Comparison and Optimization of Non-isolated DC-DC Converters for Electric Vehicle Applications

Junchi Yan*

School of Electrical Engineering, Shenyang University of Technology, Shenyang, China

*Corresponding author: 1811571126@mail.sit.edu.cn

Abstract. This paper discusses the importance of electric vehicles in solving the problem of environmental pollution. In electric vehicles, DC/DC converter is a vital part to connect many electrical units with high voltage bus, so it plays a vital and indispensable role in electric vehicles. The paper analyzes the disadvantages of isolated DC/DC converter, and concludes that non-isolated DC/DC converter is a more suitable technical solution for electric vehicles. The research paper introduces a number of fundamental non-isolated DC/DC converter topologies before analyzing the technical optimization strategies of a number of DC/DC converters in general. which are Half-bridge converters, Cascaded Half-bridge converter (CHB), multi-phase interleaved parallel converter, tri-level converter, soft-switching converter, and switched-capacitor converter (SC converter). The benefits and drawbacks of these DC/DC converter optimization measures are compared, the findings can serve as a technical framework for guiding the application of DC/DC converter technology in the context of electric vehicles. Finally, this paper analyzes and looks forward to the development prospect of flying switched-capacitor DC/DC converters (FCDCs) technology, puts forward the existing technical problems, and gives suggestions for the solution of these problems, which is conducive to the wider application of this technical solution in electric vehicles.

Keywords: Electric vehicle, DC/DC converter, non-isolated DC/DC converter, optimization.

1. Introduction

With the progress of industrial civilization and the development of science, a large amount of fossil fuels are consumed in human industrial production and daily life. Environmental problems have become very serious, such as the greenhouse effect and atmospheric pollution [1, 2]. In the transportation sector, because conventional vehicles need to burn gasoline, diesel or natural gas, they produce large quantities of harmful exhaust and greenhouse gases, such as carbon dioxide and sulphur dioxide. Greenhouse gas emissions has become a major hazard to the natural environment and human survival. According to the European Union, from 1990 to 2010, greenhouse gas emissions from other sources decreased by 15%, while emissions from the transportation sector increased to 36% [2]. Even though the technology of conventional vehicles has evolved in recent years, the transport sector still accounted for about a quarter of total greenhouse gas emissions in 2017 [2].

In order to address the overuse of fossil fuels in transportation, the world's energy consumption needs to transition to green technologies, and it is important to develop the electric vehicles. Global electric vehicle use is expected to be approximately 200 million units by 2023 [3]. An electric vehicle contains many electrical units, such as power battery, auxiliary battery, super capacitor, charging device, motor inverter, etc., which are connected through a high-voltage (HV) bus [2, 4, 5]. Fig.1 illustrates the structure of an electric vehicle.

In electric vehicles, numerous electrical components necessitate the utilization of a DC/DC converter to interface with the HV DC bus. For example, power batteries, super capacitors and fuel cells can exhibit substantial voltage fluctuations in their output when electric vehicles experience rapid acceleration or abrupt braking events. DC/DC converter ensures that the HV DC bus's voltage remains unaffected [2]. To summarize, DC/DC converters find extensive application in electric vehicles, the technology optimization in terms of system efficiency, power density and device cost are very important for the development of electric vehicles.

DC-DC converters can be categorized into isolated and non-isolated types based on the level of input and output isolation. Isolated DC/DC converters incorporate a transformer to provide isolation between the input and output sides. Because The size and weight of transformer is large, the isolated DC/DC converters are not appropriate for use with electric vehicles. Transformer is not required by a non-isolated DC/DC converter, the circuit is simple and the weight of the inductor is light. Due to the substantial power density of this DC/DC converters, they align more closely with the application demands of electric vehicles [2-5].

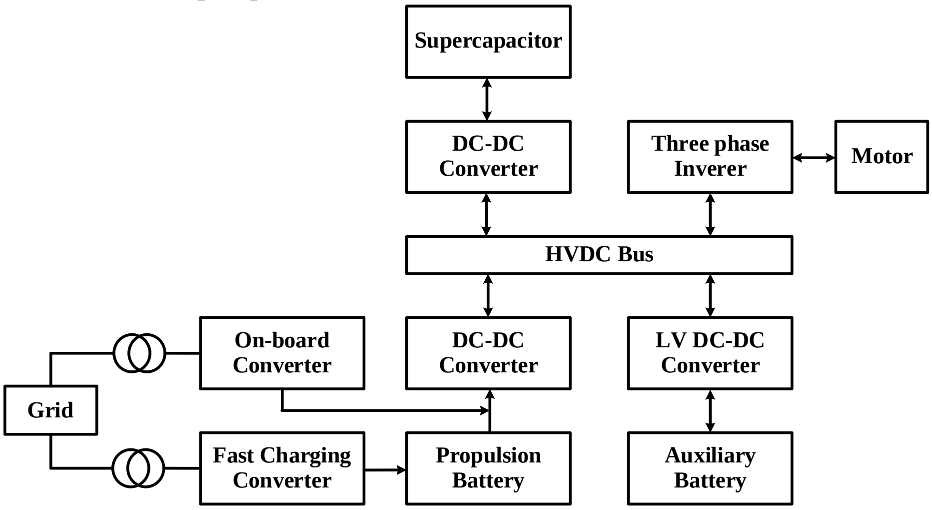

Fig. l Module diagram of an electric vehicle [2]

Based on the above analysis, this paper exclusively focuses on non-isolated DC/DC converters in the subsequent discussion

In this paper, DC/DC converters for electric vehicles are analyzed and studied in the following three areas:

Analyze the basic topology principles of DC/DC converters, and compare the merits and demerits of various topologies;

Examine multiple optimized configurations for DC/DC converters, along with their enhancement principles concerning converter power, efficiency, voltage ripple, and electromagnetic compatibility (EMC).

Analyze the strengths and weaknesses of the enhanced DC/DC converter circuit and their application characteristics in electric vehicles.

2. Basic of Non-isloated DC-DC Converters

DC/DC converters can be categorized into various topologies. For example, Boost topology, Buck topology, Buck-Boost topology, and Cuk topology.

Buck topological circuit converter can reduce the input voltage in a certain proportion, output from the output terminals of the same polar voltage value. The topological circuit converter can increase the input voltage in a certain proportion, and the voltage value of the same polarity can be output from the output terminals of the same polar voltage value. The Buck-Boost topological circuit converter can increase or decrease the input voltage in a certain proportion, and output the opposite voltage value from the output terminals. These three-circuit topological converter s consists of a power switch, a filter sensor, a filtering capacitor and a diode. One common advantage of these topological structures is that the circuit structure is very simple and can greatly reduce the cost of manufacturing the converter [6].

The number of components of the Cuk topological circuit converter is large. Because Cuk circuit has the inductors on both inputs and outputs, so the circuit structure is very complex, the cost of producing the converter of Cuk topological to will be very expensive. The Cuk topological circuit converter is not suitable for energy-intensive conversion applications. Because the input and output terminals of the Cuk circuit have Filter inductors used for current filtering., so that both the inputs and outputs of the current wave’s ripple is minimal [5].

Figure 2 describes the circuit topology of the four voltage converters described in this chapter, all in the form of input to output without the use of voltage separation measures.

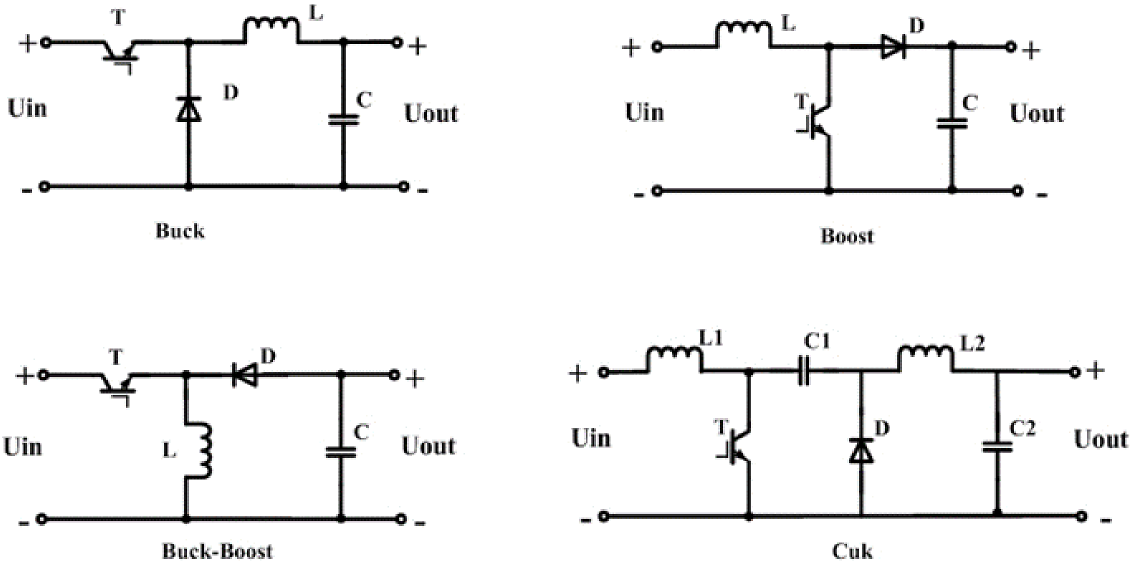

Fig. 2 Circuit schematic of classic DC/DC converter

Table 1.Characteristics and Utilizations of DC/DC Converters.

type	Advantage	Disadvantage	Applications
Buck	Low costs, highly efficiency	Unidirectional	Charging for auxiliary battery
Boost	Low costs, highly efficiency,	Unidirectional, high output ripple	Connected to power battery and motor drive
Buck-Boost	Low cost, high efficiency, step-up/ down	high output ripple	The reversal polarity conversion

Table 1 lists the characteristics of the four DC/DC converters described in this chapter by comparing their respective the strengths and weaknesses. Based on these comparisons, several best applications of circuit topology are listed. In the above comparison, Buck topological and Boost topological converter are more suitable to electric vehicles, and this paper will study to improve these two topologies' circuits.

3. Improved Topology for Non-Isolatect DC-DC Converters

3.1. Half-bridge Converter

Buck topological and Boost topological circuits are unidirectional converter circuits. We can form a converter with a Buck topological and a Boost topological circuit, and this new converter has the functions of two converters. The new converter will transform the input voltage for step-up, and output voltage by the output terminal. The new converter also enables the step-down, conversion of voltage from the output terminal to the input terminal. We call this new conversion circuit the half-bridge converter, as shown in Figure 3.

When switch T2 is deactivated, switch T1 and diode D2 collaborate to establish a Boost topological circuit, allowing power to flow from the input to the output. Conversely, when switch T1 is deactivated, switch T2 and diode D1 cooperate to create a Buck topological circuit, enabling power transfer from the output to the input.

The circuit in Fig. 3 is the step-up converter. The step-down DC/DC converter can be achieved by interchanging the switch and inductor. The two types of circuit work methods are symmetrical [5], this paper do not discuss here.

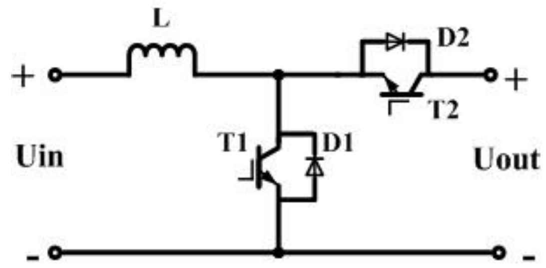

Fig. 3 Illustration of the half-bridge converter schematic diagram [5]

3.2. Cascaded Half-bridge Converter

Half-bridge converter has a great limitation, only to perform step-up conversion, or only to step-down conversion. If we need a DC/DC converter that can simultaneously lift and drop, we designed the CHB. Its circuitry is as shown in Fig. 4. Because the new converter circuit- Cascaded Half-bridge Converter (CHB) requires only one inductor, it contributes to reducing the cost and size of the device.

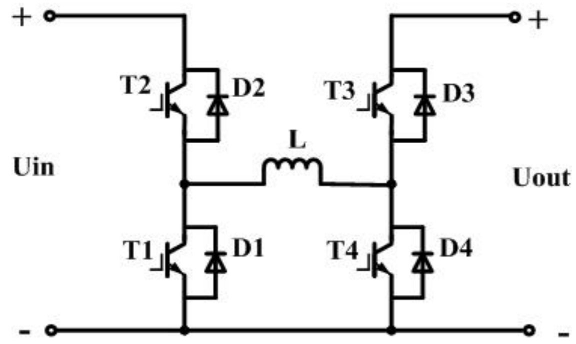

Fig. 4 Schematic diagram of CHB [5]

Table 2 show the operational modes of the four power switches when the CHB circuit operates in various operating states.

Table 2. The operational modes of the CHB

Directional	Model	T1	T2	T3	T4
Input to output	Boost	—	++	—	P
Input to output	Buck	—	P	—	—
Output to Input	Boost	P	—	++	—
Output to Input	Buck	—	—	P	—

"-" means OFF; "++" means ON; "P" means PWM

The Table 2 shows that when the CHB circuit is in operation, more serial switching devices are required, so the conversion efficiency is reduced, which is a disadvantage of CHB. Improving the efficiency of the CHB circuit requires that the power switch components have smaller conduction voltage drops.

3.3. Interleaved Parallel Converter

When the inputs and outputs of several converters are connected in parallel to form a new topology, great power and low current ripple is realized. We call this circuit interleaved parallel converter.

Figure 5 depicts a circuit topological structure of a circuit that is intersected by three Boost topological converter circuits, resulting in a three-phase interleaved parallel boost converter. The current of the filter inductor L1 can be adjusted by the power switch T1 via PWM control. Two other filter inductors can also be controlled by the corresponding power switch. The total current at the output end of the transformer is equal to the sum of the current of the three above-mentioned filter inductors [2, 5].

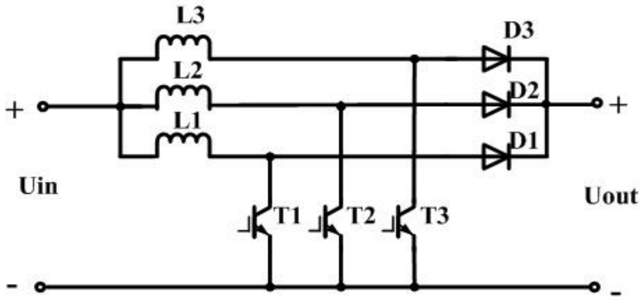

Fig. 5 Illustration of Interleaved parallel converter schematic diagram [5]

To illustrate the working process of the Interleaved parallel converter, take the N-phase intersection parallel converter as an example. The N-phase intersection parallel converter contains N power switches, corresponding to the control of N filter inductors. Each road power switch is cyclically fixed, and the pulse width of the high voltage level can be adjusted to control the wave shape. In the control strategy, we aim to disconnect the control pulse of this N power switch at 360/N phase interval, so that the current wave shapes obtained on the filtering inductors will dislike each other at the same angle. The current wave shapes of these filtering inductors are combined, and the frequency of the total output current obtained at the output terminal of the transformer can be enhanced by a factor of N, thereby significantly reducing the current ripple of the outputs.

3.4. Soft-Switching Converters

Enhancing the switching frequency can lead to a reduction in the dimensions and mass of the inductor in DC/DC converters. When the switch operates at high frequency, the switching losses will increase rapidly and the efficiency of the converter will decrease. The use of soft switching technology can solve this problem [2].

Because the rise of the current in the switching element during conduction is earlier than the fall of the switch terminal voltage, the conduction loss occurs. Conversely, during the switching off process of the switch, the fall of the current occurs later than the rise of the terminal voltage of the switching element, and the switching off loss occurs in this way. Soft turn-on can be achieved if the switching element is capable of making the rise in current occur after the rise in switch terminal voltage during turn-on. Conversely, if the rise in voltage of the switching element during turn-off occurs after the fall in current, soft turn-off can be realized.

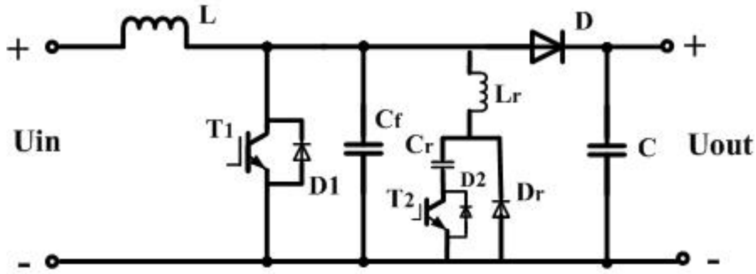

Fig. 6 Illustration of a Soft-Switching DC/DC Converter Schematic Diagram [2]

Fig. 6 shows a soft-switching converter with resonant circuit. The Boost topology adds Cf and an RC resonant circuit. The RC resonant circuit consists of Lr, Cr, Dr r and an auxiliary switch T2.

The presence of capacitor Cf and the RC resonant circuit facilitates soft-switching operation for the primary switch T1, while the resonant circuit enables the auxiliary switch T2 to operate in the ZCS mode.

Resonant soft-switching technology makes the switching loss of the switch very small. The converter's efficiency has been significantly enhanced, and, furthermore, it has led to a notable reduction in electromagnetic interference. These enhancements to the DC/DC converter align effectively with the demands of electric vehicle applications, for example the charging of auxiliary batteries.

3.5. Three-Level DC/DC Converter

The traditional DC/DC converter, the switch operates at two levels. The circuit structure is simple and reliable. Because the voltage stress on the switches of a two-level DC/DC converter is very high, the electromagnetic interference in the converter circuits is great. A three-level converter circuit can be used to solve this problem.

The Three-Level DC/DC converter (TLDC) can cut switching voltage stress in half, the electromagnetic interference in the converter circuits will be greatly improved. There are many circuit forms that can be triple-level functions, for example, you can string four power switches to string three connectors. Connection points 1 and 3 are connected to the middle point of the direct current mother line by diode, respectively Connection point 2 as the output. This type of circuit topology is called the Type I triangular technique. It is also possible to connect two power switches, the serial connection point on one side as the output end, and the end is also connected to the middle point of the direct current mother line through two reverse serial power switches. We call this circuit the T-type three-level technology. Finally, this chapter adopts the technology of using the capacitor, which Replace the two diode tubes in the type I triple-plane topology with a high-frequency capacitor, and do not connect the middle point of the DC mother line. we call flying capacitor TLDC.

Because the reliability of the flying capacitor method is better, the TLDC of the flying capacitor method is more suitable for electric vehicle applications [7, 8].

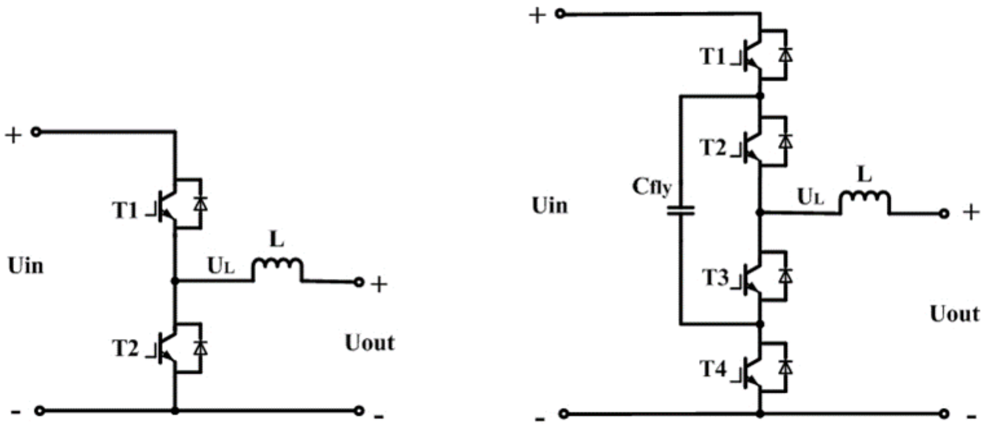

Fig. 7 Schematic diagram of two-level and three-level circuits [7,8]

Fig. 7 shows the Buck topological converter circuit topology with the two-level and the three-level. The two-level circuit topology is illustrated in the left-hand portion of Fig. 7. When the switches TI and T2 conduct alternately, the voltage UL changes between Uin and 0. As a result, the voltage UL can realize two-level controlled at the converter output. The three-level circuit topology is depicted in the right-hand section of Fig. 7. The voltage of the flying capacitor Cf1 is stabilized at Uin/2. Table 3 presents the operating modes of the three-level converter. As can be seen from Table 3, the voltage UL of the TLDC can vary between Uin, Uin/2 and 0, which can realize three-level controlled at the converter output [8].

Table 3. The operational states of the three-level converter.

T1	T2	T3	T4	U_L
++	++	—	—	Uin
++	—	—	—	Uin/2
—	++	P	++	Uin/2
—	—	—	++	0

"-" means OFF; "++" means ON; "P" means PWM

3.6. Switched-Capacitor Converter

The traditional Energy conversion components converter in the converter is filter inductor or transformer, so elevating the power density of the DC/DC converter poses a formidable challenge.

The use of capacitors instead of inductors can reduce the volume and weight of the DC/DC converter. This technology is referred to as the Switched-Capacitor Converter (SC) in the field of DC/DC converters [9].

SC converter technology have been successfully applied in the low-power area, e.g., distributed power systems, communication power supplies and power supplies for mobile devices. Many companies have developed highly integrated switched-capacitor control chips, which can realize Optimized efficiency and power density in SC converter.

The circuit topology shown in Fig. 8 is a kind of SC converter, named flying capacitor DC/DC converter (FCDC). While the conversion ratio of the FCDC is constrained to a fixed integer, the control approach for this converter circuit remains highly straightforward. This converter put forward several merits, including elevated conversion efficiency, enhanced power density, and reduced electromagnetic interference.

From the circuit topology, it is not difficult to see that TLDC and Flying SC circuit structures are very close, the main difference is that the TLDC has a filter inductor on the output side, which is the main energy transmission component, so it belongs to the Buck topological circuit, the capacitor in a circuit is only a level state when providing three-level. The energy transmission component of the Flying SC circuit is a cross-capacitor, so the capacity of the capacitor is far greater than the capacitive value in the SD circuit.

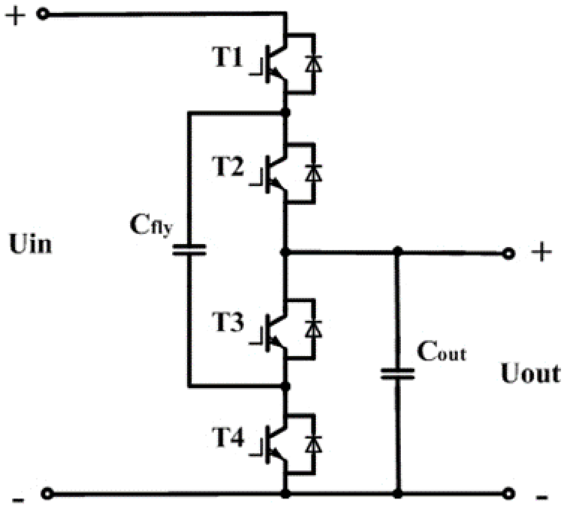

Fig. 8 Illustration of a Schematic Diagram for a Flying Switched Capacitor Converter [9]

The current research trajectory in FCDCs is oriented towards high voltage and high-power applications, thereby enabling their utilization in contexts such as photovoltaic power generation systems, uninterruptible power supply (UPS) units, and electric vehicles. [10].

4. Comparison of Different Improved Non-isolated DC-DC Converter

Based on the conclusion that the DC/DC converter is a more suitable technical solution for electric vehicles, previous section analyzes the overall technical optimization strategies for DC/ DC converters, which are Half-bridge converters, Cascaded Half-bridge converter (CHB), multi-phase interleaved parallel converter, tri-level converter, soft-switching converter, and switched-capacitor converter (SC converter). Improved DC/DC converters have significant improvements in performance and functionality, such as the bidirectional conversion function, increasing in conversion power, improving the converter efficiency and power density, reducing the output voltage ripple and electromagnetic interference. The benefits and drawbacks of the corresponding circuit topological structure are summarized by analysis of each technical optimization measure. It will serve as a technical framework to guide the application of DC / DC converter technology in electric vehicles.

The traits of the aforementioned six enhanced DC/DC converters are presented in Table 4.

Table 4. Improved DC/DC converters' features

Converter type	Advantage	Disadvantage
Half-bridge	Simple circuitry, low-cost, High efficiency	Step-up or step-down conversion only
Cascaded Half-bridge	Step-up and step-down conversion	Complex circuit, high cost, low efficiency
interleaved parallel	High power, Low ripple	control strategy complex
Soft-switching	Low loss of switching, low EMI high efficiency	Complex circuit, high cost, poor reliability
Three-Ievel	Low ripple, low EMI	Complex circuitry, high cost, poor reliability
Switched capacitor	Low device weight, Simple control, low EMI	Low Voltage, Low Power

5. Conclusions

This paper analyzes the basic converters' principle, converters such as Buck topology, and Boost topology. The basic DC/DC converters are adapted to electric vehicles because of their advantages such as low cost and high conversion efficiency. This paper obtains Six improved non-isolated DC/DC converters, using lots of measures such as interleaved parallel technology, TLDC technology, soft-switching technology, and SC conversion technology, etc. The improved DC/DC converters exhibit substantial enhancements in performance and functionality, such as the bidirectional conversion function, increasing in conversion power, improving the converter efficiency and power density, reducing the output voltage ripple and electromagnetic interference. This paper compares various improved DC/DC converters and summarizes each topology's strengths and weaknesses. The results of the comparison can be the basis for selection of converter technology in electric vehicle applications. As the FCDC does not necessitate the inclusion of filtering inductors, it put forward significant advantages with regard to converter power density and system efficiency. If the FCDC make breakthrough in the HV and high-power conversion capability, it will be very suitable for application in electric vehicles. High-power optimization of FCDC requires the solution of two problems. One is power switching devices with high frequency characteristics, the other is the capacitors with high ripple current characteristics. The research on High Power Silicon Carbide Switch and Current Resistant Capacitor can lead to solutions of these two problems.

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