The invention relates to an intermediate frequency power supply fast start and digital phase locked loop control technology

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Abstract. Intermediate frequency induction heating is widely used because of its low energy consumption and high thermal efficiency, but the speed of traditional intermediate frequency power supply is slow and its frequency tracking accuracy is limited. In order to maintain the resonant state of the load during the working process of the induction heating power supply and realize the automatic frequency tracking control during the working process. The frequency tracking of the 40kW intermediate frequency power supply is researched, and a method of combining the resonant frequency automatic identification algorithm and the digital phase locked loop frequency tracking control method is proposed. MATLAB simulation and experiment show that the system based on this control method can save the time of searching the load resonance frequency in the initial stage of the power supply, improve the frequency tracking speed, accelerate the dynamic response speed of the system, avoid the failure of frequency lock, and play the role of fast and stable startup.

1. Introduction

The core task of the inverter control of the intermediate frequency power supply is to track the change of the resonant frequency of the load. Okuno A et al. began to apply the phase-locked loop to achieve frequency tracking, but the use of a single phase-locked loop frequency tracking system has a long transition time, and when the load disturbance changes, the lock is volatile [1]. Tian J et al. put forward a FUZZY-PLL compound control strategy, which uses the two-stage control for frequency correction to achieve system frequency tracking [2]. Zang X H et al. used a proportional integral control combined with a digital phase-locked loop (PI-DPLL) compound control method to achieve real-time tracking of the frequency and phase of the resonant inverter power supply [3].

The above methods have achieved good tracking results, but the resonant frequency search time is longer in the early stage. In order to save the frequency search time and improve the frequency tracking efficiency, this paper proposes a digital phase locked loop (DPLL) frequency tracking control method with automatic resonant frequency identification. The resonant frequency of the load can be roughly determined with only two calculation cycles, and then the frequency automatic tracking is realized through DPLL frequency tracking method. This method has short frequency tracking transition time and good frequency tracking effect.
2. Frequency tracking method

2.1. Maximum current search resonant frequency method
The relationship between load impedance and operating frequency is shown in figure 1. When the load is working at the resonance frequency, the impedance is the smallest. This method is simple in design, easy to operate, but the load resonance frequency will drift during operation. If the resonance frequency is continuously scanned, it will affect the working state of the load. Moreover, the control accuracy of this method is not high.

2.2. Phase-locked loop frequency tracking method
The basic structure of the phase-locked circuit is shown in figure 2, which is actually a phase difference automatic correction and adjustment system [4]. The voltage and current sampling signals are converted by the comparator into square wave signals in phase with the output voltage and the output current respectively.

The Q output terminal of the D flip-flop can reflect the phase relationship between voltage and current, and can be used to determine the direction of change of the output voltage alternating frequency. The pulse width of the output pulse signal of the XOR gate can reflect the phase difference between the voltage and current signals. The size of the value can be used to determine the size of the frequency change [5].

2.3. Resonant frequency automatic identification algorithm
The automatic resonant frequency identification algorithm uses the following formula to find the resonant frequency. The specific algorithm is as follows: take the output voltage frequency \( f_a \) and \( f_b \) of any two power sources, and the corresponding phase difference Angle of output voltage and output current is \( \theta_a \) and \( \theta_b \) respectively [6]. The phase difference Angle is the same as the load impedance Angle. The phase difference between the output voltage and current can be obtained by using the duty ratio \( D_a \) and \( D_b \) of the output pulse of the phase-locked circuit:

\[
\begin{align*}
\theta_a &= D_a \pi \\
\theta_b &= D_b \pi
\end{align*}
\]

According to the power frequency: \( \omega_a = 2\pi f_a \), \( \omega_b = 2\pi f_b \), \( \tan \theta_a \), \( \tan \theta_b \) is the tangent value of the load impedance angle, and its calculation formula is:

\[
\begin{align*}
\tan \theta_a &= \frac{\omega_a L - 1/\omega_a C}{R} \\
\tan \theta_b &= \frac{\omega_b L - 1/\omega_b C}{R}
\end{align*}
\]
\[
\frac{1}{RC} = \frac{\omega \alpha \tan \varphi_1 \tan \varphi_2}{\omega_2^2} = A
\]
(5)

\[
\frac{L}{R} = \frac{\omega \tan \varphi_1 - \omega \tan \varphi_2}{\omega_2^2 - \omega_1^2} = B
\]
(6)

The resonant frequency of the load is:

\[f_0 = \frac{1}{2\pi \sqrt{LC}}\]
(7)

Incorporating formulas (5) and (6) into formula (7), we can get:

\[f_0 = \frac{1}{2\pi} \sqrt{\frac{A}{B}}\]
(8)

Among them, A and B can be obtained by sampling calculation of the digital control system. Through the resonant frequency automatic identification algorithm, only the output frequency and are needed to obtain the load resonant frequency. This method can greatly shorten the transition time of frequency tracking.

3. Digital phase locked loop frequency tracking control method for resonance frequency automatic recognition

In order to make the load always get the maximum power, the output frequency \( f \) of the intermediate frequency power supply is required to follow the change of the natural oscillation frequency \( f_0 \) of the load and keep frequency tracking at all times. This paper proposes a method of combining the resonant frequency automatic identification algorithm and the DPLL frequency tracking control method. Using DSP as the control processor, the resonant frequency of the load can be basically determined with only two calculation cycles \( f_0 \), and then use the DPLL frequency tracking method to correct the error of \( f_0 \) and follow the change of the load resonance frequency. This method can save the time of searching load resonant frequency in the initial stage of power supply, shorten the time of frequency tracking process, and help the system to keep working state better.

3.1. Sampling circuit

In this paper, the voltage transformer and current transformer are used for sampling, and the input voltage signal is converted into square wave. The rising edge and falling edge of square wave are captured to realize the phase capture of intermediate frequency power supply. The phase capture circuit is shown in figure 3. DSP capture unit can get the phase change of voltage and current, and adjust the pulse frequency of the full bridge of phase shift through the phase difference between them, adjust the frequency output, and achieve frequency tracking.

(a) Voltage waveform capture phase diagram
3.2. Frequency tracking control system

The functions implemented by the intermediate frequency power supply control system include the design of digital phase-locked loops, control of power regulation and overvoltage and overcurrent protection. The digital signal processor uses TI’s TMS320LF28335 DSP, which has high performance, low power consumption, fast execution speed and strong real-time control capabilities.

The DSP collects the working state of the load in real time through the peripheral circuit, adjusts the PI according to the voltage and current phase difference signals, and outputs a PWM wave with a suitable frequency, so that the load always works in the best state [7]. The flowchart of the DPLL control method with automatic resonant frequency identification is shown in figure 4.

4. System simulation and verification

4.1. System Simulation

This article uses Matlab simulation software to model the intermediate frequency power load, uses frequency calculation to obtain the resonant frequency, and then uses the phase-locked loop frequency tracking method to lock the load resonant frequency. There is no load matching transformer designed in the model. The load directly adopts R, L and C series resonant load [8]. Part of the simulation models of the control system are shown in figure 5.
Simulation parameters: input voltage is 540V, power is 40kW, power frequency is 8-15kHz; load resonance frequency is about 9kHz, load resistance is 3.5ohms, inductance is 0.09mH, and capacitance is 4.4uF. When starting, output the alternating voltage at 11kHz and 12.5kHz, and then output at the calculated frequency, the load output voltage and current waveforms are shown in figure 6.

It can be seen from figure 6(a) that the calculated frequency fixed frequency time is shorter, which can realize fast fixed frequency. It can be seen from figure 6(b) that the output current and voltage phase are basically the same, and frequency tracking is well realized. The simulation results show that this method has the advantages of fast algorithm dynamic response and high DPLL steady-state accuracy.

4.2. Experimental verification

In order to verify the above theory, an intermediate frequency power supply experimental platform was built. The complete intermediate frequency power supply is controlled by the DSP digital control.
system, and the designed control algorithm is written into the digital control system. Specific experimental parameters: power supply 40KW, voltage 380V, duty ratio 0.75, resistance 14.25 ohms, starting output frequency is set to 25K, given $f_a$ is 11K, $f_b$ is 12K, and the final calculated resonant frequency is about 9K. Other same simulation parameters.

Figure 7. The output waveform when the interval is 4ms

It can be seen from figure 7 that when the input voltage is 380V and the resonant frequency is around 9kHz, the output voltage and current of the power supply under the load resonance state have a good phase state, the steady-state error is small, and the frequency tracking is better realized.

5. Conclusion
This paper designs the frequency tracking of the 40kW intermediate frequency power supply, using the method of combining the resonant frequency automatic identification algorithm and the DPLL frequency tracking control method. The simulation and experimental results show that compared with the traditional frequency tracking method, this method can save the searching time of resonance frequency in the early stage of the load power supply, and can realize the automatic tracking of the load resonance frequency, and improve the output power precision of the power supply. In the future work, the sampling circuit is optimized to improve the speed and accuracy of the system, and this method is combined with intelligent temperature control to make the intermediate frequency power supply play a better performance.

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