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Research on the Efficiency Improvement and Thermal Management Design of Resonant Converters

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ABSTRACT

Resonant converters can realize zero voltage switching or zero current switching when working at a specific frequency, thus effectively reducing the switching loss and improving the conversion efficiency. However, with the increase of output power and system operating frequency, the thermal management problem of resonant converters becomes increasingly prominent, which directly affects the performance and reliability of resonant converters. Based on this, this paper discusses the efficiency improvement and thermal management design of resonant converters, aiming at improving conversion efficiency, reducing heat loss, and promoting the application of resonant converters in high power scenarios.

KEYWORDS

resonant converter; efficiency improvement; thermal management; soft-switching technology

Compared with the traditional hard-switching converters, the resonant converters can reduce the switching loss and improve the overall conversion efficiency by operating at a specific resonant frequency, and has been widely used in many fields such as power transmission, electric vehicles, photovoltaics, and power management systems. However, the switching elements, power devices and magnetic components in resonant converters will generate a lot of heat in the application process, and especially in the high-efficiency energy conversion. Too high operating temperature will affect the performance and stability of devices, and shorten the service life of devices. Therefore, thermal management becomes the core problem in the design of resonant converters. In addition, with the continuous improvement of global requirement for energy efficiency, the design concepts and technical standards of all kinds of high-efficiency power electronic equipment are constantly updated, which requires resonant converters not only to have the high-efficiency power conversion capability, but also to ensure good thermal stability in a limited space. Under this background, it is important to study the efficiency improvement and thermal management design of resonant converters. In this paper, the thermal management mechanism is analyzed and optimized, in order to provide a reference for improving the work efficiency of resonant converters and reducing the power loss of the system.

1 Working Principle and Applications of Resonant Converters

1.1 The Working Principle of Resonant Converters

The resonant converter uses the natural oscillation of the resonant circuit to make its voltage and current waveform show sine or quasi-sine wave in the switching process of the switching device, so as to significantly reduce the switching loss of the switching device and the electromagnetic interference and switching stress caused by the fast switching process, and then improve the efficiency and reliability of the overall system. The key feature of the resonant converter is to achieve zero current or voltage at the switching moment, and avoid the peak voltage or current generated by the traditional hard-switching converter at the switching moment, through precisely designing the resonant circuit, so as to reduce the switching loss [1]. The efficiency advantage of resonant converters is not only reflected in the significant reduction of switching loss, but also reflected in its tolerance to input voltage variations. The resonant converter uses high-frequency switching technology, so it can smaller magnetic components and filters, and the overall volume and weight of the system can be significantly reduced, which meets the needs of compact design applications such as electric vehicles and power adapters.

1.2 Applications of Resonant Converters

In power electronic systems, resonant converters are widely used in electric vehicles, power adapters, wireless charging, photovoltaic systems and power transmission. Among them, resonant converters are mainly used for efficient power conversion and battery management systems in electric vehicles and hybrid vehicles. Electric vehicles have strict requirements for charging efficiency and power transmission efficiency, and resonant converters can significantly improve power conversion efficiency and reduce system heating by their characteristics of zero voltage switching or zero current switching, thereby improving the endurance and battery life of vehicles. In the photovoltaic system, the resonant converter can convert the direct current generated by the solar cell into the alternating current or improve the stability of the output voltage and current by DC conversion. The photovoltaic system often faces the challenge of input voltage fluctuation, and the resonant converter can provide stable power output by its wide input voltage adaptability. In wind power generation, resonant converters can efficiently convert electrical energy at high frequencies and reduce the energy loss in the system. In addition to applications in the field of energy conversion, resonant converters are also widely used in power adapters, LED drivers, medical equipment power supplies and other fields. For example, in the LED driver, the resonant converter can efficiently adjust the current to extend the service life of the LED light source, and reduce the noise generated by the power supply, thereby providing a stable working environment.

2 Efficiency Improvement Methods of Resonant Converters

2.1 Optimize Soft Switching Technology and Efficiency

Soft switching technology can effectively reduce the loss in the switching process by making the switching device switch when the voltage or current is zero. In order to further optimize the soft switching technology, it is necessary to precisely match the resonant frequency and the switching frequency to make the switching process fully meet the conditions of zero current or zero voltage, so as to minimize the loss in the conduction and turn-off processes of the switching device. At the same time, in order to optimize the soft switching technology, it also needs to reduce the influence of parasitic parameters (parasitic capacitance, parasitic inductance, etc.) in the resonant loop to improve the overall efficiency of the converter and support the efficient power conversion. At the same time, the values of resonant inductors and resonant capacitors should be selected reasonably to maximize the energy storage and release processes in the energy conversion. And it should accurately control the switching frequency to avoid the efficiency decline caused by frequency mismatch. In addition, the optimization of soft switching technology also needs to be combined with high-frequency PWM and phase modulation to ensure that a stable zero-voltage or zero-current switching state is maintained under high-frequency operation, so as to further optimize the performance of the resonant converter and enable it to maintain a high efficiency under complex working conditions [2]. It follows that the efficiency improvement of the resonant converter needs the coordination and optimization of soft switching technology, resonant circuit design and control, so as to ensure the efficient collaborative work of all parts.

2.2 Reduce Noise Suppression and Power Loss

Resonant converters can produce strong electromagnetic interference due to their characteristic of high-frequency operation, which not only affects the normal operation of the surrounding electronic equipment, but also increases additional power loss. In order to suppress the noise, the inductance, capacitance and topology structure of the filter should be selected to suppress the transmission of high-frequency noise, and the generation source of the high frequency signal should be isolated by shielding materials. At the same time, the positions of power supply cords, earth wires and signal lines should be reasonably arranged to avoid the coupling and propagation of high-frequency switching noise. To reduce the power loss, it is necessary to start from the aspects of switching loss, conduction loss and optimal design of magnetic components. Specifically, the traditional silicon-based semiconductor can be replaced by low-loss semiconductor materials such as gallium nitride (GaN) and silicon carbide (SiC) to effectively reduce the heat generated in the switching process and improve the switching efficiency. For the high-frequency switching loss, the matching of resonant frequency and switching frequency must be precisely adjusted, so that the switching time falls exactly at the intersection of zero current or zero voltage. Switching devices with low on-resistance can be selected and the switching period can be optimized to effectively reduce the loss [4].

3 Thermal Management Design of Resonant Converters

3.1 Heat Source Analysis and Power Loss Distribution

The heat loss of the switching device comes from the switching loss and conduction loss in the switching process. The sudden change of voltage and current in the switching process of the switching device will produce instantaneous energy loss, and the size of this loss is closely related to the switching frequency, the material characteristics of the device, the operating voltage and other factors. Therefore, the accurate evaluation of switching loss requires comprehensive consideration of switching characteristics, parasitic capacitance, switching frequencies and other factors of devices. The conduction loss is derived from the on-resistance of the switching device in the on-state, and the larger the on-resistance, the higher the loss, so the low-on-resistance switching devices can effectively reduce this loss. In resonant converters, power loss is also reflected in components such as wires, inductors and filter capacitors in the circuit [4]. The loss of inductance mainly comes from the copper loss and the iron loss. The copper loss is closely related to current density and wire materials, and the iron loss is related to magnetic flux density and material characteristics. Based on this, low loss materials should be used and the core volume should be reduced to improve the inductive efficiency. The loss of the capacitor is mainly related to its internal resistance and operating frequency. The capacitor with high quality and low equivalent series resistance can be selected, and the heat dissipation component should be arranged in a reasonable position to effectively reduce the heat accumulation and power loss, so as to improve the overall efficiency of the resonant converter.

3.2 Design of Heat Dissipation Technology and Heat Dissipation Structures

For key heat sources such as switching devices and magnetic components in resonant converters, the heat dissipation structure should give priority to aluminum alloys, copper alloys and other high thermal conductivity materials to manufacture heat sinks or fins, which can effectively improve the heat dissipation efficiency and reduce the local overheating phenomenon. In the design of the heat sink, it is necessary to ensure that its surface area and shape can maximize the contact with air or cooling liquid, and increase the heat exchange with the environment, which can be further improved by using micro-channel cooling technology and heat pipe technology. Micro-channel cooling technology is to design a micro-channel to make the cooling liquid flow and directly contact with the heat sink to enhance the heat exchange efficiency. Heat pipe technology conducts heat efficiently from the heat source to the radiator through the evaporation-condensation cycle of liquid metals or liquids inside the heat pipe [5]. In the air cooling design, the use of auxiliary equipment such as fans and air deflectors to strengthen the air flow can improve the heat exchange capacity of the air and reduce the temperature around the heat source, and the liquid cooling system takes the heat away quickly through the cooling liquid flowing through the heat dissipation pipe and connecting with the heat source.

4 Conclusion

To sum up, the improvement of the efficiency and thermal management of resonant converters needs the optimizations of many aspects. Among them, the application of soft switching technology can effectively reduce the energy loss in the switching process, so that the resonant converter can still maintain a high efficiency under high frequency operation. The efficient heat dissipation structure and the combination of liquid cooling and air cooling can effectively avoid overheating and improve the reliability of the converter. In the future, it is necessary to continue to explore the application of new high-efficiency devices and more refined thermal management schemes to further improve the overall performance and application range of resonant converters.

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