **5**.

Table 3. Isolated Fly-back DC-DC converters.

Fly-back Converter	N_S	N_C	N_L	Efficiency (%)
[18]	2	2	2	95.5
[19]	4	1	2	87

Table 4. Isolated cuk & sepic DC-DC converters.

Forward Converter	N_S	N_C	N_L	Efficiency (%)
[13]	7 or 8	3	2	92
[14]	4	1	2	91
[15]	4	3	1	88

Table 5. Isolated multilevel DC-DC converters.

Isolated Multilevel	N_S	N_C	N_L	Efficiency (%)
[22]	3	5	1	94
[23]	5	5	2	97.3

Table 6. Isolated bidirectional DC-DC converters.

Bidirectional Converter	N_S	N_C	N_L	Efficiency (%)	
				Step Up	Step Down
[24]	6	3	3	95	94.5
[25]	14	3	7	95	96

Table 7. Conventional boost DC-DC converters.

Boost Converter	N_S	N_C	N_L	Efficiency (%)
[29]	2	1	4	94.72
[30]	2	1	1	90
[31]	8	2	3	95

2.1.6. Bidirectional Converters

Bidirectional DC-DC converters are playing a vital role in many emerging applications, like batteries, super-capacitors, and ultra-capacitors. Isolated bidirectional converters are more suitable for various applications due to their higher voltage gains along with galvanic isolation as they are safe to use [24]. These converters are simple in configuration. The only problem with these converters is high voltage spikes across the switches. To reduce them, additional voltage clamping circuits [25] are required that lead to complexity in converters. Bidirectional DC-DC converters [24, 25] are summarized in Table **6**.

2.2. Non-isolated DC-DC Converters

Transformers cause inductance voltage leakage and high voltage spikes in active components, which leads to high power dissipation [26]. Due to the non-utilization of a transformer, this configuration is simple, of less cost, and involves minimal weight and size [13]. As isolated converters involve the limitation of voltage surge in the transformer [18], non-isolated converters are used. Non-isolated DC-DC structures can typically operate at low power levels while being smaller and more affordable. Several studies have been conducted on non-isolated DC-DC converters due to their wide range of applications and ease of implementation and design [26]. These converters are mostly used in applications where a backup of power is necessary. Some of the non-isolated DC-DC converters are described and tabulated below along with their efficiencies and component counts.

2.2.1. Boost Converter

Due to its simple structure as well as high efficiency, the classical boost converter is used in many step-up applications. When a high step-up ratio is required, utilizing the boosting technology can be disadvantageous due to its low efficiency and maintenance. Many techniques have been proposed to extend the voltage gain of conventional converters [27]. The boost converter [28] is one of the popular topologies for non-isolated DC-DC converters. It has led researchers to the development of novel topologies [29] aiming to improve the efficiency. These efficient converters can be used in many other applications instead of other advanced topologies. Based on the conventional buck-boost converter, several step-up DC-DC topologies [30] have been proposed in order to improve key issues, such as efficiency, voltage gain [31], and power handling capacity. Different types of these converters [29-31] are summarized in Table **7**.

2.2.2. Switched Capacitor Converter

To achieve high voltage gains at lower duty cycles, switched capacitors (SC) are a suitable option [32]. Switched capacitors are simple in structure and flexible to meet voltage stress requirements. Voltage gradually increases whenever a switched capacitor is connected with a conventional step-up converter [33], which leads to the drawback of high input ripple currents. Switched capacitors are categorized into Dickson and Ladder [34] configurations based on the structure. These converters achieve high voltage gain with low voltage spikes by attaining soft switching. These converters [32-34] are summarized in Table **8**.

Table 8. Switched capacitor DC-DC converters.

Switched Capacitor	N_S	N_C	N_L	Efficiency (%)
[32]	2	4	3	96.2
[33]	2	3	2	95.6
[34]	2	3	2	97.2

Table 9. Switched inductor DC-DC converters.

Switched Inductor	N_S	N_C	N_L	Efficiency (%)
[35]	2	1	4	95.1
[36]	3	1	6	95.6
[37]	3	3	3	95.72
[38]	4	3	2	95.58

Table 10. Multi-level DC-DC converters.

Multi-Level Converter	N_S	N_C	N_L	Efficiency (%)
[39]	1	3	3	93.3
[40]	15	6	2	94.3

Table 11. Interleaved DC-DC converters.

Interleaved	N_S	N_C	N_L	Efficiency (%)
[41]	2	2	2	95
[42]	2	3	2	92

2.2.3. Switched Inductor Converter

Switched inductor topology helps to reduce the ripples in input current [35]. A wide range of voltages are achieved at low duty ratios and few components [36]. Active switched inductor topology reduces input current spikes and high tendency to enter saturation regions. This topology achieves high efficiency at low-duty ratios [37]. The different types of this converter [35-38] are summarized in Table **9**.

2.2.4. Multi-level Converter

Multilevel converters are categorized into cascaded and modular. Multilevel inverters are designed without an inductor so their cost is very low and they reduce voltage stress across the switches. This control method is simple and efficient because switches are operating at a fundamental frequency [39]. As this converter uses more number of switches, it is difficult to control the power flow and high switching losses. Further, due to an increase in the voltage level, it requires extra clamping diodes. The different types of this converter [39, 40] are summarized in Table **10**.

2.2.5. Interleaved Converter

To improve the voltage gain, interleaved converter with a Dickson voltage multiplier has been proposed [41]. On active switches, it has low switching stress [42]. It has comparatively lower voltage gain at high duty ratios and high current ripples. The different types of this converter [41, 42] are summarized in Table **11**.

2.2.6. Bidirectional Converter

Non-isolated bidirectional converters are superior to isolated converters in terms of high efficiency, low cost, high power density, and simpler structure. Several non-isolated converters are reported in the literature [43-45]. In the first type [43], a ladder-switching network of inductors and capacitors is used to attain voltage gain for EV onboard charger applications. In the second type [44], a combination of the switched capacitor and switched inductor techniques attains high gains at lower duty ratios using a less number of passive elements. An extendable bidirectional converter has also been reported [45] for attaining high gains, less number

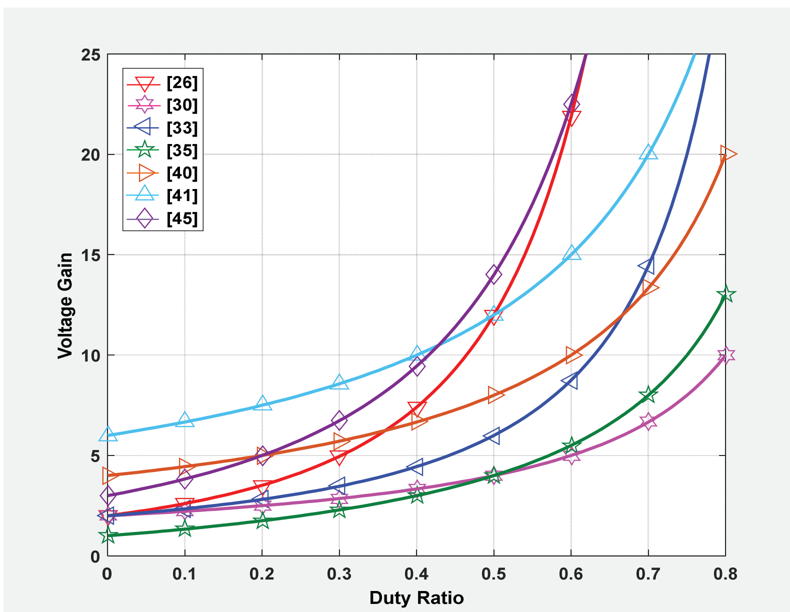

Fig. (3). Compassion of voltage gain *versus* duty ratio of the non-isolated DC-DC converters. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Table 12. Non-isolated bidirectional DC-DC converters.

Bidirectional Converter	N_S	N_C	N_L	Efficiency (%)	
				Step Up	Step Down
[43]	4	2	3	95.4	94.9
[44]	5	2	4	95.3	95.6
[45]	4	3	4	96	96.8

Table 13. Comparative study of DC-DC converters.

S. No.	Methodology	Features	Demerits	Efficiency	Complexity	Gain
1	Isolated high-gain DC-DC converter [46-48]	1. Regulating the high-frequency transformer's winding turns-ratio (k) 2. Applicable to high power levels 3. Meets grid standards 4. Easy to implement	1. Mismatch in the input-output conversion ratio by the transformer's turn ratio; at this time, the switching loss rises exponentially. 2. Transformer leakage inductance creates surge voltage spikes on power switches. 3. Size and cost increases, and circuit's implementation is complicated.	Medium	High	-
2	Voltage multiplier [29, 49]	1. Very high voltage stability 2. Simple cell-based structure 3. Integrated into various structures	1. Components show high voltages. 2. Multiple levels are complex to handle at a higher voltage.	Medium	Medium	Low
3	Capacitor clamped [31]	1. Integration is easy 2. Responds quickly	1. Only discrete output voltage 2. The number of switched capacitors boosts voltage gain mostly, leading to an increase in component count	High	High	Medium
4	Switched inductor [35, 50]	1. Boosting ability is high 2. Designed for medium voltage levels so applicable in many converters' configurations	1. Requires a high number of passive elements 2. For high-voltage applications, it is not suitable	Medium	High	Medium
5	Switched capacitor [51-53]	1. Low in design cost and simple integration 2. High power density	1. At starting, it has high inrush currents 2. Sensitive to the ESR of capacitors 3. Difficult to control the output voltage	Low	Low	Medium
6	Magnetic coupling [54, 55]	1. High design freedom 2. Tunable turns ratio	1. Large voltage spikes have a negative impact on the system 2. Bulk in size	High	Low	Low
7	Coupled inductor [56]	1. Switches can be used to reduce conduction losses on the low-voltage side. 2. High efficiency in soft-switched type	1. Snubber circuit is mandatory 2. Requires precise magnetic couple design	High	Medium	Low
8	Multi-stage/multi-level [40]	1. Used in high-power applications 2. It is highly reliable	1. Requires more components 2. High cost and bulky	Low	High	Low
9	Interleaved [57]	1. Applicable in high-power applications 2. Highly efficient 3. No transformer for boosting	1. Low voltage conversion ratio 2. Voltage stress across the switch is high 3. Complexity in control of the circuit	High	High	Low
10	Cascaded [39]	1. Voltage gain is high 2. Low output ripple currents	1. High voltage stresses 2. Components count increases	Low	High	High

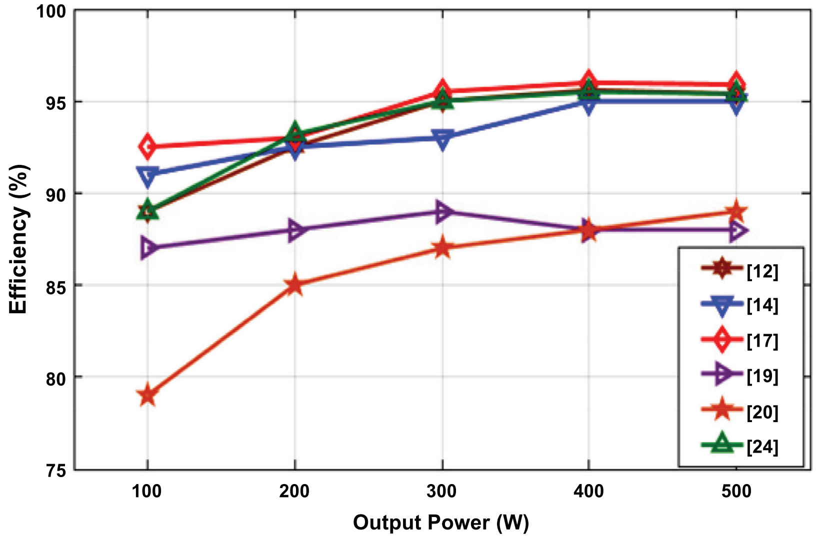

Fig. (4). Comparison of efficiency *versus* output power of DC-DC converters. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

of switches, lower voltage stresses across the switch, and extendable configuration. Different types of this converter [43-45] are summarized in Table **12**.

3. COMPARATIVE ANALYSIS OF DC-DC CONVERTERS

From the detailed literature survey, voltage gain ratios of different DC-DC converter methodologies have been studied.

The characteristics of the DC-DC converters have been studied in this paper. Their various methodologies, features, demerits, complexities, and gains are summarized in Table **13**. The comparison between voltage gain and duty of the various non-isolated DC-DC converters is presented in Fig. (**3**). The efficiency versus output power of isolated DC-DC converters is presented in Fig. (**4**).

CONCLUSION

This review paper has addressed several DC-DC converter-based topologies. The DC-DC converters reported in the literature with a focus on their gain, efficiency, and component count, are categorized and tabulated for various methodologies in the comparative study table. According to the design, the optimal DC-DC converters are chosen. Gain comparative analysis plot has also been drawn in this work for different converters. Through evaluating the performance of the converter, topology selection can be done for any particular application.

LIST OF ABBREVIATIONS

PV	=	Photovoltaic
HEV	=	Hybrid Electric Vehicle
FCV	=	Fuel Cell Vehicle
VMC	=	Voltage Multiplier Cells
SCs	=	Switched Capacitors
DC	=	Direct Current

CONSENT FOR PUBLICATION

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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