Research On the Application of High Efficiency DC-DC Converter in New Energy Vehicles

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Abstract. In response to the global energy crisis and pressing environmental concerns, new energy vehicles (NEVs) have emerged as a critical solution. The shift from traditional fuel vehicles, which exacerbate environmental pollution and deplete energy resources, has heightened interest in NEVs due to their eco-friendly and efficient properties. Within the technological framework of NEVs, the DC-DC converter plays an essential role. It enables efficient electrical energy management and regulation, ensuring the stability, efficacy, and safety of the vehicle's systems. This paper conducts a review of innovative DC-DC conversion technologies, with a particular focus on their application in NEVs. Initially, it presents an overview of the fundamental principles underlying DC-DC converters. It proceeds to describe the design and operational mechanisms of the three classical topologies of DC-DC converters—namely Buck, Boost, and Buck-Boost circuits. The ensuing section details the pivotal DC-DC converter modules utilized in NEVs. Furthermore, the paper elaborates on various novel conversion technologies across three dimensions: multilevel converters, bidirectional converters, and soft switching technologies. This includes the development of new circuit topologies and control strategies, and discusses the advantages these innovative technologies offer. The aim is to contribute to the progressive enhancement of DC-DC converter technologies in forthcoming NEV designs.

Keywords: Efficient conversion technology; NEV; DC-DC converter; Topological circuit.

1. Introduction

Regarding the present worldwide energy crisis and environmental issues, new energy vehicles have garnered significant interest as a crucial remedy. The emission of traditional fuel vehicles not only aggravates environmental pollution, but also causes serious pressure on energy supply [1]. In this case, the rise of new energy vehicles has become the focus of attention, and its clean and efficient characteristics have attracted wide attention and support [2].

In the technical composition of new energy vehicles, DC-DC converter, as a key technology, plays an indispensable role. More importantly, this technology can be used to efficiently manage and control the flow of electrical energy, ensuring the stability, efficiency, and safety of the vehicle system. It can also convert the voltage of the high-voltage DC battery system into a voltage suitable for motor drives or low-voltage electronic equipment power supplies [3].

This paper presents a detailed introduction to the concept of a basic DC-DC converter. It also analyzes and presents the basic topological circuits of Buck, Boost, and Buck-Boost classical DC-DC converters, and goes into great detail into the workings of their switching circuits, which use PWM control technology. The key DC-DC converter parts found in new energy cars—such as the battery and the vehicle equipment part—are then presented to demonstrate the close relationship between the two. This paper focuses on DC-DC high-efficiency conversion technology, lists and discusses the new technologies of modern multilevel converter, bidirectional converter and soft switch technology, analyzes and studies their effects, and introduces the new circuit topology and control strategy. In an effort to suggest future directions for the development of DC-DC converters in new energy vehicles, this research examines their use in these types of vehicles.

2. Theoretical foundation

A DC-DC converter, often referred to as a power converter in electrical engineering, is a type of electric circuit that modifies the voltage of a direct current (DC) source. It functions by initially storing the input energy and then discharging it at a different voltage level to the output. The storage in these converters can be in the form of either magnetic field storage components or electric field storage components. Notably, a DC/DC converter is designed to transfer power solely in one direction, from the input to the output [4]. But nearly all of them are capable of having topologies for bi-directional DC/DC converters.

The switching power supply is a high-frequency power conversion device that mostly uses MOSFET switching devices. It achieves input voltage pulse modulation, voltage conversion, and automatic voltage regulation capabilities by periodically controlling the switching device switch [5]. A type of switching power supply known as a DC-DC converter employs DC voltage as both its input and output. In a direct current circuit, it is a power conversion device that transforms the electric energy of one voltage value into another voltage value. In short, these DC-DC converters accept one DC input voltage as input and output a different DC voltage. There is a possibility that the output DC voltage will differ from the input DC voltage.

2.1. Common DC-DC Converter Circuit

The following sections of this article list three common DC-DC converter circuits

2.1.1 Buck Converter Circuit

Basic buck converter circuit is shown in figure 1.

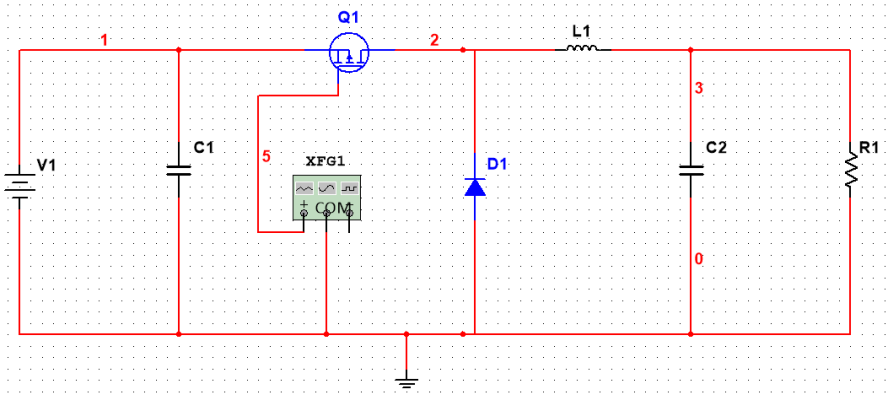


Fig. 1 Basic Buck Converter Circuit (Photo/Picture credit: Original)

$$\text{Vout} = \frac{Ton}{T} Vin \tag{1}$$

Buck circuit is a voltage step-down circuit and C1 is the input filter capacitor. When mos tube Q1 is switched on, current passes through mos tube Q1 and filter inductor L1 to charge capacitor C2 and supply power to load R at the same time [6]. The inductor will produce a self-induced electromotive force as a result of its properties. The circuit is through the filter capacitor C2 to supply power to the load when the inductor on the electromotive force is reduced or disappears. When the mos tube is disconnected, the current flowing through the inductor L1 will be reduced. Similarly, the inductor will also produce a self-induced electromotive force to hinder the current reduction. The electromotive force is then filtered by the filter capacitor C2 filter, through the load R1, and then through the continuous current diode D1 to form a loop. By adjusting the mos switching time duty ratio, the voltage at both ends of the load can be regulated using PWM control technology [7].

2.1.2 Boost Converter Circuit

Basic boost converter circuit is shown in figure 2.

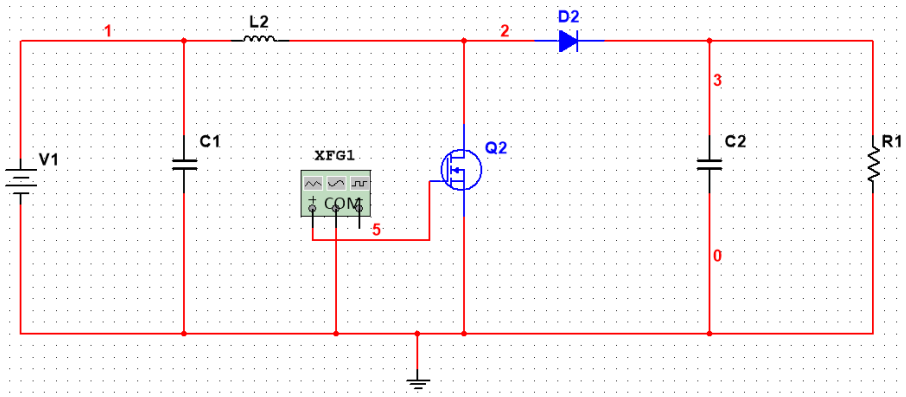


Fig. 2 Basic Boost Converter Circuit (Photo/Picture credit: Original)

$$\text{Vout} = \frac{T}{Ton} Vin \tag{2}$$

The boost circuit is a voltage step-up circuit, which is also based on PWM control technology. The input voltage passes through the inductor L2 when the mos tube Q2 is closed, and the diode D2 then stops the capacitor from discharging to earth. The inductor L2 has a linear increase in current and a certain amount of energy storage. Due to the inductor L2's ability to store current, when the mos tube Q2 is unplugged, L2 starts charging the capacitor. As a result, the voltage at both ends of the capacitor C2 rises, fulfilling the intended voltage boost function. The output voltage at the output end may continuously be higher than the input voltage if this process is carried out repeatedly. By adjusting the switching time duty ratio, it is also possible to alter the voltage at both ends of the load.

2.1.3 Buck-boost Converter Circuit

Basic boost converter circuit is shown in figure 3.

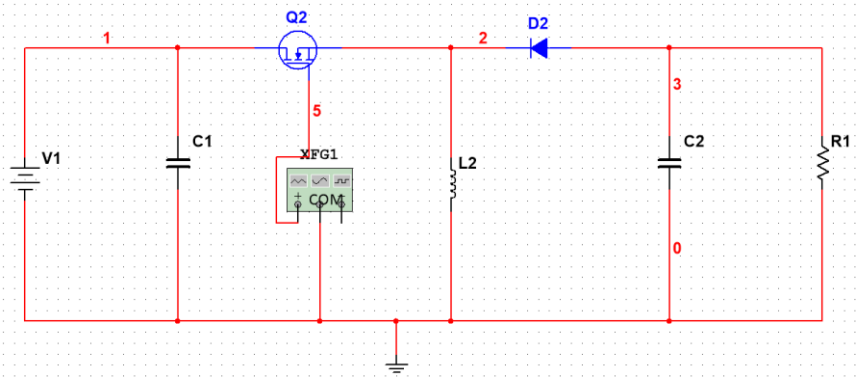


Fig. 3 Basic Boost Converter Circuit (Photo/Picture credit: Original)

$$Vout = \text{Ton}/\text{Toff}\ \text{Vin} \tag{3}$$

The Buck-Boost circuit achieves voltage rise and decline, respectively, by combining the features of both circuits. The inductor L2 in the Buck-Boost circuit is directly linked to both ends of the power supply when the mos tube Q2 is closed, causing the inductor L2 current to progressively increase. At this stage, the load R1 is powered by the input capacitor C1, while the output C2 depends on its own discharge to supply energy. When the Q2 is detached, the input V1 charges the input capacitor C1, and as the inductor current is constant, the output inductor L2 powers the output capacitor C2 and load R1 via the continuation tube D2.

When the system is running steadily, the inductance follows the volt-second conservation principle. Put another way, when the mos tube is turned on, the inductance voltage equals the input terminal voltage VIN, and when it is shut off, it equals the output terminal voltage VOUT. Modifications to

the duty cycle of the switch, which is the ratio of the on-time to the period, can alter the output voltage's amplitude and polarity with respect to the input voltage [8].

To be more precise, the output depressurizes if the duty cycle D is less than 0.5 and the voltage is increased if it is larger than 0.5. With the output voltage polarity opposite the input voltage, this circuit can be used as a buck or boost circuit.

2.2. NEVs DC-DC converter

Four important DC-DC converters in new energy vehicle are shown in Figure 4.

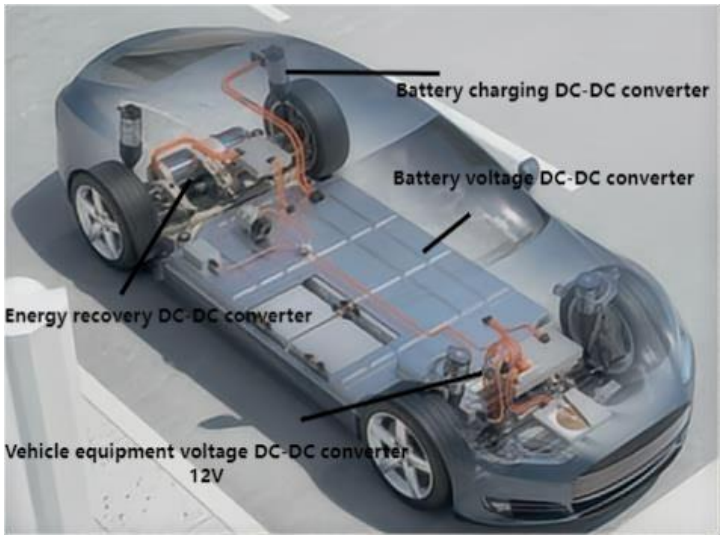


Fig. 4 New energy vehicles' (NEVs) DC-DC converter (Photo/Picture credit: Original)

Based on discharge and charging, the DC-DC converter predicts that the battery voltage of the new energy vehicle will change while it is in use. The battery voltage may be continuously monitored by the DC-DC converter, which may then adjust the output voltage to preserve stability and keep the battery voltage within the optimal working range [9]. The purpose of the DC-DC converter used in new energy vehicle battery charging is to maximize charging efficiency by converting the voltage and current supplied by the charging apparatus into a standard that is appropriate for battery charging. Different types of battery charging require different voltages and currents, and charging piles or other charging devices may output voltages that do not match the requirements of the battery. Furthermore, the battery charging DC-DC converter provides charge protection and control functions to ensure the safety and reliability of the charging process [10]. Furthermore, many battery types, like nickel-metal hydride and lithium-ion, may be used in new energy vehicle batteries. The properties and needs for charging vary depending on the type of battery. Battery charging DC-DC converter enables charging adaptability, adjusting charging parameters according to different types of battery to provide the best charging performance.

When the new energy vehicle is driving or braking, a large amount of inertia force and braking energy will be generated. Usually, this energy is wasted and is lost to the environment through the brake as heat. The energy recovery DC-DC converter can recover this wasted energy, convert it into electricity and store it in the battery, improving energy efficiency [11].

The Vehicle equipment DC-DC converter convert high battery voltages (such as 400 volts) to low voltages (such as 12 volts) required by other electrical equipment on the vehicle. In this way, it can achieve effective conversion and transmission of electricity, ensuring that electricity from the battery is efficiently supplied to the various devices on the vehicle.

3. DC-DC high efficiency conversion technology

3.1. DC-DC multilevel converter

Several cascaded DC-DC converters, each in charge of converting the input voltage to a distinct output voltage, make up a DC-DC multilevel converter. This structure enables efficient conversion of electrical energy while providing outputs of different voltage levels to meet the needs of various applications. The DC-DC multilevel converter works by converting the input voltage into an intermediate voltage in stages, and then converting the intermediate voltage into the desired output voltage [12]. This phased conversion helps to reduce the working pressure difference of each converter and improve the overall conversion efficiency. In addition, the multistage structure can also achieve a large input-output voltage conversion ratio, while maintaining high efficiency and stability.

The problem of voltage imbalance in capacitors during DC-DC conversion is effectively resolved by the hybrid modular multilevel DC-DC converter topology that Diab, M., Elserougi, AA, and Abdel-Khalik, AS from the Alexandria University Faculty of Engineering in Egypt present [13]. Together with half-bridge and full-bridge submodules in the upper and lower arms and soft-switched high-voltage valves, the suggested topology makes use of a single MMC leg. Since the concerned arms' capacitors are connected in parallel, arm energy equalization is sent down to the suggested hybrid modular multilevel converter. To promote energy transfer between the involved arms and maintain balanced capacitor voltages during the equalization phase, series-connected upper arm capacitors are linked in parallel to series-connected lower arm capacitors. It can also be utilized as a DC transformer because the proposed modular DC-DC converter is a bidirectional converter that permits power to flow from a high-voltage side to a low-voltage side and vice versa. FB-SMs should be used instead of top HB-SMs in order to give the DC-fault blocking capacity that is absent from the suggested DC-DC converter's building structure.

A proposal for a multilevel DC-DC power conversion system employing multiple bridge modular switched-capacitor converters (BMSCC) is presented by Him, LZ from Xiamen University in China [14]. Without a magnetic component, this conversion system may operate at very high temperatures and change the output voltage almost continuously. This switched-capacitor converter has less device needs and a low semiconductor VA rating compared to other ones that are currently available on the market. The proposed step-up converter has a higher efficiency advantage than other conventional step-up converters that use the output impedance analysis method.

Modular multilevel bidirectional (MMB) non-isolated dc-dc converter with a novel topology is provided by Monteiro, V., Tiago Sousa, J.C., and Afonso, J.L. of the Universidade do Minho in Portugal [15]. Given its features, it makes obvious that the suggested MMB dc-dc converter would function as a back-end converter with a large number of dc-links, connected to front-end ac-dc converters through cascade structures.

Two distinct characteristics of the MMB dc-dc converter presented in this study are that, although it is not an interleaving converter, it is operated in accordance with the interleaving operating principle and may run at five voltage levels, therefore decreasing voltage stress in a single semiconductor.

In new energy vehicles, the DC-DC multistage converter can stabilize the voltage output, provide an appropriate voltage protection mechanism for electronic devices by adjusting the voltage, and shield electronic devices from fluctuations in voltage. It can also convert the DC voltage of the car battery into the working voltage of each electronic device. At the same time, the DC-DC multistage converter can achieve an increase in power utilization efficiency regardless of the charging or using process.

3.2. DC-DC bidirectional converter

In addition to bidirectional energy conversion between DC power sources and electric energy transfer from one DC power supply to another, the DC-DC bidirectional converter may also provide energy recovery and feedback. This bidirectional converter usually consists of one or more power switching devices (such as MOSFET, IGBT, etc), control circuits and filters. Its working principle

mainly involves controlling the switching state of the power switching device to adjust the flow direction and power size of the electric energy [16]. In forward mode, the converter transfers power from one power source to another, while in reverse mode, it can return energy from the load to the power source, achieving feedback and recovery of energy.

The National Sun Yat Sen University's Teng, JH, Shen, PS, Liu, BH, and Chen, SW introduce a bidirectional DC-DC converter for defunct batteries that can be adjusted by circuit configuration [17]. The suggested converter can be configured in four distinct ways based on the voltage requirements at its terminals: interleaved boost/buck, single boost/buck, cascaded-buck-boost, and single buck/boost. Additionally, the design encompasses both a voltage-doubler circuit and a two-phase interleaved half-bridge circuit. With the circuit customized design of the recommended converter, it is possible to acquire a broad range voltage conversion ratio as well as bidirectional buck and boost capabilities. For the intended bidirectional DC-DC converter, a prototype circuit is created and put into use. Its rated voltage at the two-phase interleaved half-bridge circuit terminal is 150V, and its rated power is 1100W. Its rated voltage at the voltage-doubler circuit is 25V to 1050V.

Wu, YE, and Chen, KC of the National Kaohsiung University of Science & Technology present a novel, highly efficient bidirectional isolated DC-DC converter [18]. To accomplish isolation and bidirectional power flow, the proposed converter combines a switched-capacitor voltage doubler with a coupled inductor. The proposed topology, featuring five switches and an inductor with a common core, allows for achieving large voltage gains without relying on high turn ratios or excessive duty cycles. It controls and uses only a set of complementary pulse-width-modulated signals. Additionally, the suggested topology can increase conversion efficiency by recovering the energy lost through leakage inductance. Zero-voltage switching is present in the main switches, which lowers switching losses.

The Harbin University of Science and Technology's Zhou Meilan, Liu Yang, Huang Fengtao, and Wu Xiaogang demonstrate a bidirectional DC-DC converter [19]. The primary architecture utilized in the bidirectional DC/DC converter was the two-phase interleaved bidirectional half-bridge circuit. By increasing the converter's power level, this circuit lowers the overall inductor current ripple. Small signals were used to simulate the converter's boost and buck modes, and the double closed-loop control approach was employed to correct the converter. The converter has strong dynamic and steady-state performance, according to the compensation results. The bidirectional DC/DC converter employs asymmetric soft switching technology, which lowers switching loss and enhances the converter's overall performance.

Bidirectional DC-DC converters can control the energy flow between various power sources for new energy vehicles, resulting in more effective energy distribution and utilization. The new energy vehicle may adaptably take direct current energy from external charging equipment during the charging process thanks to the bidirectional DC-DC converter. In certain scenarios, the vehicle's kinetic energy can be transformed into electricity via the bidirectional DC-DC converter and stored in the battery, such as in brake energy recovery systems.

3.3. DC-DC soft switching technology

During the power conversion process, the DC-DC converter's soft switching technology provides high efficiency and stability by utilizing a proper management approach and a soft switching mechanism. Value switching (ZVS) and zero current switching (ZCS) are common PWM control technologies that manage the output voltage by periodically adjusting the on and off timings of the switching device [20].

Henan Agricultural University's Sun ZY and Hanyang University's Bae S introduce a new multiple-input soft-switching DC-DC Cuk converter [21]. Edge-resonant soft-switching modules are used in the converter to improve its performance over the traditional multiple-input Cuk converter. Zero voltage and zero current switching turn-on and turn-off are realized by all the switches in the edge-resonant soft-switching modules. By employing these modules, the proposed converter achieves higher power efficiency, wider soft-switching range, and reduced current stress on the switches

compared to the conventional multiple-input Cuk converter. Soft-switching states and costs are maximized by the edge-resonant modules, which yield these gains. In addition, the wide soft-switching range of the edge-resonant soft-switching modules makes the soft-switching states easily accessible.

Zhou, LW, and Preindl, M from Columbia University provide a switch that is variable steady sampling frequency important soft switching model predictive control approach (VSCS-MPC) [22]. There are two governing components in VSCS-MPC. The frequency controller comes first in order to keep the important soft switching function going by varying the switching frequency with a constant sample frequency in accordance with the pre-established boundary conditions. By keeping the sample frequency constant, a discretized frequency controller is created to increase system stability. The second element is made up of the model predictive controller, which is in charge of maintaining considerable soft switching during dynamic periods and monitoring the output voltage and current. The MPC controller uses over-representation and explicit optimization techniques to satisfy the high frequency demand. To accomplish the crucial soft switching and lower the inductance, a significant current ripple (Delta i(L) >= 200%) is added. The frequency controller reduces switching losses, and the MPC's quick response ensures that important soft switching is maintained, particularly during dynamic times.

A novel soft-switched non-isolated bidirectional converter is presented by Drabek, P. from the University of West Bohemia and Bhajana, VVSK from the Kalinga Institute of Industrial Technology [23]. Through the use of soft switching, the converter alternates between zero voltage and zero current. When the primary switches are activated, an auxiliary resonant circuit, comprising an auxiliary switch, a diode, a capacitor, and an inductor, is incorporated. This setup allows for soft switching of the main switches, greatly reducing switching losses and thus boosting the efficiency of the system. Additionally, the auxiliary switches in this architecture also benefit from soft switching. Under this topology, Zero-Voltage Switching (ZVS) is observed during buck mode operations, while Zero-Current Switching (ZCS) is evident in boost mode operations. In order to minimize battery damage during the charging and discharging process, DC-DC soft switching technology can improve the current and voltage waveform for new energy vehicles. With the use of soft switching technology, electric energy can be converted and controlled effectively, energy waste and loss can be decreased, and new energy vehicles can use less energy overall. At the same time, the soft switching technology can realize the precise control of the electric motor of the electric vehicle, providing a smooth and quiet driving experience, and can be dynamically adjusted according to the driving needs, improving the driving comfort and responsiveness.

4. Conclusion

This paper's first section presents the history of new energy vehicle development, highlights the tight connection between DC-DC converters and new energy vehicles, and demonstrates the critical importance of DC-DC efficient conversion technology development. The second section begins with an overview of the fundamentals of DC-DC converters and goes into their traditional circuit topology as well as operation. The functional significance of significant DC-DC converter components in new energy vehicles is explained below. For example, in electric vehicles, the battery is a crucial energy storage component, and its voltage and current might fluctuate depending on the vehicle's state and usage conditions. By using efficient DC-DC conversion technology, the utilization rate of battery energy can be maximized, and the driving range of electric vehicles can be extended. The third part of this paper summarizes a variety of DC-DC efficient conversion technologies from the three aspects of multistage converter, bidirectional converter and soft switch technology, introduces their advantages, and provides ideas for their application in new energy vehicles.

Based on the above research, DC-DC efficient conversion technology also faces many challenges. Implementing multilevel DC-DC technology requires complex hardware and control systems, which can increase the cost of vehicle manufacturing. How to reduce cost while ensuring performance is an

urgent problem to be solved. Complex electrical systems and control algorithms are a part of multilevel DC-DC technology, and they must guarantee the stability and dependability of the system. How to guarantee the long-term steady operation of the system is a challenge that needs to be carefully studied in light of the challenging working environment of vehicles and the complex electrical load. In order to satisfy the demands of automotive engineers for lightweight and high performance, bidirectional DC-DC converters must guarantee high efficiency while minimizing size and weight. Future bidirectional DC-DC converters may develop in the direction of multifunctional integration, integrating more functional modules to reduce system complexity. A certain amount of heat is produced during the operation of bidirectional DC-DC converters, and in the automotive environment, temperature fluctuations and high temperatures can have a detrimental effect on the functionality and lifespan of electronic components. Therefore, how to effectively manage the temperature of the converter to ensure its stable operation over a wide temperature range is an important challenge. Traditional automotive electrical systems often use DC-DC converters to manage power flow, but with the rise of electric vehicles, there is an increasing need for more efficient and lightweight systems. The mode and strategy of control are critical, and a well-designed control strategy can enhance the circuit's operational efficiency and performance. Second, higher performance circuit topologies will become the trend of future converters.

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