Equal Losses control strategy for all switches of intermediate frequency heating power supply

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Abstract. The energy loss of the switches of the lead legs and lag legs during the operation of the intermediate frequency heating power supply using the traditional full bridge control method has a certain difference, and the greater the power of the device, the more obvious the difference. This phenomenon seriously affects the reliability of high-power intermediate frequency heating power supplies. In this paper, the original full-bridge inverter drive is adjusted, and the conditions for implementing ZVS are analyzed. Finally, the equal losses control strategy for all switches is achieved by using the waveform generated by the FPGA controller.

1. Introduction

The intermediate frequency induction heating power supply is one of the electromagnetic induction heating power supplies. It relies on an inductor to transfer electrical energy to the heated metal through electromagnetic induction, and generates eddy currents inside the metal to convert electrical energy into thermal energy for the purpose of heating the metal load. At present, intermediate frequency heating power supplies have replaced many processes that require large amounts of coal and oil.

However, as the demand for intermediate frequency heating equipment increases, how to maximize the efficiency of the intermediate frequency heating power supply, especially the high power intermediate frequency heating power supply, becomes a problem worthy of discussion. After analyzing its working principle, it can be found that in the full-bridge inverter using the conventional driving method, the temperatures of the lead legs and lag legs are different when working. This not only affects the efficiency of devices, but also becomes an unstable factor in the high-power intermediate frequency heating power supply in practical applications.

The main circuit structure of the intermediate frequency heating power supply is the full bridge converter shown in the Figure 1. At present, the control mode of the full bridge circuit is mainly controlled by ordinary bipolar control, phase shift control, finite bipolar control and so on. The latter three have adopted zero-voltage switching (ZVS) technology, so they have higher efficiency in the application of high-power power supply equipment. Based on finite bipolar control, this paper adjusts the full-bridge drive control waveform to realize equal losses of all switches.

2. Analysis Power Loss Analysis of Switches of Full-Bridge Inverters

According to the opening and closing laws of the lead legs and lag legs, the power loss on the switch of the full bridge converter circuit can be calculated as:

$$P_1 = R\left(\frac{I_1^2 \Delta D}{6} + I_1^2 D_{eff} \right) + R\left(I_1 \Delta I_1 D_{eff} + \frac{\Delta I_1^2}{3} D_{eff} \right) \tag{1}$$

$$P_2 = R\left(\frac{I_1^2 \Delta D}{6} + I_1^2 D_{eff}\right) + R\left(I_1 \Delta I_1 D_{eff} + \frac{\Delta I_1^2}{3} D_{eff}\right) + R(1-D)\left(I_p^2 - I_p \Delta I_2 + \frac{\Delta I_2^2}{3}\right)$$

(2)

Among them, equation (1) is the power loss of the lead lags and the equation (2) is the power loss of the lag legs. From the equation we can see that the lag legs soft switch is difficult to achieve zero voltage conduction when the circuit works at light load due to the lack of freewheeling energy. Therefore, the energy loss of the lag leg is more than the energy loss of the lead legs.

In actual operation, different switching losses cause the temperature of the lag legs to be higher than the lead legs. The increase of temperature causes the body resistance of the switch tube to increase, which in turn increases the loss of the switch, forming a positive temperature feedback. When the loss reaches a certain level, the switch of the lag legs will be damaged first, and the reliability of the converter is reduced. If the heat sink is designed according to the difference between the lag legs switching loss and the lead legs switching loss, the system design is difficult and the cost increases.

3. Equal losses PWM control strategy

The basic idea of the equal losses PWM control strategy is to make each leg work as the lead leg and lag leg in two cycles, that is, if a switch works as the lead leg, then it works as the lag legs in next cycle. The equal loss PWM control strategy is shown in Figure 2. Among them, Qa and Qb are the driving signals of the upper and lower switch of a certain bridge arm during operation. Qc and Qd are divided into anti-phase control signals of Qa and Qb. As can be seen from the figure, the working time of the four switches is the same in two cycles, and since the switch is cycled as the lead and leg legs, theoretically, the power losses of the four switches is the same.

Figure 1. Mode of main circuit	Figure 2. Mode of main circuit equal losses PWM control.
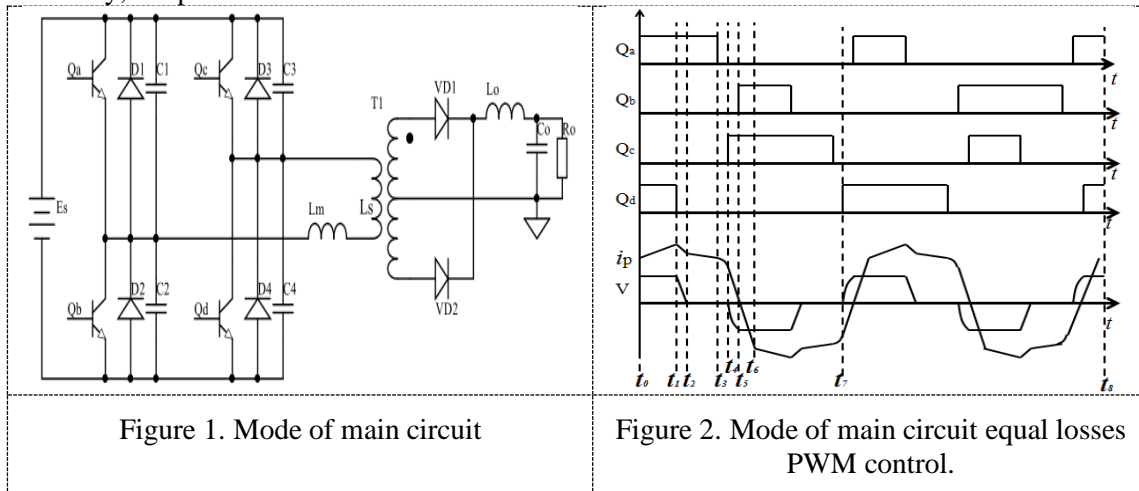
The modals of the power losses control PWM exists in 2 cycles as follows:

- [t0-t1]: The switches Qa and Qd are turned on, and the circuit is in the power output phase. At this time, the current Ip transfers the electric energy to the load through the transformer and leakage inductance Lm stores energy.
- [t1-t2]: The lag leg switch Qd is turned off at time t1, and the primary current Ip can only flow through capacitors C3 and C4, where C4 is charged and C3 is discharged. At time t2, the voltage of C3 is 0, ready for the zero voltage turn-on of Qc.
- [t2-t3]: The circuit is in the clamped freewheeling state. The primary side leakage inductance Lm is almost in a short circuit state, and the circuit Ip decays slowly.
- [t3-t4]: Qa is turned off, the circuit switch is in the rest period, and the circuit continues to flow through diode D3.
- [t4-t5]: Qc is turned on, the primary leakage inductance Lm continues to flow through the capacitors Ca and Cb, and the current Ip gradually decreases due to the reverse voltage.

- [t5-t6]: Qb is turned on, the primary current increases in the reverse direction. When the working state of this segment ends, the circuit starts the power transmission phase of the negative half cycle.
- [t6-t7]: The circuit is in the negative half cycle, the working state is the same as [t0-t6], the waveform is symmetrical but the direction is opposite.
- [t7-t8]: The switches exchange between the lead leg and the lag leg. Since the voltage of the capacitor C4 is 0 at the end of the previous state, the Q4 can achieve zero voltage turn-on. The working state of the circuit is the same as the previous cycle.

Through the improvement of the PWM control strategy, it can be seen that the four switches circulate as the lead leg and the lag leg in two cycles. So we can get the average loss of each switch is:

$$P_Q = R\left(\frac{I_1^2 \Delta D}{6} + I_1^2 D_{eff}\right) + R\left(I_1 \Delta I_1 D_{eff} + \frac{\Delta I_1^2}{3} D_{eff}\right) + \frac{1}{2}R(1-D)\left(I_p^2 - I_p \Delta I_2 + \frac{\Delta I_2^2}{3}\right) \tag{3}$$

After analysis, the new PWM control strategy will not affect the ZVS condition of the lag bridge implementation. Therefore, the theoretical maximum dead time (4) can be obtained.

$$t_{d(lag)} = \frac{1}{4}T_r = \frac{\pi}{2w_r} = \frac{\pi}{2}\sqrt{L_k C_{total}} \tag{4}$$

Among them, L_k is the leakage inductance, C_{total} is:

$$C_{total} = C_j + C_{external} + C_{transformer} \tag{5}$$

4. Implementation of Equal Loss PWM Control Strategy

4.1. Drive control signal generation

The power control PWM control signal is generated by Xilinx FPGA chip. The phase shift value is calculated by setting the frequency, power signal and output voltage signal sampled from the main circuit. Finally, the PWM control signal of equal power loss is generated by looking up the table.
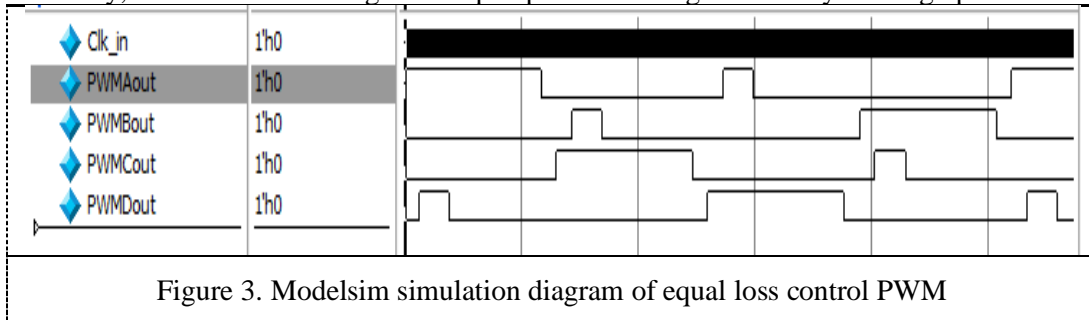

Figure 3. Modelsim simulation diagram of equal loss control PWM

Figure 3 is a logic waveform diagram of four PWM control signals obtained by simulating the Xilinx FPGA compiler and ModelSim. As can be seen from the figure, the waveform of the equal-loss PWM control can theoretically be generated. After the verification is passed, the program is downloaded into the FPGA controller (the Xilinx xc6slx45 controller is selected), and the PWM output waveform is tracked by the oscilloscope. Finally, the equal-loss controlled PWM waveform can be implemented in hardware, which means that the control waveform can be applied to actual engineering, and the hardware waveform will be given in the next section.

4.2. System implementation

This paper was verified by a 40kW intermediate frequency induction heating device. In the main circuit, the three-phase electric input is converted into direct current through the three-phase rectifier bridge; after that, it is converted into a square wave of the corresponding frequency according to the control signal by the full-bridge inverter; finally, the power is output after passing through the transformer. In terms of control circuitry, the intermediate frequency induction heating power supply uses two different controllers, Xilinx's xc6slx45 (the FPGA controller mentioned earlier) and

STMicroelectronics' Stm32F103 series. The FPGA controller is responsible for collecting relevant information of the load to judge the current working state of the device, and generates a PWM control signal to be sent to the full-bridge inverter through the driving circuit. The stm32f103 controller mainly implements LCD display and provides user interaction interface to facilitate observation and adjustment of real-time parameters of the device. In addition, there are protection circuits in the circuit structure that can protect the device in real time when the device is working abnormally.

Figure 4. System frame for intermediate frequency heating power supply
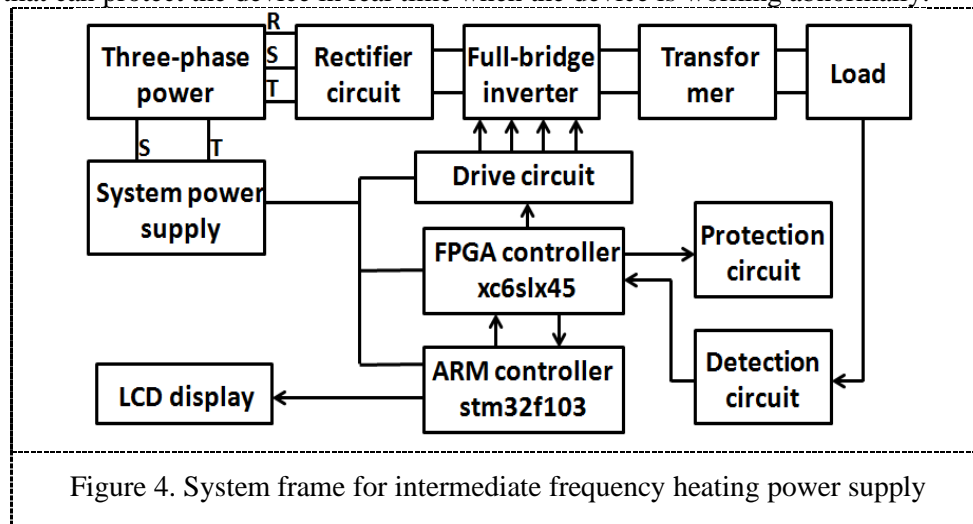
The equal loss control waveform generated by the FPGA in the system is shown in Figure 5. It is not difficult to see that the actual output waveform of the FPGA is almost the same as the waveform obtained on the simulation tool. Figure 6 is the output voltage waveform of the intermediate frequency heating system in actual operation. It can be seen that the equal loss control strategy verified in this paper can be verified under the system.

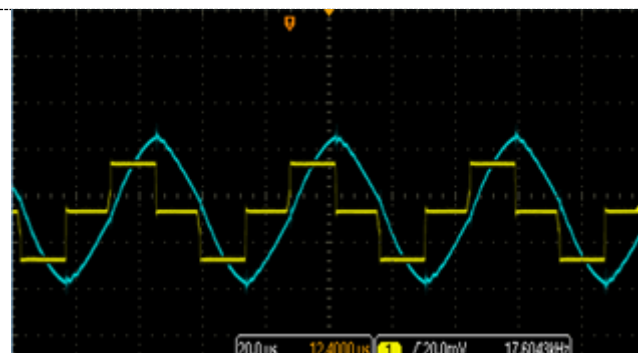| Figure 5. PWM drive waveform output from hardware | Figure 6. Driving voltage and output current waveform |

4.3. Efficacy analysis of control strategies

The easiest way to verify the effects of the equal loss control strategy is to collect the temperature of the switches when the intermediate frequency heating power supply is operating at different power levels. In the figure below, Figure 7 shows the temperature of the switch of the intermediate frequency induction heating power supply under different powers under the traditional control method. Figure 8 shows the temperature of the switch of the intermediate frequency power supply under different powers under the equal loss control method.

It can be seen that in the intermediate frequency heating power supply using the traditional control method, the temperature difference between the lead leg and the lag leg can be as close as 8 ° C. If the power of the equipment is continuously increased, this will inevitably become an important factor

affecting the stability of the equipment. In contrast, under the equal power control strategy, the temperature difference of the switches is significantly smaller or even disappears. Although there are still gaps in the temperature of different switches, in actual systems, these temperature differences are unavoidable due to differences in heat dissipation. In addition, due to the reduction of the body resistance of the total switches, the power loss is reduced overall, so the power of the inverter is also slightly improved.
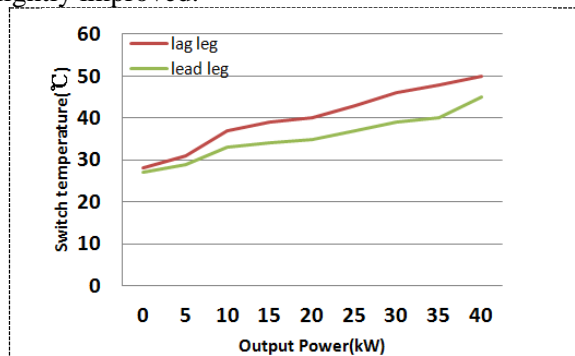
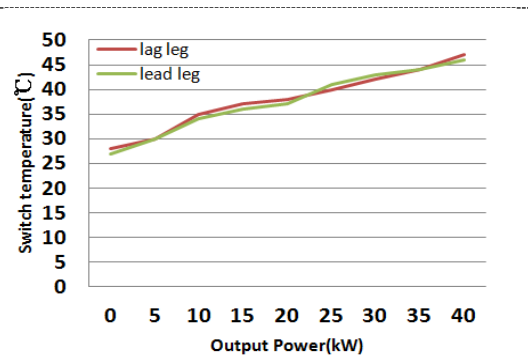|	
Figure 7. The temperature of the switch of the traditional control method	Figure 8. The temperature of the switch of the equal loss control method

5. Conclusion

This paper presents an improved PWM control strategy. Under the control strategy, the shortcomings of the inconsistent heat generation of the lead leg and the lag leg during the operation of the high-power full-bridge inverter are overcome. The feasibility of the control strategy is demonstrated by a 40 kW intermediate frequency induction heating device, and the efficiency of the equipment operation is improved.

References

[1]   Du Guiping, Zhang Bo, Chen Lijun. (2007) A PWM Control Strategy for ZVS PSFB With Equal Losses for All Switches. Transactions of china electrotechnical society,22(1):103-107.

[2]   Wang Jiwei. (2008) Study on a New Limited Double Control Method of Poles PWM Full Bridge. Power supply technologies and applications,11(6):35-39.

[3]   Wang Liangliang, Yang Yuan, Liu Haifeng, Gao Yong. (2015) A Soft Switching Driver Circuit for High-power IGBT. Power Electronics,49(7):79-82.

[4]   Chen Zhong, Chen miao, Luo Yingpeng, Shi Liangchen. (2011)A Novel ZVS Full Bridge Converter With Auxiliary Network in Parallel With the Lagging Leg. Proceedings of the CSEE,31:56-61.

[5]   Zeng Wanghui, Li Cuimei. (2005)Novel Finite Both Positive Control ZVZCS Full-bridge PWM Converter. Journal of Jiangxi normal university (Natural science),29(6):499-504.

[6]   Redl R, Sokal N O, Balogh L. A novel soft-switching full-bridge DC/DC: analysis, design consideations and experimental results at 1.5kW 100kHz.(1991). IEEE Transactions on Power Electronics,6(3):408-418.