Design of Medium Frequency Induction Heating Power Supply for Contact Rail De-icing

Yuchao Liang[1], Gang Zhang[1,2](✉), and Yifan Liu[1]

[1] Beijing Jiaotong University, Beijing, China
{21121434,gzhang}@bjtu.edu.cn
[2] Rail Transit Electrical Engineering Technology Research Center, Beijing, China

Abstract. In order to solve the problem of frequent contact rail icing in urban rail transit under low-temperature environments, a contact rail de-icing method based on medium frequency induction heating technology is proposed. A control strategy for medium frequency induction heating power supply suitable for contact rail de-icing is put forward to address the issues of low control accuracy and complex circuit of traditional induction power supply. A simulation model of the system was built using MATLAB/Simulink, and the main circuit and control strategy of the system were simulated and studied. Frequency automatic tracking and phase shifted PWM power regulation were achieved, and the correctness, feasibility, and rationality of the scheme were established.

Keywords: Contact rail de-icing · Induction heating converter · Frequency tracking · Phase-shifting power regulation

1 Introduction

When encountering winter ice and snow weather, the contact rail in urban rail transit used for power supply may experience icing and snow under harsh environmental temperature and humidity conditions; The accumulation of ice and snow will cause the current collector of the train to be unable to take flow normally, affecting normal operation. Therefore, it is necessary to conduct in-depth research on technology for contact rail de-icing. With the rapid development of power electronics technology, equipment based on power electronic components has become more advanced and complete [1]. Induction heating is a popular heating method in industrial production [2]. Compared with traditional heating methods, induction heating is usually more efficient, and it uses non-contact forms to achieve local heating, with lower energy consumption and no environmental pollution. It is an energy-saving, environmentally friendly, efficient, and safe new heating method [3]. In industrial production where heating is required, the power supply for induction heating equipment is usually an medium frequency power supply [4]. However, the current induction heating power supply has problems such as low control accuracy and complex circuits, so it is necessary to further research on medium frequency power supply [5, 6]. In response to this issue, this article proposes a design scheme for a medium frequency induction heating power supply suitable for contact rail

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de-icing. By adopting frequency automatic tracking and PWM power regulation control technology, both efficiency and performance are taken into account, improving the performance of the medium frequency induction heating power supply. The feasibility of the above design was verified through Simulink simulation software, and the system control accuracy and stability were improved.

2 System Circuit Design

2.1 Overall Circuit Topology

The main circuit topology of the induction heating power supply is shown in Fig. 1. The power supply adopts a three-phase power supply, and the rectification method adopts three-phase uncontrolled rectification, where U, V, and W are the input lines of three-phase AC power. The rectified result is filtered out by the LC filter circuit to obtain a stable DC power supply to the inverter circuit. The inverter circuit is a series resonant circuit, and the power switching device is an IGBT. Diodes D_1 ~ D_4 are connected in parallel at both ends of four IGBT T_1 ~ T_4, providing channels to prevent direct short circuits between the upper and lower tubes during load commutation. The load electromagnetic induction coil is equivalent to simplifying the series connection of *R*, *L*, and *C*, and adopts impedance matching method. The resonant capacitor is placed on the primary side of the matching transformer, and the equivalent *R* and *L* are placed on the secondary side.

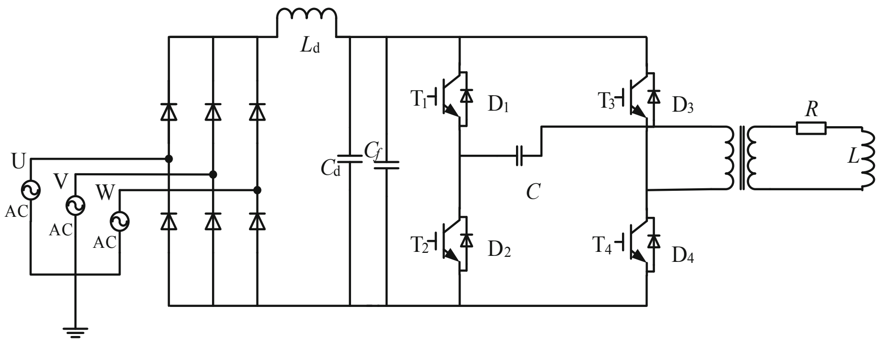

Fig. 1. Main circuit topology

2.2 Inverter Circuit Design

The series resonant inverter composed of a series resonant circuit is shown in Fig. 2.

Due to the parallel connection of a large capacitor at the front end, a series inverter circuit can also be approximated as a constant voltage source, so it can also be called a voltage source inverter circuit. When a series resonant inverter experiences resonance, the load can exhibit pure impedance phenomenon [7]. During normal operation, the voltage is constant, and the voltage and current on the load are approximately rectangular and sine waves, respectively.

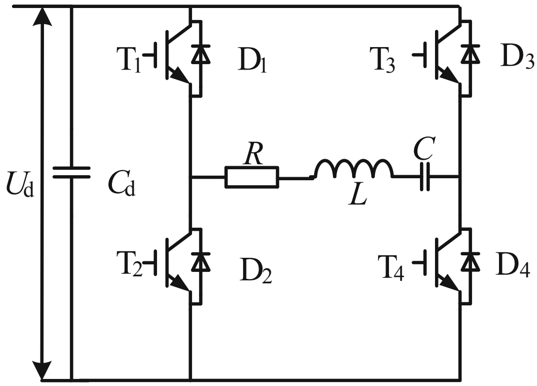

Fig. 2. Series resonant inverter

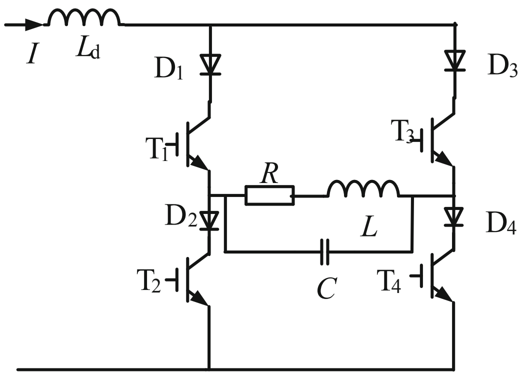

Fig. 3. Parallel resonant inverter

The parallel resonant inverter composed of parallel resonant circuits is shown in Fig. 3.

When resonance occurs in a parallel resonant inverter, the impedance is high. When using a voltage source for power supply, it will inevitably result in a relatively small current near the resonance. To prevent this situation from happening, the rectifier link at the front end of the inverter needs to use a large impedance inductor filter instead of a large capacitance filter. At this time, the rectifier link is similar to a constant current source, which is equivalent to using a current source to power the parallel resonant inverter. When resonance occurs in a parallel resonant inverter, the resonant circuit exhibits low impedance for higher harmonics in the load current and high impedance for fundamental waves with similar harmonic frequencies [8]. The voltage of the harmonic component decays, and the load voltage and load current are approximately sinusoidal and square waves, respectively.

This paper selects the series resonant inverter circuit as the inverter circuit of the medium frequency induction heating power supply. The advantages of a series resonant inverter circuit are that the switch tube is easy to implement the soft switching technology of ZVS/ZCS, reduces switching losses and electromagnetic interference EMI, has a wide range of power regulation, fast speed, high power factor, and good load adaptability.

As a parallel resonant inverter powered by a constant current source, when the main switch tubes of the upper and lower bridge arms of the inverter are simultaneously turned off, the DC power supply is in an open circuit state. To prevent this situation from happening, it is necessary to follow the soft turn on principle of first turn on and then turn off during circuit commutation. It should be maintained for a certain period of time, and all switching devices should be in a conductive state. This time is called the overlap time of the circuit.

From the perspective of circuit principles, these two types of circuits are dual in many aspects, such as circuit parameters, waveform of current and voltage, circuit structure, etc. This is very beneficial for analyzing and comparing these two types of circuits, as well as designing effective and reliable protection circuits.

Below is a comparative analysis of some of its characteristics and differences in application in Table 1.

Table 1. Comparison of series resonance and parallel resonance circuits.

	Voltage type series resonant circuit	Current type parallel resonant circuit
Structure	General switching devices are connected in parallel with reverse diodes to prevent them from withstanding reverse voltage	Need to quickly restore large capacity diodes in series to avoid switching devices from withstanding reverse voltage
Load requirements	Due to the load connection method, the influence of equivalent parameters is small, and the requirements for load wiring are low	Due to limitations in load connection methods, equivalent parameters have a significant impact and high requirements for load wiring
Equivalent resistance	When in resonance working state, the equivalent resistance is small	When in resonant working state, the equivalent resistance is high
Load vibration	Easy to initiate load vibration, suitable for frequent startup applications	Difficult to initiate load vibration, not suitable for frequent startup applications

In summary, the series resonant input can be regarded as a voltage source, with an output voltage of square wave and an output current of sine wave. It requires parallel connection of large capacitors to maintain a constant input voltage, making it suitable for medium to small power induction heating power supplies [9, 10]. The parallel resonant input can be regarded as a current source, with a sine wave output voltage and a square wave output current. A large inductance needs to be connected in series to maintain a constant input current [11, 12]. The requirements for designing a medium frequency induction heating power supply in this paper are that its output voltage is square wave, the output current is sine wave, the output power is small to medium power level, and the output frequency is in the medium frequency range of 20 kHz. At the same time, considering the complex industrial environment and the requirements for frequent vibration, according to the load characteristics, this design selects a series resonant circuit as the inverter main circuit.

3 Control Strategy Analysis

3.1 Frequency Automatic Tracking

The medium frequency induction heating power supply mainly uses a phase-locked loop circuit to achieve automatic tracking of the resonant frequency of the load. The phase-locked loop system is a system that controls the phase error between two signals, and its function is to achieve completely error free frequency tracking of the output signal to the input signal [9–12]. The sampling circuit first samples and processes the voltage and current in the load, and then undergoes zero detection to obtain the phase information in the voltage and current. Then, phase comparison is performed to obtain the phase difference. The difference is used to control the drive circuit to output the drive pulse signal. The new drive pulse signal acts on the inverter circuit to change the output frequency of the medium frequency induction heating power supply. Figure 4 shows the schematic diagram of frequency tracking for an medium frequency induction heating power supply.

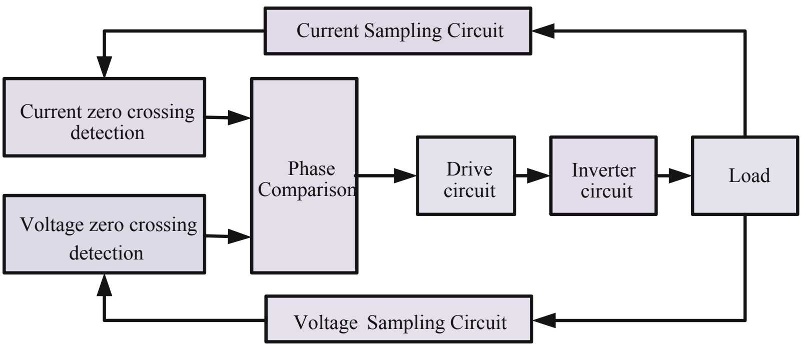

Fig. 4. Principle block diagram of frequency tracking

3.2 Phase Shift Power Regulation

The control core of the induction heating power supply system is to control the conduction and shutdown of the power switch IGBT. The modeling process of phase-shifting drive control pulse is as follows: the standard signal source frequency is 40 kHz, and the sawtooth wave with amplitude of −1 to +1 is used as the reference signal, which is adjusted and converted into a sawtooth wave between 0 and 1. The edge D trigger is used to achieve the output PWM duty cycle of 50%, and PWM control signals are obtained. Two complementary signals are obtained through the inverter, and two comparison values U_1 and U_2 are set to achieve four drive control pulse signals, and the phase-shifting angle is β It can be adjusted arbitrarily between 0 and 2π. The carrier wave is sawtooth wave U_c, U_1 and U_2 are constant, forming IGBT drive control pulse wave. The frequency of generated PWM pulse can be changed by changing the frequency of sawtooth wave Uc, The phase shift angle β can be changed by changing the values of U_1 and U_2, the expression for phase shift angle is:

$$\beta = (U_2 - U_1) \times 180^\circ \tag{1}$$

After the voltage and current are phase-locked, the fundamental output active power of the inverter is: P_{AB1max} is:

$$P_{AB1} = U_{AB1} I_{AB1} \cos\varphi_1 = \frac{8U_d^2}{\pi^2 R}[\cos\frac{\beta}{2}]^4 \tag{2}$$

U_{AB1}, I_{AB1} is the effective values of the fundamental voltage and current output by the inverter, φ_1 is the phase difference between the fundamental voltage and current output by the inverter, and U_d are the input DC voltage of the inverter.

Due to the RLC series connection of the load circuit, the load power factor angle can be obtained φ_1 is

$$\tan\varphi_1 = \frac{\omega L - \frac{1}{\omega C}}{R} \tag{3}$$

The conversion equation is:

$$LC\omega^2 - RC\omega\tan\varphi_1 - 1 = 0 \tag{4}$$

From Eq. (4), it can be solved that:

$$\omega = \frac{RC\tan\varphi_1 + \sqrt{(RC\tan\varphi_1)^2 + 4LC}}{2LC} \tag{5}$$

The quality factor Q of the RLC series resonant circuit is:

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 CR} \tag{6}$$

Among ω_0 is the load resonance angle frequency.

By introducing Eqs. (6) into (5), the unit value of load angular frequency can be obtained as follows:

$$\frac{\omega}{\omega_0} = \sqrt{\frac{1}{4Q^2}(\tan\frac{\beta}{2})^2} - \frac{1}{2Q}\tan\frac{\beta}{2} \tag{7}$$

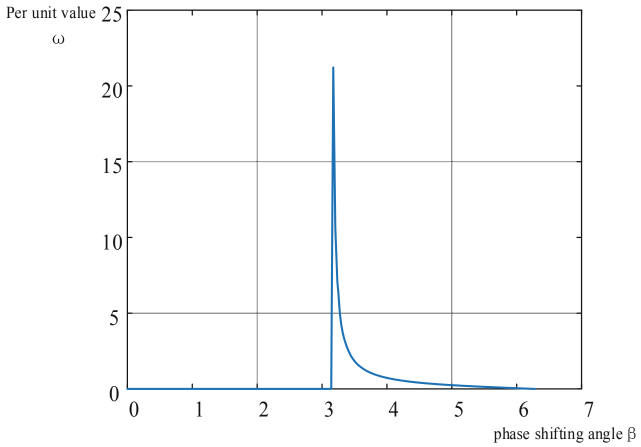

Fig. 5. Angle frequency unit value and phase shift angle relationship

When $Q = 3$, The relationship curve of the working angular frequency ω unit value and phase shift angle β is shown in Fig. 5.

This design selects the inductive phase shift PWM power regulation control method. In order to ensure that the entire heating power system is always in a series resonant state during the phase shifting and power adjustment process, it is necessary to maintain the driving pulse signal of the directional arm always following the load current signal, and then change the phase shifting angle of the phase shifting arm relative to the driving pulse signal of the directional arm β to change the size of output power P.

4 Simulation

The input power supply is a three-phase AC power supply of 380V/50Hz. The DC voltage output after rectification passes through a series resonant inverter circuit with a resonant frequency of 20kHz. Among them, DC filter capacitor $C_d = 1$ mF, current limiting reactor $L_d = 2.5$ mH, and high-frequency filter capacitor $C_f = 40$ μF. Load resistance $R = 18.3\ \Omega$, inductance $L = 437$ μH. Capacitance $C = 0.145$ μF. At this point, the quality factor Q is 3.

The relationship between phase shift angle, resonant operating frequency, and output power is summarized in Table 2.

By analyzing the output voltage and current waveforms at phase shift angles of 0°, 36°, 90°, and 144° in Fig. 6, it can be seen that changing the phase shift angle β The size and duty cycle of the output voltage change accordingly, and the specific relationship is: The larger the phase shift angle β, the smaller the effective value of the output voltage, and the smaller the output power. At the same time, the phase-shifting PWM power regulation can be achieved by requiring the driving pulse signal of the directional arm to follow the load current signal, it is actually a composite power regulation strategy - PWM&PFM, which increases the phase shift angle while also increasing the operating frequency of the power supply. Similarly, when the equivalent inductance parameters of the load circuit change, the frequency of the load circuit will also change.

The above simulation results indicate that the simulation experimental results are basically consistent with the theoretical analysis, and the control circuit and main circuit designed in this paper meet the requirements. By building a MATLAB/Simulink simulation structure platform for the medium frequency induction heating power supply system, the feasibility of voltage type series resonant circuit under phase-shifting PWM power regulation control scheme was verified.

Table 2. Phase shift power adjustment relationship table.

Phase shifting angle	Resonant frequency/kHz	Output power/kW
$\beta = 0°$	20	12.2
$\beta = 36°$	21.3	10.1
$\beta = 90°$	24	4.8
$\beta = 144°$	27	1.0
$\beta = 180°$	–	0

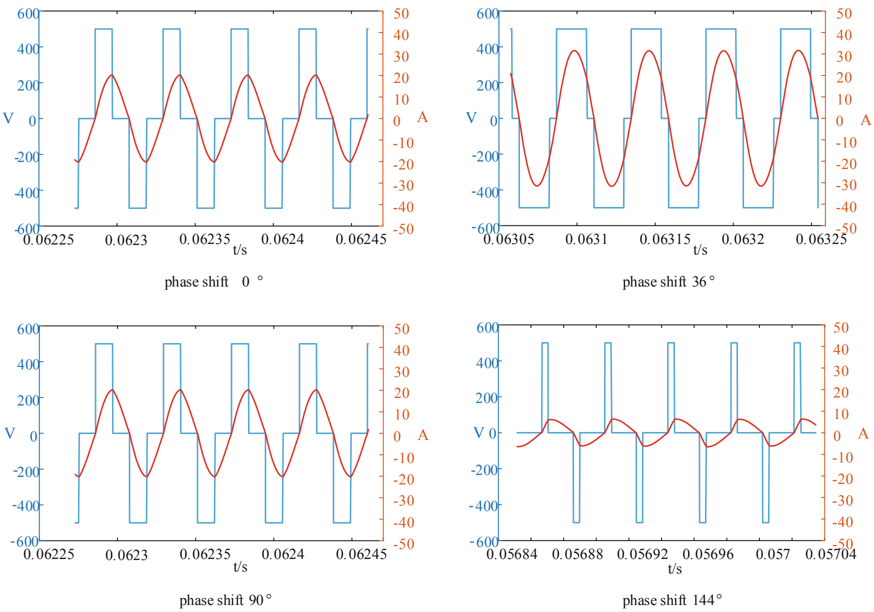

Fig. 6. Phase shift waveform

5 Conclusion

By using the simulation software MATLAB/Simulink module, various modules of the medium frequency induction heating power supply were built, and these modules were integrated. Then, the entire system was simulated and the results were analyzed, achieving automatic frequency tracking and phase-shifting PWM power regulation control. The correctness of the theoretical design was verified through simulation.

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