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Optimizing DC-DC Converters through Interleaved Parallel Magnetic Integration: A Research Review

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Abstract — One of the main areas of focus for power electronics development nowadays is interleaved parallel magnetic integration technology. On the basis of introducing the staggered parallel connection technology of internal combustion engines and power systems, the staggered parallel connection magnetic integration technology of power electronics is introduced. First, the interleaved parallel magnetic integration technology of various non-isolated and isolated DC-DC converters and their latest research results and applications are introduced; then, the three interleaved parallel technologies of internal combustion engines, power systems, and power electronics are compared; and finally, the current situation is pointed out. In China, research on interleaved parallel magnetic integration technology is not lagging behind internationally, but there is relatively little research on interleaved parallel magnetic integration technology for isolated DC-DC converters. It is recommended that research in this area be strengthened in the future. Looking to the future, the staggered parallel magnetic integration technology of power electronics will develop even more like the staggered parallel technology of internal combustion engines and power systems and make significant contributions to the development of industry and the national economy. Through this exploration, the paper aims to provide a critical analysis of the current state of research, offering valuable insights for engineers, researchers, and industry professionals involved in power electronics and converter design.

Keywords: DC-DC Converters, Interleaved Parallel Magnetic Integration, Power Electronics, Staggered Parallel Connection

INTRODUCTION

During "interleaving," a large periodic energy source is divided into several smaller energy sources, and these smaller energy sources operate at the same frequency with a constant phase difference, thereby increasing the periodic energy. Effective operating frequency of the source [1]. Parallel interleaving technology has been used successfully in many engineering fields. As you know, in the field of mechanical engineering, internal combustion engines are classified as single-cylinder. Multi-cylinder engines are commonly used in vehicles to increase power output and enhance engine performance. By having multiple cylinders, the workload is distributed, resulting in smoother power delivery and reduced vibrations compared to single-cylinder engines. This design allows for higher RPMs and better torque characteristics, improving the overall driving experience. Additionally, multi-

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cylinder engines offer advantages such as reduced temperature stresses due to increased cooling surface area and better fuel efficiency [2]. Overall, multi-cylinder engines are favored in vehicles for their ability to deliver higher performance, smoother operation, and improved efficiency, and multi-cylinder engines are ranked according to the number of cylinders, as shown in Figure 1 [2]. It is connected to the crankshaft. Each cylinder operates continuously to configure each cylinder's power stroke in specific phases. If you do not increase the operating frequency of the cylinders, the number of cylinders will increase. The total operating frequency and total power are reduced, and the total torque ripple is reduced. 5-cylinder star-class engines are a type of engine configuration featuring five cylinders arranged in a radial pattern around a central crankshaft. These engines are commonly used in various applications, including aviation, model engines, and some historical locomotives. They offer benefits such as smooth operation, compact size, and a good power-to-weight ratio. Examples of modern 5-cylinder radial engines include those manufactured by UMS (Ultimate Motorrad Service) for both model aircraft and other applications. These engines are known for their reliability, efficiency, and unique sound characteristics, as shown in Figure 1 (b) [3]. It is expected to be the most successful example of the application of parallel-stage technology in the field of mechanical engineering. At present, the total number of cylinders connected in parallel is 12.

A three-phase staggered parallel power system involves the parallel connection of multiple power sources or converters, typically in a staggered manner across the phases. This configuration enhances system reliability, efficiency, and power handling capability. Each phase of the system may consist of multiple sub-converters or power modules that work synchronously to distribute the load and balance the power distribution across the phases. Staggering the connection helps reduce working time and improve overall system performance. The system can be designed to accommodate load changes efficiently while maintaining stable operation [4]. It finds applications in various fields, including power electronics, renewable energy systems, and industrial power distribution. [4]. As shown in Figure 2, "larger units, larger networks, higher voltage, and larger capacity" of the power system can be achieved. It is expected to be the most successful example of the large-scale application of parallel technology in the field of power systems. In the field of power electronics, interleaved parallel technology has been applied for many years for power conversion, such as in three-phase controllable rectifier circuits, three-phase inverter circuits, double-inverter star rectifier circuits with balanced reactors, and multiple rectifier circuits, etc. [4]. In high-output electrical energy conversion circuits, the voltage or current transmitted by power electronics devices exceeds what they can handle. In high-output electrical energy conversion circuits, the voltage or current transmitted by power electronics devices exceeds what they can handle. Therefore, to solve the above problem, it has been proposed to connect multiple devices in series or parallel, but at the same time, voltage equalization and current sharing problems arise. Among these, the way to solve the problem of current sharing is to connect the transformers in parallel. In fact, staggered parallel connection technology has the advantages of increased capacitance, elimination of harmonics, better efficiency and power density, and easier thermal management. A successful example in this regard is superconducting magnetic energy storage systems [5]. In this system, the current voltage of the electronic device is very high, and the switching loss of the device increases proportionally with the increase in switching frequency. The solution to this is to use multiple three-phase step current source converters in parallel. This divides the high current into many smaller parts, allowing devices like GTOs to withstand high current voltages and reduce conduction losses. There are also stationary reactive power generators (SVG) [6], high-voltage direct current buses (HVDC) [7], etc. Interleaved parallel technology has been quickly applied to small and medium-sized power conversion circuits [8–9]. Its main purpose is to reduce input and output filters. This is because the interleaved parallel technology can reduce the switching pulse flowing in the filter. The amplitude of the current doubles, and the frequency of the pulse current also doubles [10]. By rationally choosing the number of parallel channels and duty cycle, the ripple current can be

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reduced to zero, which can significantly reduce the filter size. In addition, scale-parallel technology can improve the thermal management of transformers, realize modular manufacturing, realize parallel redundancy and high-speed online product backup, and easily increase capacity [11]. In summary, parallel interconnect technology has been the subject of much research and application in power electronics [5–16].

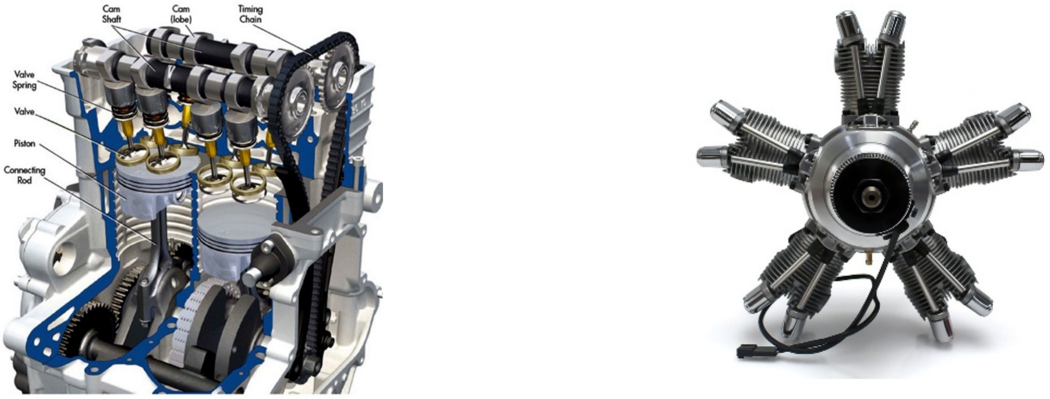

Figure 1. (a) Multi-cylinder engines used in vehicle [2] **(b)** 2.5-Cylinder star class engines used in jet plane [3]

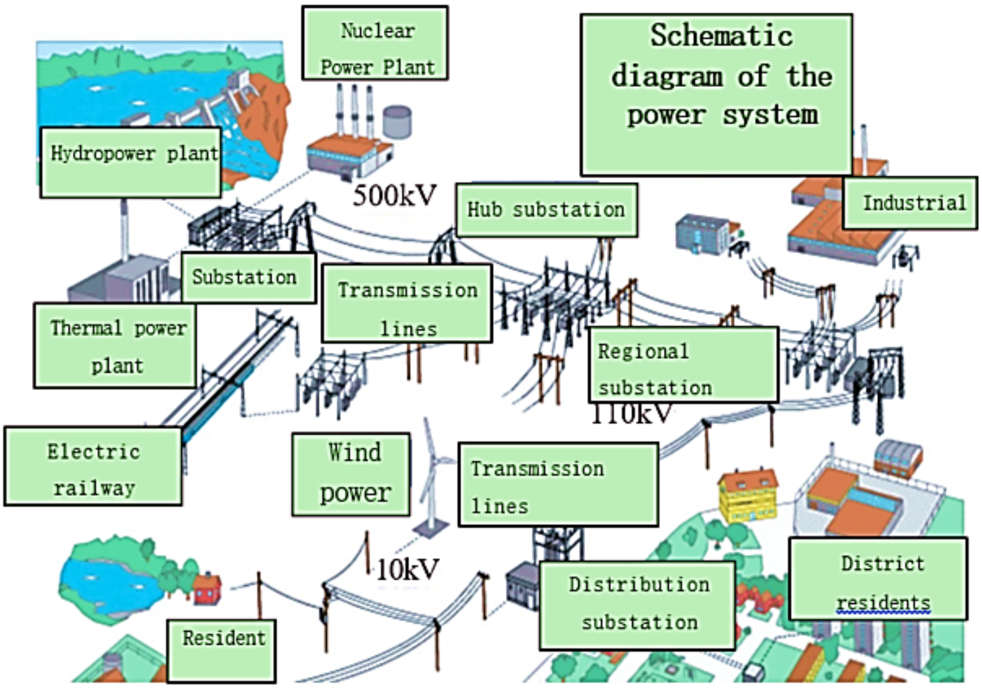

Figure 2. Three-phase staggered parallel power system [4]

LITERATURE REVIEW

According to the definition in the literature review, magnetic integration technology means that two or more separate magnetic components of the transformer are wrapped around a magnetic core and structurally centered on each other. Those with concentrated magnetic components are called dense magnetic components. Based on this, this article seeks to improve the definition of self-integration technology. The nominal magnetic integration technology aims to improve the performance of power electronics converters. Through specific magnetic field coupling methods and proper parameter design, magnetic integration technology can be applied to power electronics converters. A technology that structurally combines two or more magnetic components with one function (i.e., an inductor and a transformer, called a magnetic component) into a composite magnetic component that performs multiple functions (an integrated component is called the magnetic component). When an electronic power converter adopts magnetic integration technology, it can reduce the number of magnetic components, reduce the overall size of magnetic components, reduce the loss of magnetic components, and reduce current ripple. Could. Can do. Output Transformer. The dynamic response speed of the converter can be improved. [18-19]. Parallel interleaved power electronics converters can use magnetic integration techniques [20–21]. It combines the advantages of parallel interleaving technology and magnetic integration technology to further improve the performance of the converter. The article is called "Interleaved Parallel Magnetic Integration for Power Electronics." (interleaved and self-integrated). Recently, research on nested parallel communication in the field of power electronics technology has been gradually increasing [20–30]. Taking the most popular publication in the international power electronics community, IEEE Transactions on Power Electronics, as an example, we retrieved a total of 189 articles on interleaving as of October 27, 2023, which contains some of the oldest writings. This paper was published in 1988 [23]. A total of 145 articles over the past five years (since January 1, 2008) were retrieved. A total of 145 articles were searched over the last 3 years (since January 1, 2020). Up to 116 articles. And about "entangled parallel conduction (magnetic coupling)" and "entangled parallel conduction" (interleaved) + "self-coupling," there are a total of 48 articles [20, 22, 31–32]. The first article was published in 2001 [20], and in the last 5 years (since January 1, 2008), A: total 40 The units were recovered. Last 3 years (2020). A total of 32 articles were searched (after January 1, 2018). Look at this country again. Information on China's national knowledge infrastructure as of October 27, 2013 was found in 228 journal papers on 'Interlaced Parallel Communication'. The first of these papers was published in 1999 [33], and over the past five years. A total of 159 articles (from January 1, 2008) were searched. Last 3 years (from January 1, 2020), total 122 articles. About "Interleave + Magnetic Integration" and "Parallel Current Interleaving" (interleaved) + self-coupling, last 5 years (2008), total 56 articles [21, 34–35] A total of 43 articles were searched in the last 3 years (since January 1, 2010). A total of 31 articles were searched in the last 3 years (since January 1, 2020). This shows that parallel technologies, both foreign and domestic, are interconnected. A growing area of study in the field of power electronics is this technology and its magnetic integration technology. The development of magnetic integration technology and interleaved parallel connection technology for isolated and non-isolated DC-DC converters is first briefly discussed in this article. Next, the DC-DC converter's magnetic integration and interleaving parallel connection technologies are contrasted with more advanced, established technologies. The purpose of this paper is to compare the step-by-step parallel connection technology of internal combustion engines and the step-by-step parallel connection technology of power systems and to objectively review the step-by-step parallel connection from DC-DC, converter and magnetic integration technology. Finally, some important conclusions are drawn to provide inspiration for DC-DC converters. We are working hard to develop the superimposed parallel DC converter technology and its self-integration technology.

DC-DC CONVERTERS IN POWER ELECTRONICS

Non-isolated unidirectional DC-DC converters play a crucial role in various applications, particularly in power electronics. These converters offer advantages such as simplicity, cost-effectiveness, and high efficiency. They are commonly used in off-board charging systems for electric vehicles, where standards and references are carefully considered [3]. Designing and implementing such converters involve selecting suitable topologies derived from Boost, SEPIC, Cuk, Luo, and Zeta converters to ensure clean charging for electric vehicles Guidelines and recommendations for the development of DC-DC converters for renewable energy applications are available, focusing on cost-effectiveness and reliability [5]. Additionally, detailed performance analysis of non-isolated DC-DC converter topologies is conducted to understand their advantages and optimize their functionality. In the hierarchy of power electronics converters as shown in Figure 4, non-isolated unidirectional DC-DC converters play a significant role. These converters are designed for step-up and step-down voltage applications, featuring a distinct inductor-capacitance (LC) impedance design structure. They are essential components in various systems, including electric vehicles, where non-isolated bidirectional DC-DC converters are utilized [3]. Configuration options include non-isolated common ground single-stage converters and non-isolated floating output converters. Understanding these converters is crucial for applications like fuel-cell power conditioning, where full-bridge DC/DC converters are commonly employed when electrical isolation is needed. However, it's important to note that non-isolated DC-DC converters lack electric shock [56].

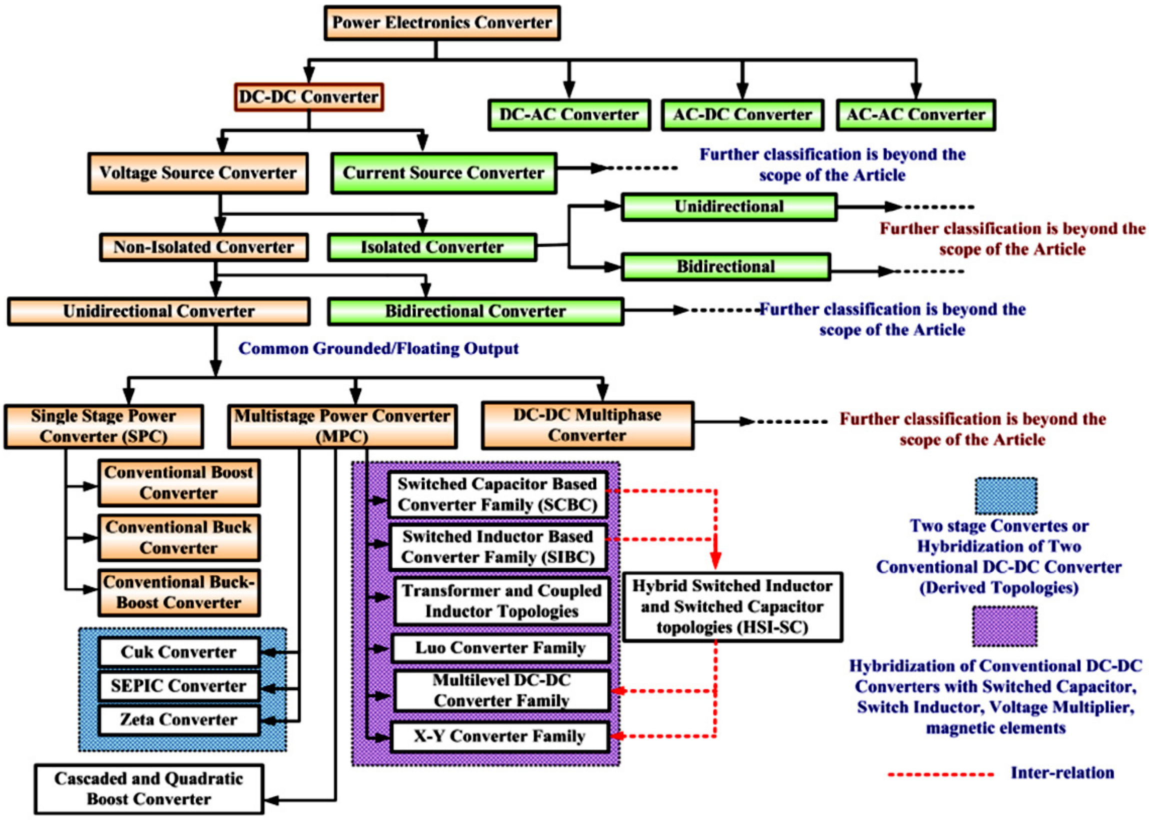

Figure 3. Hierarchy of Power Electronics Converter with more focus on non-isolated unidirectional DC-DC Converter [56].

INTERLEAVED PARALLEL MAGNETIC INTEGRATION TECHNOLOGY FOR NON-ISOLATED DC-DC CONVERTERS

As you know, DC-DC converters can be divided into isolated and non-isolated types. Among these, the basics of non-isolated DC-DC converters are step-down type and boost type, so this article focuses on these two non-isolated types. Nested parallel magnetic integration technology for DC-DC converters and bidirectional converters. Because isolated DC-DC converters typically use flyback, forward, and bridge converters, we introduce these three converters. On the basis of interleaved parallel magnetic integration technology, we introduced interleaved parallel magnetic integration technology for a bidirectional bridge DC-DC converter.

A. Interleaved parallel magnetic integration technology of Buck converter

The most studied and detailed aspect of interleaved parallel integrated magnetic buck converters is the study of multi-channel parallel integrated magnetic buck converter applications in non-isolated voltage regulation modules (VRMs) [15–16, 20, 22, 35–37]. According to Moore's Law, an integrated circuit's transistor count doubles every two years. Intel microprocessors over the last 50 years. Figure 5 shows the variation in the number of transistors in memory. In 2010, the number of transistors on each Intel processor chip reached 10 billion. To increase the number of transistors in the processor, the power should reach 130 W, the voltage should drop to 1 V, and the current should increase to 150–200 A, as shown in Figure 6. CPU clock frequency (4 MHz), own power. Accordingly, the current rise rate (transient response speed) of the power supply also increases. To meet the above CPU power requirements, VRM power is printed on the computer's motherboard using a multi-stage parallel voltage converter topology, as shown in Figures 7 and 8.

B. Staggered parallel connection technology reduces current ripple amplitude and increases ripple frequency

A Voltage regulator module (VRM) uses a parallel voltage converter topology, it can reduce the output current ripple and increase the ripple frequency, as shown in Figure 8 [15].

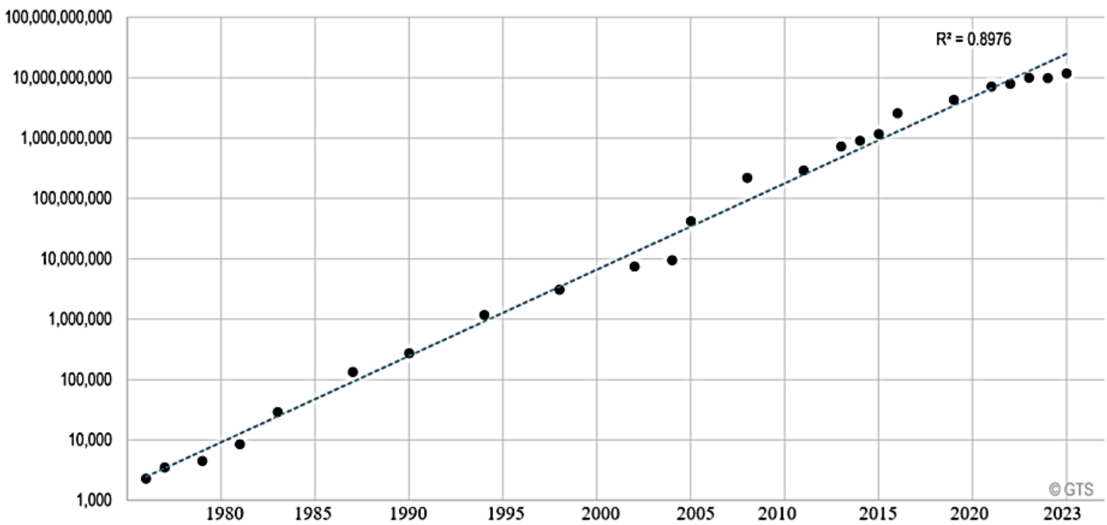

Figure 4. Moores Law Transistors per Microprocessor 1980-2023 [57]

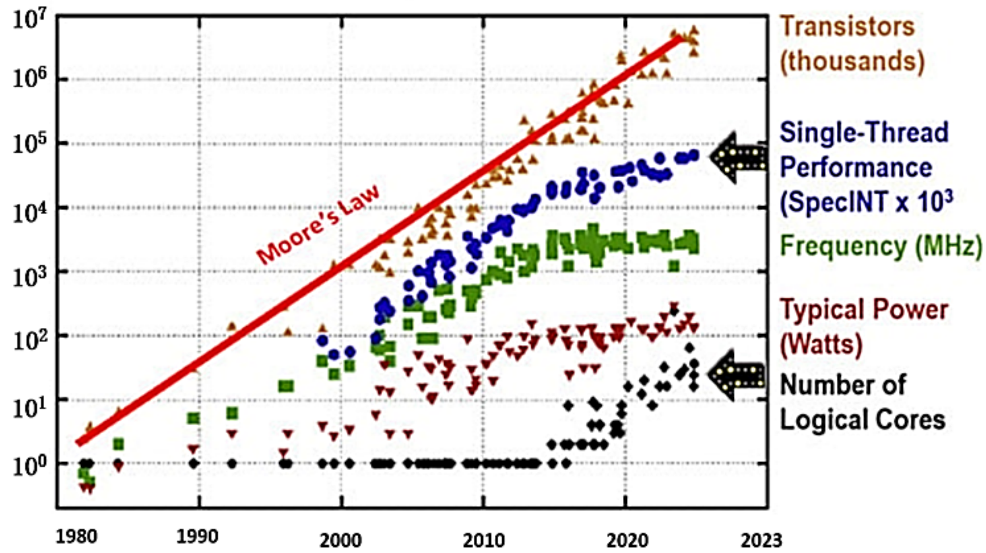

Figure 5. Road mapping of Nano electronics for the New Electronics Industry [58]

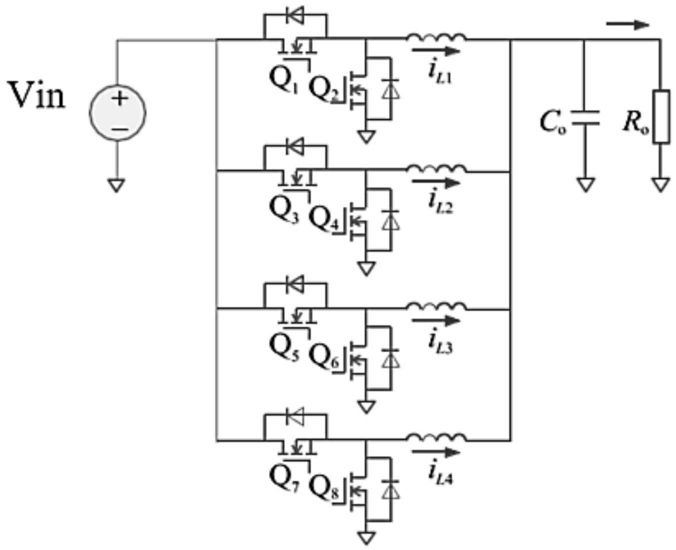

Figure 6. Multi-channel interleaved parallel synchronous rectification Buck converter [59]

As can be seen in Figure 6, we see that the ripple becomes zero under certain duty cycle conditions. Additionally, the capacitance of the output filter is reduced, cost is reduced, size is reduced and power density is increased. A Voltage Regulator Module (VRM) on a computer motherboard is a specialized electronic circuit responsible for regulating and controlling the voltage supplied to the CPU (Central Processing Unit) and other critical components. It takes the higher voltage from the power supply unit (PSU) and converts it into a lower, more stable voltage suitable for the CPU's operation. VRMs are essential for maintaining the stability and efficiency of the CPU by ensuring it receives the precise voltage required for optimal performance. Additionally, VRMs often incorporate features such as overcurrent protection and thermal management to safeguard the CPU from damage due to power fluctuations or overheating. In summary, VRMs play a crucial role in powering and protecting the CPU, contributing to the overall reliability and performance of the computer system [23].

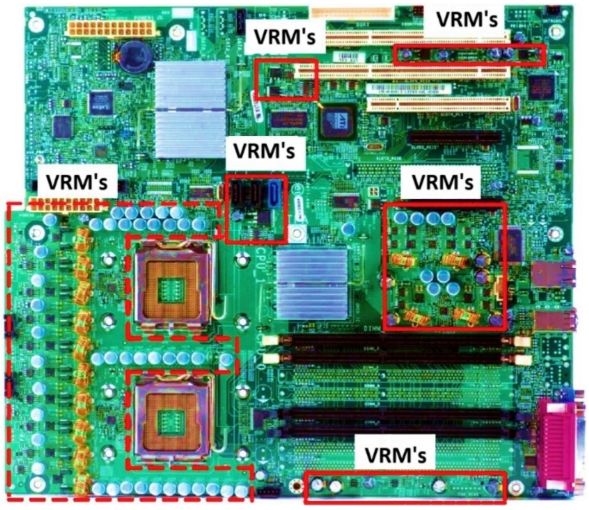

Figure 7. Voltage regulator module (VRM) on computer motherboard [23]

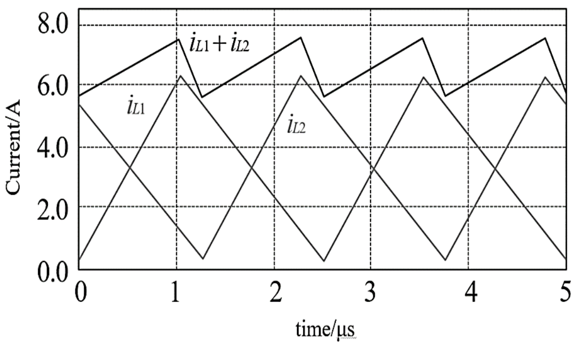

Figure 8. Interleaved Parallel Buck Converters Reduce Output Current Ripple [61]

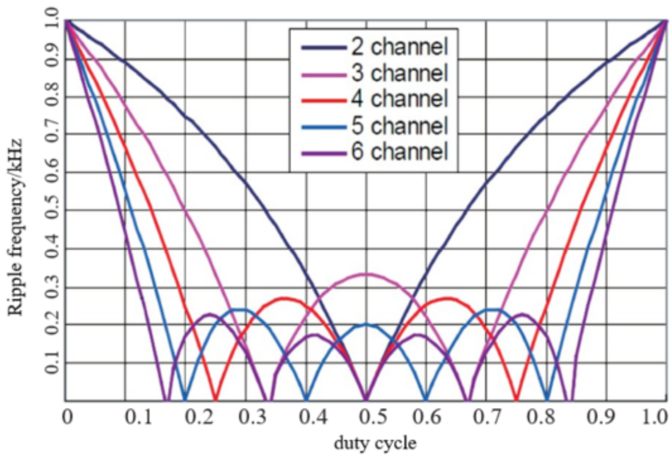

Figure 9. Current ripple cancellations in multiphase Buck converter [62]

Additionally, input filter current frequency could be increased and input current amplitude can be decreased using parallel voltage converters. As a result, the input filter's amplitude is decreased, capacitor losses are decreased, and capacitor life is increased. As an illustration: This could be found in Figure 9.

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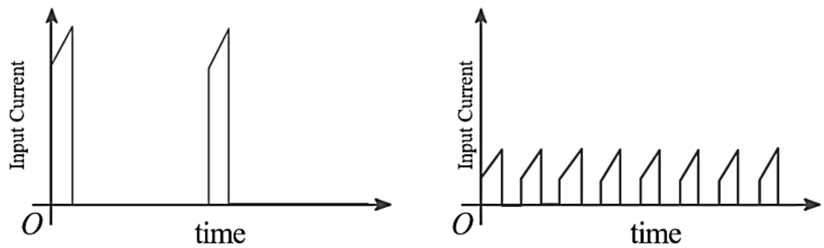
C. Staggered parallel technology improves light load efficiency

A parallel stepping converter operates at light loads, device losses in idle channels can be reduced by reducing the number of channels running in parallel, improving light load efficiency and allowing the converter to achieve higher efficiency across the load range can be terminated as shown in Figure 12 [11].

D. Staggered parallel technology improves converter capacity

The continuous development of CPUs, their power consumption is increasing. The use of interleaved parallel technology can exactly meet this development demand. With continuous improvement over the years, 20A single phase buck transformer modules have become the industry standard. As CPU power demands increase, adding a 20A parallel buck converter module shortens the product design and manufacturing cycle and reduces costs. At present, Voltage regulator module (VRM) power supplies consisting of nested parallel buck converters, as shown in Figure 13, have been applied in distributed power systems and have become an industry standard [22].



(a) Single-phase Buck converter (b) four-phase Buck converter

Figure 10. (a) Single-phase Buck converter (a) and four-phase Buck converter Input current comparison (b) [63]

E. Staggered parallel magnetic integration technology improves converter steady-state and transient performance

In general, the advantages of interleaved multistage parallel buck converters are: Converter capacity is doubled. Light load efficiency has been improved. The supplied energy is distributed and transferred through each stage, helping with heat management. The output capacitor's equivalent series resistance (ESR) drops as the output current's ripple frequency rises. Reduce the output voltage ripple, the quantity of the output capacitor, the output current ripple, or use a smaller inductor without affecting the output current ripple in order to increase the transient reaction speed. However, there are some disadvantages to using nested parallel multistage buck converters as voltage regulators (VRMs). The point is that the total output current ripple can be minimized, so the current ripple inductance of each stage cannot be minimized. If the inductor is shortened to increase the transient response speed, the current ripple of each phase inductor increases, the conduction loss or switching loss of the switching tube increases, and the copper loss of the inductor increases, which reduces efficiency.

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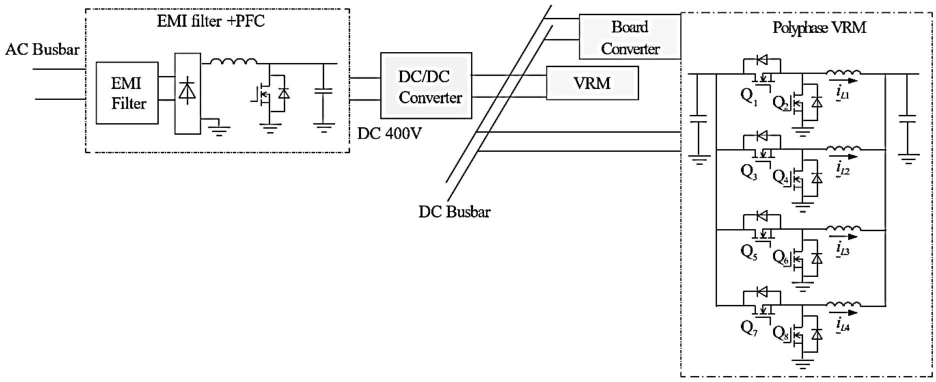


Figure 11. Distributed power systems and their interleaved parallel VRMs [68]

Therefore, the efficiency ratio and transient response speed ratio of a typical parallel interleaving buck converter become a pair of contradictions. Literature [15] proposes to solve this discrepancy by using magnetically coupled integrated inductance structures and the concepts of steady-state equivalent inductance and equivalent transient inductance. In other words, the induction magnet generator's two ends integrate the output of each stage of the parallel buck converter. As shown in Figure 11, it becomes the coupling inductor to form a parallel integrated magnetic step-down converter. By changing the coupling coefficient k and the duty cycle value D, the steady-state equivalent inductance increases, the steady-state output current ripple of the converter decreases, and the equivalent transient inductance decreases, thereby increasing the transient response. Improvement occurs, converter speed. In the literature [15], the step-down converter adopts interleaved parallel magnetic integration technology, and since the equivalent inductance value of the converter is different in steady state and dynamic state, not only high efficiency is secured in steady state but also excellent characteristics. Can be obtained. Dynamics. Therefore, the full load efficiency of the transformer increases by 2%, and the light load efficiency increases by 10%. The relationship between the steady-state phase current waveform and the decoupling of the interleaved three-phase parallel inductive coupling is illustrated in Figure 15b, using the three-phase parallel integrated magnetic voltage converter as an example. Compared to the uncoupled state, the inductively coupled state's current is lower. More coupling and a lower steady-state phase current ripple are produced by higher-duty cycle D. The boost ratio of the overall transient output current in coupled and uncoupled modes is displayed in Figure 16. In the coupled state, as opposed to the uncoupled state, the maximum total output current increases at a faster pace; the increase increases with increasing duty cycle D. The greater the number, the stronger the rear coupling. The slope area beneath the line accelerates the rise of the total transient output current while attenuating the ripple in the steady-state phase current. Both D and |k| rise in this area.

F. Advantages of staggered parallel magnetically integrated Buck converters

In summary, the advantages of a parallel integrated magnetic voltage converter are mainly reflected in the following points: The number of inductor components can be reduced. Improve steady-state operating efficiency. Improves momentary response speed. It can reduce the current ripple of each phase inductor and reduce the copper loss in the inductor. By reducing the magnetic flux ripple of the magnetic main axis, the iron loss of the inductor can be reduced. Since the current in each phase is less, switching losses and voltage current are reduced.

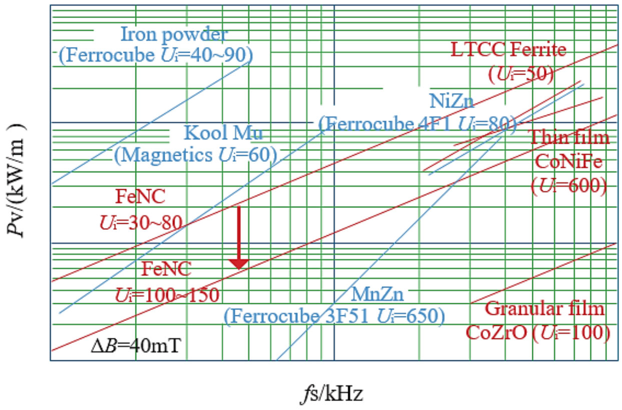


Figure 12. Relationship between loss density and frequency of high-frequency magnetic materials [57]

G. Application fields of staggered parallel magnetically integrated Buck converters

Possible application fields of interleaved parallel magnetically integrated Buck converters are shown in Figure 13.

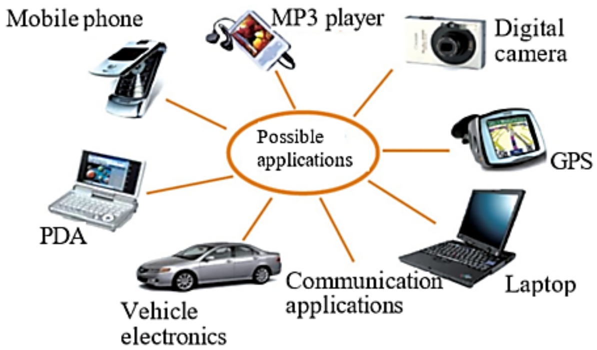
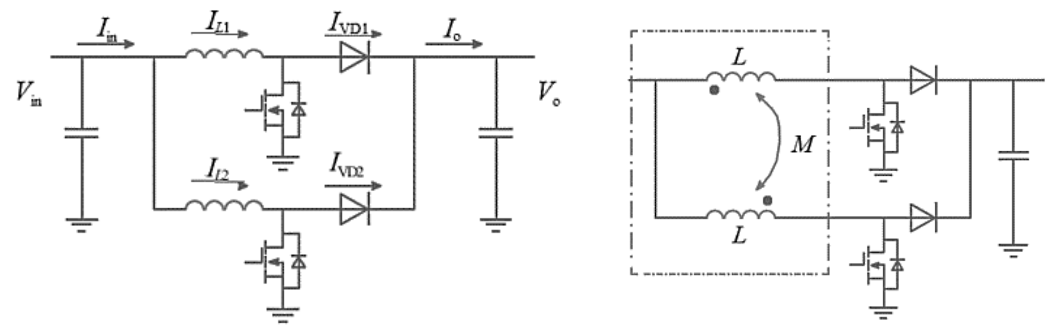


Figure 13. Application areas of interleaved parallel magnetically integrated Buck converters [58]

H. Staggered Parallel Magnetic integration Technology of Boost Converter

Figure 14 (a) and (b) show the circuit topologies of the integrated stepwise and parallel magn etic boost converter, respectively. Parallel superimposed boost converters were first used in power factor correction (PFC) circuits and in recent years have been used in hybrid cars, solar power, and LED lighting. A typical application of interleaved parallel magnetic boost converters is AC-DC forward power factor correction (PFC) circuits such as [11].



(a) (b)

Figure 14. (a) Interleaved Parallel Boost Converters [69] (b) Converters Interleaved Parallel Magnetic Integrated Boost Converters [59]

1) Challenges and solutions faced by AC-DC front-end converters

The problem that distributed power systems' AC-DC front-end converters must solve is how to boost capacity while enhancing efficiency and power density. Increased productivity results in cost savings and the installation of more equipment in a smaller space. The significance of attaining optimal efficiency at full load is growing owing to its effects on the economy and environment. The life cycle of front-end AC-DC conversion devices has been reduced by the quick development of IC technology, and capacity expansion has emerged as a workable remedy. However, the primary reasons limiting efficiency advances are now the device's switching losses and reverse recovery losses. The size of passive components such as EMI filters, PFC inductors, capacitors, and DC-DC converter inductors is a crucial factor impacting power density. Certain single-channel boost topologies are a significant constraint on scalability. An effective way to solve these problems is to use the phased parallel self-integration technique. This is because sequential parallelism increases the total switching frequency but does not increase the frequency of each channel, and it has the ability to lower the number of channels needed under low loads. It can reduce machine losses and improve efficiency. Increasing the total switching frequency and using magnetic integration technology can reduce the size of passive components and increase power density. Extended parallel connections provide modularity to facilitate capacity expansion.

2) Comparison of staggered parallel magnetic integrated Boost and Buck converters

In fact, boost converters and buck converters have the same circuit topology, but the direction of power flow is opposite. The quantum effect of entangled parallel communication technologies is also similar. The same applies for the effect of interlaced parallel magnetic integration on input/output current ripple. The research results of the interleaved parallel integrated magnetic voltage converter, which can be applied to the interleaved parallel integrated magnetic boost converter, can also be used in the interleaved parallel integrated magnetic boost converter, such as current ripple elimination, uniform thermal stress distribution, modularity, and scalability. The electrical system can be upgraded to the structure shown in Figure 15, and the front PFC circuit can also use parallel magnetic magnets integrated into the Boost topology. Interleaved Parallel Buck Converters for VRM and Interleaved Parallel. A comparison of boost converters for PFC is shown in Table 1.

Table 1. Comparison for interleaving buck and boost converter [23-25]

Interleaved Parallel Buck Converters for VRM	**Interleaved Parallel Boost Converters for PFC**
Reduce inductance and improve transient performance	The inductance remains unchanged and the efficiency remains the same
Reduce output current ripple and reduce output filter	Reduce input current ripple and reduce EMI filter
Reduce the input current ripple and reduce the input filter	Reduce the output current ripple and reduce the output capacitance
Increase power density	Increase power density
Reduce costs (reduce capacitance, standardize design)	Reduce costs (reduce capacitance, standardize design)
Scalability (to adapt to future CPU power needs)	Scalability (to adapt to future server power needs)
Improve light load efficiency (phase shielding)	Improve light load efficiency (phase shielding)

Table 2. Comparison for interleaving buck and boost converter [17-18]

Interleaved Parallel Magnetic Integrated Buck Converters for VRM	**Interleaved and Magnetic Integrated Boost Converter for PFC**
Reduce component count	Reduce component count
Red Reduce channel inductor current ripple	Keep the channel inductor current ripple unchanged
Improve steady-state efficiency	Reduce inductor size
Improve transient response speed	Improve transient response speed

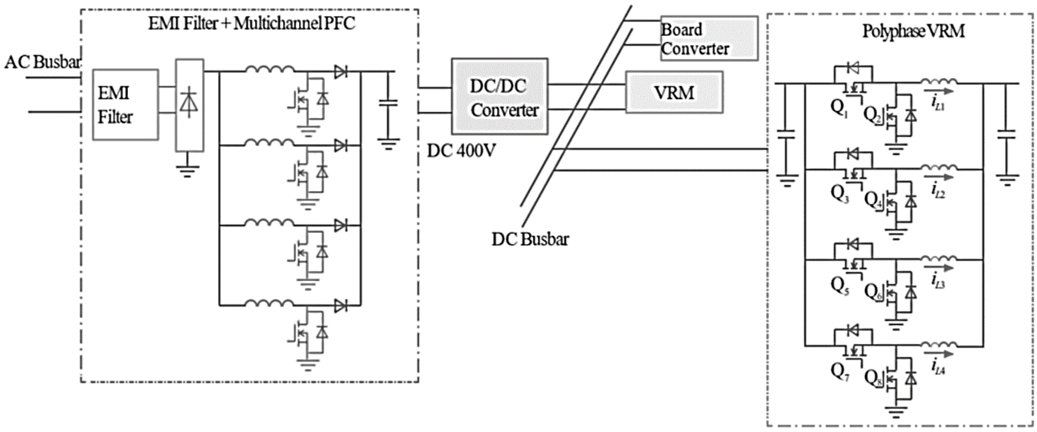


Figure 15. Distributed power system using staggered parallel VRM and PFC [70]

I. Interleaved parallel magnetic integration technology of bidirectional Buck/Boost converter

In terms of the integration of research results on interleaved parallel Buck converters and interleaved parallel Boost, research results have also been achieved on interleaved parallel bidirectional Buck/Boost converters [43–45]. Literature [43] from the perspective of low-voltage electric vehicles equipped with super capacitors Similar to the parallel magnetic integrated VRM, the coupling inductor can also be used in the staggered parallel boost converter to form the staggered parallel magnetic integrated PFC. its advantages are shown in Table 2. In response to the demand for high-current, high-speed dynamic response bidirectional DC-DC converters, buck parallel DC-DC converters are designed for electric vehicles, and the current capacity and power density of the converters have been improved. In the literature [44], a switched capacitor was added, and the location of the phase switching tube was changed based on the existing bidirectional parallel interleaved buck/boost converter. Therefore, the new structure is simple. It not only realizes the characteristics of interleaved parallel converters, such as low input current ripple and simple EMI design, but also achieves the goals of a high input-output voltage ratio and a low switching voltage ratio. Literature [45] proposes a 16-phase bidirectional parallel DC-DC converter operating in DCM mode to reduce current unbalance and current loop cancellation. Used in hybrid electric vehicles and equipped with small inlet and outlet filters. Benefits include fast dynamic response and low device voltage. Literature [34] provides coupling inductor design criteria for phased bidirectional parallel DC-DC converters with magnetic integration in buck mode operation.

ISOLATION TYPE DC-DC CONVERTER, MUTUAL INTEGRATION TECHNOLOGY

The main types of isolated DC-DC converters that DC-DC converters use are two-stage converters, inverting converters, bridge converters, and double bridge converters

A. Interleaved parallel magnetic integration technology of flyback converter

Literature [46] proposes a two-stage interleaved parallel flyback converter using zero-voltage active switching to reduce the rectifier diode's reverse recovery loss. At maximum load (500 watts), efficiency reaches 91%; at low load, it reaches 10%. The efficiency of 50 W reaches 83%. In small and medium-sized power applications, the current ripple of the transformer is large, the gap-spreading magnetic flux generated by the inductor component is greatly affected, and this is often the main cause of coil eddy current loss. Literature [21] combines the multi-channel coupled inductor technique with a flyback converter. In order to reduce the coil loss characteristic current ripple and improve the inductance component loss and coil core loss, a magnetic integration technology of a multi-channel parallel flyback converter was proposed.

B. Interleaved parallel connection technology of forward converter

According to the operating characteristics of the twin-tube direct converter with a parallel stage structure, the literature [47] analyzed the self-reset process of the converter under two operating modes and different duty cycles of the converter and established a small signal model. For systems using the average circuit method. the compensation function of the output voltage and the design method of closed-loop control parameters are introduced, and it is shown that a double-tube direct converter with a parallel stepper structure is operated with a half-square wave and by using Can be controlled by a conventional fixed-frequency PWM. Literature [48] proposes a new type of soft-switch pulse width modulation DC-DC converter with two parallel interleaving tubes without voltage or current. Compared with the existing two-tube series-parallel DC-DC converter, there is no auxiliary resonance circuit. Smooth switching of the switch tube is achieved by using smoothing inductance of the switching output, a snubber condenser, and parasitic inductance of the transformer. It effectively suppresses the maximum voltage and maximum current of the transformer switching tube, reduces the circulating current loss in the circuit, and has no saturation effect on the transformer. Literature [49] proposes a method to increase the duty cycle range of nested direct parallel converters, which can reduce the number of components and conduction loss.

C. Interleaved parallel technology of forward-flyback converter

In the literature [50], a fuel cell power generation system is proposed that uses a live clamp flyback converter to step up DC12V to AC voltage 220V/50Hz, which can achieve the advantages of high efficiency and high output density [46].

D. Interleaved parallel connection technology of full-bridge converters

The literature [51] suggests a full-bridge converter with step-parallel current feedback. Fuel cell criteria may be satisfied by this converter, which boasts low input current ripple, low output voltage ripple, downsizing of magnetic components, and low current voltage of the switching device. A two-stage configured inverter is proposed in the literature [52]. A full-bridge inverter circuit powers the rear end, while a parallel shift full-bridge (Inductor-inductor-capacitor) LLC resonant circuit powers the front. Used in isolated inverters in solar power production systems. 1 kW trial version

E. Interleaved parallel connection technology of bidirectional flyback converter

Literature [53] proposes a multi-stage bidirectional flyback converter for hybrid electric vehicles with the advantages of high gain, wide charging range, low output current ripple and battery current energy sharing.

F. Interleaved parallel technology of bidirectional full-bridge converters

A three-phase current feedback bidirectional parallel interleaved double bridge active DC-DC converter with zero voltage switching (ZVS), high efficiency across a broad input voltage range, and a large output power range is presented in the literature [54]. Its small input current ripple is a benefit. A bidirectional interleaved parallel full-bridge DC-DC converter without a snubber circuit was presented in the literature [55] for fuel cell cars' energy storage systems. It has low voltage and low current in switching devices, low conduction loss, high efficiency, high power density, big capacitance, minimal input current ripple, and compact passive components. AC and DC converters also employ parallel technology (three-phase rectifier circuits, etc.), DC-AC converters (three-phase inverter circuits), AC-AC converters (three-phase AC frequency conversion circuits), etc.

COMPARISON OF THREE INTERLEAVED PARALLEL TECHNOLOGIES

Table 3. The comparison of three interleaved parallel technologies [15-29]

Internal combustion engine	Power Systems	DC-DC converter
Gasoline engine, diesel engine, aviation Kerosene engines, gas turbines	Generators, motors, transformers	Non-isolated, isolated
2 ~ 12 cylinders staggered and parallel connected	Three-phase staggered parallel connection	2 to 36 phases staggered in parallel
There is no coupling between cylinders	There is magnetic coupling between the phases	Each phase can be uncoupled or magnetically coupled (magnetic integration)
Convert chemical energy into mechanical energy	Convert mechanical energy into power frequency electrical energy (generator); convert electrical energy into mechanical energy (motor); increase, decrease and electrical isolation of electrical energy Isolation (transformer); three-phase power grid (power transmission)	Convert a certain type of DC power into precise DC power that meets user needs (boost, step-down, bidirectional, etc.)
For machinery and transportation equipment (automobiles, trains, locomotives, airplanes, ships) to provide power	Power electrical equipment (non-speed motors, incandescent lamps wait)	Provide precision electric energy for electronic and electrical equipment (motor speed regulation, metering computer, LED, etc.)
Expand capacity, improve efficiency and power density, improve steady-state performance and dynamic performance	Expand capacity, significantly improve efficiency, improve steady-state performance and dynamic performance, and realize "large units, large grids, high voltage and large capacity" of the power system	Staggered parallel connection: expand capacity, improve efficiency, especially light load efficiency,

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CONCLUSION

The field of power electronics is currently focusing on the advancement of parallel connection and magnetic integration technology in DC-DC converters. Domestic research has been slow, but recent advancements in parallel electronic technology and self-integration technology are more recent than in foreign countries. The study of magnetic integration technology and interleaving parallel connections in non-isolated DC-DC converters, particularly buck converters, is extensive and well-implemented. Industry standards have been created for various converter types, including VRMs, spot-mount converters, and PFCs. The superimposed parallel technology of isolated DC-DC converters has been extensively researched and successfully applied in various fields. However, there is limited research on interleaved parallel "self-integration" of isolated DC-DC converters. The circuit topology of DC-DC converters is more complex, and self-integration technologies will become more complex. Magnetic integration technology significantly improves converter performance, and future research is recommended to improve this area. The parallel connection and magnetic integration technology of DC-DC step converters will continue to develop, contributing significantly to industries like internal combustion engines and electric systems and the national economy.

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