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Overview of Quadratic DC-DC Converters

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Abstract: With the rapid progression of new energy resources technology and the increasing application of new energy resources, solar energy, fuel cell and other new energy resources power generation systems have higher requirements for the input voltage range of DC-DC converter. When the input voltage range of traditional DC-DC converter is wide, its duty cycle must be changed in a relatively large range to keep the output voltage stable, which leads to complex controller design and low system stability. The quadratic Boost converter can achieve high voltage gain with squared duty cycle using only a single switch. Thus, it has a wider input voltage range than the traditional switching Boost converter in the same duty cycle range and reduces the design difficulty of the control system. At the same time, the large range undulation of the output voltage of the new energy power generation system also puts forward higher demands for the load transient response speed of the circuit. Therefore, it is very important to study the control technology of quadratic Boost converter with fast load transient response.

Keywords: Quadratic Boost converter; Small signal model; Load transient response speed.

1. Introduction

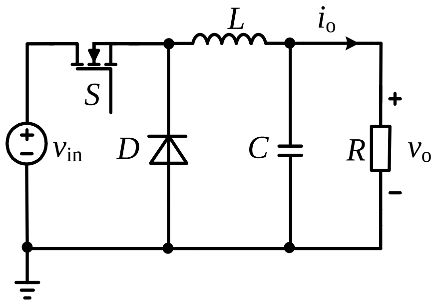
From the 19th century to the 20th century, fossil energy such as coal, oil and natural gas have always been the primary raw materials for human survival and development. They have supported the progress of human civilization and economic society [1], [2]. With the continuous development of social economy and science and technology, people are increasingly dependent on these non-renewable resources, but due to the non-renewable nature of fossil energy and the extensive use of fossil energy by people, it has gradually been exhausted [3].

With the rapid economic development and rapid social progress, the quality of life of residents has continued to improve, resulting in high demand for traditional fossil energy. According to statistics, fossil energy is the largest energy consumed in the world [4]. In 2021, its proportion in primary energy consumption reached 82.3%, an increase of 0.1% over last year. In 2022, coal consumption will continue to grow, and the proportion of fossil energy consumption is expected to rise slightly. Therefore, the consumption of fossil energy is inevitable, and most fossil energy will be exhausted by this century, which is obviously not in line with the requirements of social sustainable development. In addition, the use of fossil energy will also lead to environmental changes and pollution. For example, the emission of a large amount of CO2 is closely related to it, and it will eventually lead to global warming. According to statistics, in 2020, the world's average annual temperature is about 14.9^{o}C, which is 1.2^{o}C higher than that in 1850-1900. In 2020-2024, the world's average annual temperature may be at least 1^{o}C higher than that in 1850-1900. At the same time, a lot of harmful smoke will be emitted. For example, in the process of burning coal, a lot of dust will be produced, which has a great impact on the air. Although my country has taken various countermeasures to control the increasing area of acid rain to a certain extent, acid rain in some areas is still increasing, and problems such as automobile exhaust pollution are becoming more and more prominent, especially in metropolises [5]-[8]. Air pollution has gradually turned into a mixture of smoke and exhaust gas. Therefore, in order to cope with the problems of fossil energy depletion and environmental protection, the development of new energy has become an inevitable trend [9].

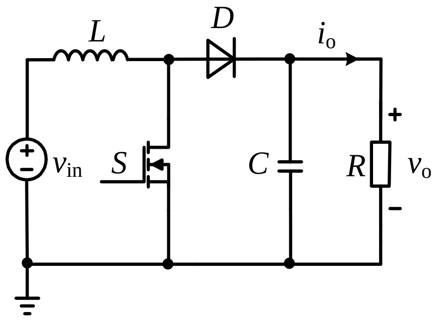
As the application of DC-DC converters becomes more and more extensive, it is required that they can simplify the control system design while having high efficiency and improve the reliability of the system. In recent years, the performance of the converter has gradually received attention, such as power loss, load transient response speed and other performance indicators. Among them, the load transient response speed is a very important indicator, which indicates the time it takes for the output voltage to recover from the current unstable state to the stable state when the load changes suddenly. Generally speaking, when the system is affected by external factors, the switching of the working mode or the sudden change of the load current requires the DC-DC converter to respond quickly to restore the system to a new stable state. If the load transient response speed of the DC-DC converter is too slow, the output voltage overshoot amplitude will be too large and the adjustment time will be too long, exceeding its allowed maximum value, affecting the normal operation of the system. In order to ensure the reliable operation of the system, the output voltage of the DC-DC converter should be able to quickly recover stability when the load current changes suddenly, and the control method of the DC-DC converter has a great influence on the load transient response speed. By optimizing the control method, its load transient response speed can be effectively improved. Therefore, it is of great significance to study the control technology to improve the load transient response speed of DC-DC converters [10].

2. Status of DC-DC Converters

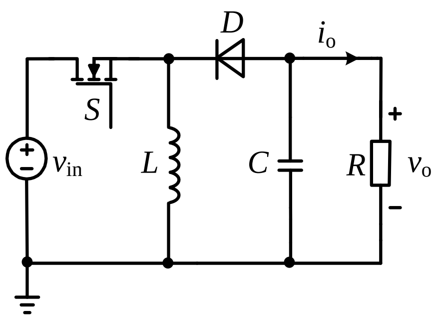
Since DC-DC converters are required in many DC power conversion situations, domestic and foreign scholars have paid more and more attention to its research. In engineering, DC-DC converters can be divided into two categories, one is an isolated DC-DC converter with a transformer, and the other is a non-isolated DC-DC converter without a transformer [11]. The basis of this classification is whether the DC-DC converter needs electrical isolation. For the first type of converter, it will also be favored by people in some occasions with special requirements. Since the transformer is added, its voltage gain can be increased by changing the ratio, that is, the isolated DC-DC converter can achieve complete electrical isolation on both sides of the input and output. For the second type of converter, since the circuit does not contain a transformer, its output voltage can be directly increased, while reducing the size of the converter and improving the power density, so researchers pay more attention to non-isolated DC-DC converters. In the past few decades, researchers have also proposed many topological structures of non-isolated DC-DC converters. Its topological types include Buck, Boost, Buck-Boost, Cuk, Speic and Zeta. Due to the simple structure and low cost of Buck, Boost and Buck-Boost, these three topologies are widely used in converters of various types of batteries and other related fields [12], [13].



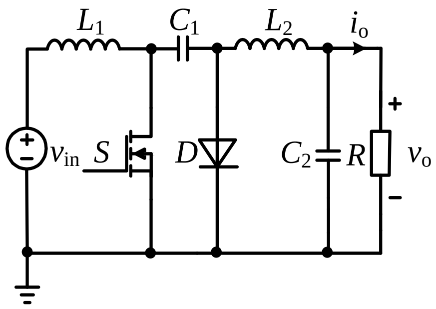
(a) Buck



(b) Boost



(c) Buck-Boost



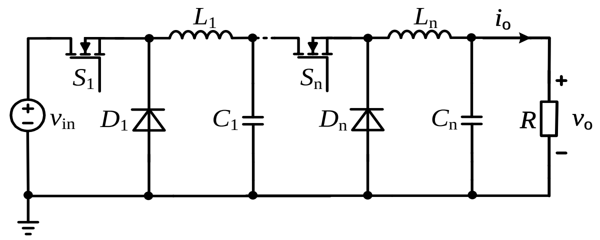
(d) Cuk

Fig. 1 Basic topology of the DC-DC converter

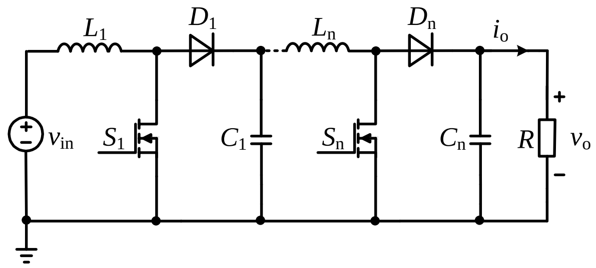
As shown in Figure 1, the basic topology of DC-DC converters mainly includes four types: Buck, Boost, Buck-Boost, and Cuk circuits. Many high-gain applications require DC-DC converters with a higher conversion voltage range. When these four basic structures are applied to specific circuits, in order to enable the converter to maintain its output voltage unchanged over a wide input voltage range, the duty cycle must be adjusted over a wide range. However, doing so will complicate the controller and deteriorate the stability of the system.

Usually, when the circuit needs to be boosted, a Boost converter can be used. If it is necessary to increase the voltage to a higher level, a high boost capability is required. Since the boost capability of the traditional Boost converter is related to the duty cycle, the duty cycle of the switch tube must be large at this time, but this situation increases the circuit loss and reduces the conversion efficiency. Therefore, the actual voltage gain of the traditional Boost converter is limited. Due to the rapid development of renewable energy, there is a high demand for high-gain DC-DC converters. In order to improve the voltage gain ratio, scholars have proposed many topologies, among which traditional cascade and secondary Boost converters are very prominent. For the former, the converters are directly cascaded, and the number of switching devices in the circuit will not be reduced, which increases the switching loss in the system and reduces the efficiency. For the secondary Boost converter, the output voltage increases widely with the reduction of the number of diodes and switches, which improves the efficiency.

3. Traditional Cascade DC-DC Converter



(a) Traditional cascade Buck converter



(b) Traditional Cascade Boost Converter

Fig. 2 Topology of the traditional cascaded DC-DC converter

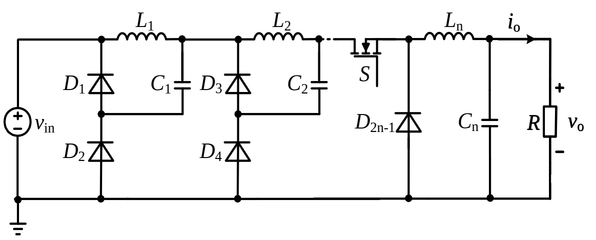
Cascaded DC-DC converters are a simple way to increase voltage gain. They consist of two or more basic DC-DC converters connected in cascade. In fact, in traditional DC-DC converters, the number of stages must be increased to obtain higher gain, that is, passive components and semiconductor components must be added. The number of power processing stages and power switches is equal to the number of cascaded converters, so multi-cascaded DC-DC conversion requires multiple controlled switches [14].

Among traditional cascaded DC-DC converters, cascaded Buck and Boost converters are representative [15]. This cascade method does not make any changes to the basic topology of the converter, but uses the output end of the previous converter unit as the input end of the next converter unit. The topology of traditional cascaded Buck and Boost converters is shown in Figure 2.

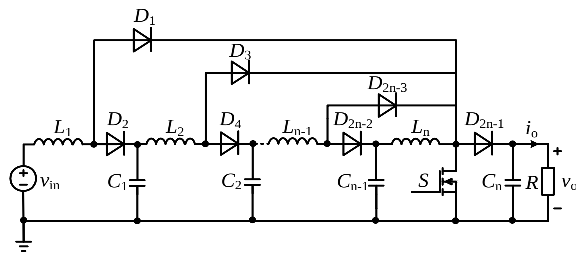
In Figure 2, traditional cascaded Buck and Boost converters are composed of a Buck and Boost converter unit respectively through n cascades. Under the same duty cycle, the more cascaded Buck and Boost converter units there are, the greater their voltage gain. Taking cascade boost as an example, the voltage gain of the traditional cascade DC-DC converter is analyzed.

4. Single-switch cascaded DC-DC converter

In order to reduce the loss of switching elements and the volume of circuits, and to reduce costs, while simplifying the design of the converter control loop, some scholars have proposed a single-switch cascade DC-DC converter. The difference from the converter introduced in the previous section is that it only retains one switch tube when cascading, which reduces the power consumption of the converter, improves efficiency, and only requires one drive circuit to achieve control, optimizing the control design [16]. The commonly used single-switch cascade DC-DC converter is shown in Figure 3.



(a) Single-switch cascade Buck converter



(b) Single-Switch Cascade Boost Converter

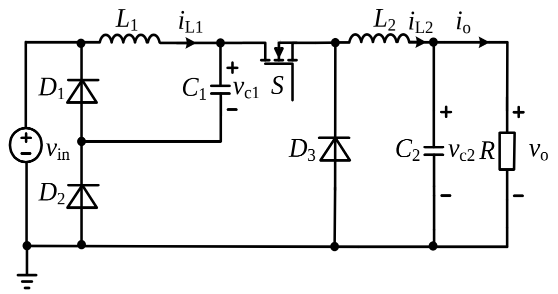
Fig. 3 The topology of the single-switch cascaded DC-DC converter

Fig. 3 shows a single-switch cascade Buck and Boost converter. Although this type of converter and the converter in the previous section are both composed of n converter cascade units, they are different from the topological structure in the previous section. This type of converter has only one switch tube.

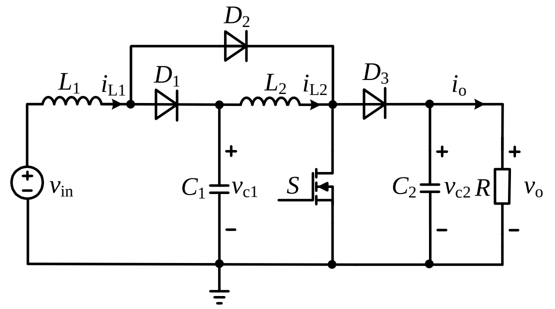
5. Quadratic DC-DC Converters

Through the analysis of the advantages and disadvantages of the above-mentioned cascaded DC-DC converter, some researchers have proposed a quadratic DC-DC converter structure, that is, a single-switch cascaded DC-DC converter with two cascaded units, which uses only one switch tube to control the two basic switch DC-DC converters after cascade processing. It can also provide a voltage gain that has a square relationship with the duty cycle, thereby expanding the input voltage range. Since the quadratic DC-DC converter used in the system only contains one controllable switch, the number of drive circuits is reduced and the control loop design is simplified. The quadratic dependence between the duty cycle and gain of this type of converter allows it to achieve high gain when the duty cycle is much less than 1, thereby reducing the restrictions on the switch. The topology of a common quadratic DC-DC converter is shown in Figure 1-5. The circuit of this type of converter contains two capacitors, a power switch tube and three diodes [17], [18], and its voltage gain is a quadratic function of the duty cycle D.

The topology of the quadratic Buck and Boost converters are shown in Figure 4 respectively. As can be seen from FIG. 4 , the quadratic Buck and Boost converters are obtained by integrating the switch tubes of two-stage cascade Buck and Boost converters into one.



(a) Quadratic Buck Converter



(b) Quadratic Boost Converter

Fig. 4 The topology of quadratic DC-DC converter

6. Research Status of Control Technology for Quadratic DC-DC Converters

In the renewable energy power generation system, the DC-DC converter is used to realize the energy conversion of the circuit, and its control circuit is to ensure that the system can work normally and stably as required. In some specific applications, there are high requirements for the quality of the power supply, and the converter needs to be able to work stably when it is affected by factors such as the external environment or sudden changes in the load, that is, it puts forward certain requirements for its load transient response speed. At present, many scholars have studied the control technology of the secondary DC-DC converter to improve its load transient response speed. Therefore, by selecting a suitable control method, the load transient response speed of the secondary Boost converter can be effectively improved.

For DC-DC converters, their control technology can be divided into two categories, one is ripple control technology, and the other is non-ripple control technology. The basis of this classification is the nature and principle of the control technology. The first control technology is to use the switching ripple of the inductor current or output voltage to generate a pulse width modulation (PWM) signal. The generation of the current ripple control duty cycle is mainly realized by the current ripple signal. Its control loop is simple, the system dynamic response is fast, and it also has a current limiting function, which can protect the circuit. The more typical current ripple control is valley current control, peak current control, average current control, and CC control. For the second control technology, the more typical ones are VM control and average current control. The generation of PWM signals or duty cycles of these two control methods depends on a given sawtooth wave signal, and is not realized by the switching ripple of the inductor current or output voltage, so they are not ripple control [19].

VM control compares the voltage loop output signal with the sawtooth wave to generate a pulse width signal to control the on and off of the switch. In the application of VM control, in order to achieve a fast load transient response speed, a larger error amplifier bandwidth is required. However, in this case, due to the interference of high-frequency switching noise, the stability of the converter is difficult to guarantee. If its stable working state is to be maintained, the bandwidth of the error amplifier will be limited. And in the case of sudden changes in input voltage or output current, only when the output voltage changes can the corresponding change be detected, and then the change is fed back to the controller, which greatly limits the transient response speed of the system. In addition, because VM control is a single-loop control technology, current feedback is not introduced in its loop, so it is likely to cause circuit overcurrent [20].

7. Conclusion

Quadratic DC-DC converters have demonstrated significant advantages in achieving high voltage conversion ratios while maintaining efficiency and reducing component stress. Their ability to provide a wider range of voltage regulation with improved performance makes them promising candidates for various emerging applications.

In the future, the integration of advanced control strategies, such as model predictive control and machine learning-based optimization, could further enhance the efficiency and dynamic response of quadratic converters. Additionally, the adoption of wide-bandgap semiconductors, such as GaN and SiC, will enable higher switching frequencies and reduced losses, pushing the limits of power density and reliability.

The potential applications of quadratic converters extend across multiple fields, including renewable energy systems, electric vehicles, and aerospace power systems. In photovoltaic and fuel cell applications, these converters can efficiently step up low input voltages to meet grid or load requirements. In electric vehicles, they can improve battery utilization and support high-voltage bus architectures. Furthermore, in aerospace and satellite power systems, their high efficiency and compact design make them well-suited for space-constrained environments.

With continuous advancements in power electronics and control techniques, quadratic DC-DC converters are expected to play a crucial role in next-generation power conversion systems, contributing to more efficient and sustainable energy utilization.

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