Research on Ultrasonic Power Supply Based on Cascade Buck Technology

W Y Zhang1,2, C Z Zhang1, C H Zhou1, Y J Zhu1 and Y H Shu1

1Hubei Key Laboratory for High-efficiency Utilization of Solar Energy and Operation Control of Energy Storage System, Hubei University of Technology, Wuhan 430068, China

E-mail: 517812245@qq.com

Abstract. In view of the large voltage harmonics and low power density of the low-power ultrasonic power supply, a low-power ultrasonic power supply based on the cascade buck technology is proposed. The converter of the power supply is composed of two buck units in cascade, and the output of the unit is forward Sinusoidal half-wave DC voltage waveform, and then commutated by the full-bridge inverter every half cycle to output sine wave AC voltage waveform, can significantly reduce the voltage harmonics of the ultrasonic power supply, reduce the inductance of the matching network, and improve the ultrasonic wave Power density. Through the combination of voltage and current phase detection and PI regulator, the tracking resonance frequency is controlled. By analyzing the system structure, working principle and control strategy of the ultrasonic power supply, modeling and simulation are carried out on Matlab / Simulink, and the feasibility and effectiveness of the scheme are verified.

1. Introduction

With the rapid development of piezoelectric materials, fully controlled electronic devices and embedded chips, ultrasonic technology is gradually entering people's lives. The low-power ultrasonic power supply is widely used in cleaning, diagnosis, treatment, telemetry, welding and other fields. With the development of high-precision and high-frequency ultrasonic technology, the performance of ultrasonic power supplies has become more and more stringent in ultrasonic applications. The development of ultrasonic power supplies is the key technology that determines the development of the ultrasonic industry. The power of low-power ultrasonic power supplies the problem of low density needs to be solved urgently. When the environment and temperature of the system change, the inherent resonance frequency of the transducing system will drift, causing the transducer to detune, which will cause the temperature of the acoustic system to rise and the amplitude to decrease exponentially. The electroacoustic conversion of the transducer the efficiency will be greatly reduced. The frequency tracking ability of the ultrasonic power supply determines whether the transducing system can stay in resonance for a long time. Therefore, the frequency tracking system has an important position in the research of ultrasonic power supply.

Reference [1] provides a comprehensive overview of the high-power ultrasound industry through a review of high-efficiency applications, focusing on industrial applications and the introduction of the development of recording technologies from the early stages of cleaning to advanced sonochemistry, cutting and water treatment today The industrial application and development prospects of high-power
ultrasonic power supply are introduced. In the reference [2], the DC / AC unit uses a buck voltage regulator circuit and a full-bridge inverter circuit to invert the DC voltage into a square wave AC voltage. The buck voltage regulator circuit adjusts the voltage size, which has the advantages of simple circuit and few switching devices. However, it generates more AC voltage harmonics, which requires larger inductance and capacitance for filtering, and the power density is low. Traditional ultrasonic power supply frequency tracking methods include maximum current search resonance frequency method, phase locked loop frequency tracking method and matching inductance adjustment method. In reference [3], the improved phase-locked loop frequency tracking technology is used to optimize the lock-in time of the phase-locked loop, but there is still the problem of unstable tracking frequency. In reference [4], an improved ultrasonic power supply variable step frequency tracking control method based on automatic identification of resonance frequency is proposed. The system based on this control method can increase the frequency tracking speed, reduce the system transition time, and improve the dynamic response characteristics, but Tracking accuracy has not improved. In reference [5], a hybrid control method combining fuzzy control theory and PID control is proposed. The precise adjustment of coarse harmonic PID with fuzzy control can quickly and stably track the frequency of the parallel resonance point of the ultrasonic transducer system. Aiming at the situation that the output voltage harmonics of the traditional low-power ultrasonic power supply are high and the power density is low, a small-power ultrasonic power supply based on the cascade buck technology is proposed, which can greatly reduce the output voltage harmonics of the ultrasonic power supply and increase the output voltage. Waveform quality, reduce noise. A combination of voltage phase detection and PI regulator is used to track the resonant frequency of the transducer. This paper first analyzes the system structure of the ultrasonic power supply and the working principle of the cascade buck circuit, introduces the control strategy of the automatic frequency tracking algorithm, and finally verifies the feasibility and effectiveness of the scheme by simulation.

2. Topology description

Figure 1 shows the structure diagram of the ultrasonic power supply based on the cascade buck technology, which includes a single-phase rectifier bridge, cascade buck converter, full-bridge inverter, high frequency transformer, matching network and transducer, where the transducer contains static capacitor $C_0$, resistance $R_d$, dynamic inductance $L_{d}$, dynamic capacitance $C_d$.

![Figure 1. System structure diagram](image-url)

First, the alternating current is rectified into a DC voltage through an uncontrolled rectifier of a diode, and then the cascade buck converter circuit is adjusted to output a sinusoidal half-wave DC voltage through a certain control strategy. The Buck circuit is a step-down circuit, which can adjust the DC voltage to adjust the output power of the ultrasonic power supply. The inverter is an H-bridge inverter, which can commutate the positive sinusoidal half-wave DC voltage every half cycle and output a sinusoid. Wave AC voltage, and then send the high frequency AC voltage into the transducer.
through the high-frequency transformer and matching network.

3. Working principle

3.1. How cascading buck technology works
The cascade buck circuit is composed of two buck circuits. After the mains is rectified, the constant DC voltage $U_i$ is transmitted to the input side of the cascade buck circuit. The cascade buck circuit transforms the constant DC voltage $U_i$ into a Forward sinusoidal half-wave DC voltage $U_o$ with adjustable amplitude and frequency. The inverter is a sinusoidal AC voltage $U_{o2}$, see figure 2 for details.

$$\text{Figure 2. Schematic diagram of input and output waveforms of cascade buck circuit and H-bridge inverter}$$

In the modulation signals of $T_1$ and $T_2$, the fundamental wave is the absolute value of the sine wave, and the triangular carrier differs by 180 degrees. The modulation signals of the two are shown in figure 3. The voltage waveforms output by the two buck circuits are similar but the harmonics are complementary. The positive sinusoidal half-wave DC voltage harmonics output by the cascade superposition can be greatly reduced. Sine wave AC voltage with greatly reduced harmonics can be obtained, as shown in figure 4.

$$\text{Figure 3. cascade buck circuit drive signal}$$
In order to make the output voltage waveform of the inverter close to the sine wave, when the modulation wave of the two buck circuits is set, the peak value of the given fundamental wave is half of the sine wave, and the fundamental waveform is the absolute value of the sine wave. The two buck circuits give the fixed triangle carrier differs by 180 degrees, and the conduction commutation time of the H-bridge inverter is set. The working mode of the H-bridge inverter is shown in Table 1.

| Working interval | Modal | T3 | T4 | T5 | T6 |
|------------------|-------|----|----|----|----|
| t0~t1, t2~t3, t4~t5 | I     | 1  | 0  | 0  | 1  |
| t1~t2, t3~t4, t5~t6 | II    | 0  | 1  | 1  | 0  |

3.2. Matching circuit and transducer

The equivalent circuit of the transducer is shown in Figure 5(b), where $C_0$ is the static capacitance of the transducer, $L_d$ is the dynamic inductance of the sensor, $C_d$ is the dynamic capacitance of the transducer, and $R_d$ is the dynamic resistance of the transducer. When series resonance occurs, the circuit can be equivalent to Figure 5(c).

Due to the presence of static capacitance, if ultrasonic power is directly fed into the transducer, a large amount of reactive power will be generated, so a matching network must be added to offset the static inductance to reduce damage to the transducer. Single series inductors can also add smaller capacitors to form LC filtering, the filtering effect will be significantly improved.

**Figure 4.** Schematic diagram of output waveform

**Figure 5.** (a) Transducer circuit, (b) Transducer equivalent circuit and (c) Simplified circuit when mechanical resonance occurs
Figure 6. (a) Simplified circuit when matching network and transducer circuit and (b) Matching circuit and transducer mechanical resonance

Considering comprehensively the influence of the equivalent impedance of the transducer and the electromechanical coupling coefficient on the matching circuit, when the ultrasonic power supply designed in this paper uses series inductance matching, when the transducer is in resonance, the $L_d$, $C_d$, and $R_d$ branches are equivalent. It is pure resistance, as shown in figure 5(c).

When the transducer is in series resonance, according to the definition of resonance:

$$f = \frac{1}{2\pi\sqrt{L_dC_o}}$$  \hspace{1cm} (1)

The total impedance of the transducer and inductor at this time is:

$$Z = \frac{R_d}{1+\left(\omega R_d C_o\right)^2} + j \left(\omega L_s - \frac{\omega R_d^2 C_o}{1+\left(\omega R_d C_o\right)^2}\right)$$ \hspace{1cm} (2)

Let reactance $X=0$, then match the inductance

$$L_s = \frac{R_d^2 C_o}{1+\left(\omega R_d C_o\right)^2}$$ \hspace{1cm} (3)

The equivalent circuit when mechanical resonance occurs is shown in figure 6(b). The matching inductance can be calculated by formula (3). Considering the filtering process, $C_m$ is added, and $C_m$ can be equivalent to $C_o$ through the parallel operation of the capacitor with the static capacitance $C_d$. At resonance, the resonant circuit can be equivalent to the resistance $R_d$.

Bring the equivalent parameters of the transducer into its equivalent impedance formula, and the calculation can be concluded that the resonance circuit can be equivalent to a resistance in the series resonance state, and the equivalent impedance formula is as formula (4).

$$R = \frac{R_d}{1+\left(\omega R_d C_o\right)^2}$$ \hspace{1cm} (4)

4. Control strategy

The ultrasonic power supply control framework based on cascading buck technology is shown in figure 7. The power system determines the direction of frequency change through the phase relationship of the capacitor voltage fed back by the matching circuit. The matching circuit is composed of a matching inductance, a parallel capacitor and a series capacitor of the same size, and respectively collects the voltage $U_1$ of the parallel capacitor in the matching circuit, the voltage $U_2$ of the series capacitor, and the voltage $U_3$ of the series-parallel capacitor.
The frequency automatic tracking technology proposed in this paper follows the following principles: If the frequency is not offset, the whole transducer is resistive, and the phase vectors of $U_1$, $U_2$, and $U_3$ are at right angles, as shown in figure 8 (a); If the frequency shifts, if the frequency is greater than the standard frequency value, the whole transducer is inductive, and the frequency should be reduced. The phase vector is shown in figure 8 (b); If the frequency shifts, if the frequency is greater than the standard frequency value, the entire transducer is capacitive, and the frequency should be increased. The phase vector is shown in figure 8 (c).

By comparing the deviation value derived from the voltage phase and combined with PI control, a new driver frequency is obtained to enable the ultrasonic power supply to operate at a transducer series resonance frequency of 40.04 kHz.

**Figure 7. Control block diagram**

**Figure 8. Schematic diagram of capacitor voltage vector analysis**

### 5. Simulation analysis

In order to prove the effectiveness of the cascade buck technology in the ultrasonic power supply, an ultrasonic power supply model based on the cascade buck technology was established in MATLAB 2018b / Simulink. The transducer parameters are: $C_d=1.84\, \text{pF}$, $L_d=8.39\, \text{mH}$, $f_s=40.04\, \text{kHz}$, $R_d=15\, \Omega$, $C_0=5100\, \text{pF}$. The matching network parameters are: $L_s=0.0112\, \text{mH}$, $C_m=36\, \text{nF}$.

In order to test the effectiveness of the cascade buck technology, the simulation simultaneously monitors the output voltage waveforms of the buck circuit 1, the buck circuit 2, and the cascade buck circuit. Figure 9 from top to bottom are the output voltage of the buck circuit 1, the output voltage of the buck circuit 2, the output voltage of the cascade buck circuit, and the output voltage after being commutated by the H-bridge. From Figure 10, the output voltage waveform of the H-bridge inverter after cascading buck technology is stable, the total harmonic distortion (THD) is 6.88%, and the square wave waveform output by the THD traditional ultrasonic power supply is about 48.3%, which Compared with the waveform, the harmonic distortion rate is greatly reduced, and the matching network inductance value and capacitance value are greatly reduced, so that the power density of the entire ultrasonic device is greatly improved.
In order to test the effectiveness of the automatic frequency tracking technology, the simulation simulates the frequency failure of the ultrasonic power supply and starts to run at 39.7kHz. A transition of the transducer dynamic capacitance value is set 0.12s after its normal operation. The simulation results are shown in figure 11 (As shown in a), the frequency tracking curve shows that the frequency curve quickly and accurately tracks its normal operating frequency, where the error is less than 5 Hz. For easy observation, the current in figure 11(b) is expanded by 5 times, as can be seen, The current and voltage are in phase, indicating that the algorithm has good frequency tracking performance.
6. Conclusion

(1) The ultrasonic power supply based on the cascading buck technology proposed in this paper has low voltage output harmonics and high equivalent switching frequency, which can greatly reduce the inductance of the parallel filter capacitor and the matching network reactor at both ends of the transducer. Effectively increase the power density of the ultrasonic power supply, greatly reduce the resonance voltage between the reactance of the matching network and the static capacitance of the transducer, and effectively improve the stability and reliability of the ultrasonic power supply system;

(2) The frequency automatic tracking technology through the combination of voltage phase detection and PI control has higher tracking efficiency than the traditional phase-locked loop technology.

(3) The principle of the cascade buck converter and the circuit model of the transducer and matching network are analyzed, the frequency automatic tracking technology combining PI control and voltage phase detection is explained, and the feasibility of this scheme is confirmed by simulation.

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