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Intelligent Ultrasonic Power Supply Based on HPWM

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Authors' contributions

This work was carried out in collaboration between all authors. Author QUB proposed the overall design scheme. Author LH designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript and managed literature searches. Author WT revised the article and made some supplement. Authors QUB, LH, WT managed the analyses of the study and literature searches. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

Aims: The design of the ultrasonic power supply based on HPWM was researched and developed to reduce the switching loss of high frequency switch and its harmonic distortion in this paper, which the performance of whole system is highly improved.
Study Design: An improved control scheme named hybrid pulse width modulation (HPWM) is proposed, in which TMS320F2812 is used as the main control chip, the HPWM control signal is generated by using a voltage and current double closed-loop PI controlling method.
Place and Duration of Study: Jiang Nan University, Key Laboratory of Advanced Process Control for Light Industry, in Wuxi, Jiang Su Province between June 2012 and July 2013.
Methodology: Two set of experiment about our research including hybrid pulse width modulation (HPWM) and traditional sinusoidal pulse width modulation (SPWM) are carried out. Device parameters of all parts were calculated precisely and the device numbers were chosen after several experiments. A ultrasonic power supply System based on HPWM was designed finally.
Results: According to the theoretical analysis, a 3KW Ultrasonic power supply is developed and the resonant frequency is 25KHz, using the hybrid PWM and double

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closed-loop control strategy proposed in this article. The power is tested successfully. The power experiment shows the system works well and gets high stability.
Conclusion: The experiment result shows that the system works well and the switching loss of high frequency MOSFET and its harmonic distortion are effectively reduced. The design of the ultrasonic power supply based on HPWM has high value of application.

Keywords: Ultrasonic; Inverter power supply; Hybrid pulse width modulation; double closed-loop control; DSP.

1. INTRODUCTION

With the development of ultrasonic technology, ultrasonic power supply is widely used in ultrasound biological treatment [1]. The process of ultrasound spread in liquid medium, a series of effects, which is mechanical, thermal, optical, electrical and chemical are produced by mechanical action, and heat effect. For biomass extraction, it not only can cause the destruction of the plant cell wall and the rapid penetration of the solvent, but also make the extracted effective component dissolve to the solvent quickly, thus improving the extraction rate, shortening the extraction time and saving solvent. Especially for high power ultrasonic, it can produce strong cavitations, and thus formed in the local instantaneous high temperature, high pressure, vacuum and micro jet. With the constantly appearance of the new power electronic devices, the development towards the direction of high-power and high-frequency ultrasonic power supply could be improved. However, because of the influence of the switching frequency of these devices, the development of high-power and high-frequency ultrasonic power supply is limited. For example, traditional control methods, like SPWM (Sinusoidal Pulse Width Modulation)control, it makes the problems of the switch be significant particularly [2], which have large switching losses and short service life, further impact on the development of high-frequency power supply.

However, with the continuous development of digitization, especially the microprocessor, it makes more advanced control strategy and the new intelligent ultrasonic power supply possible. Therefore, HPWM is applied in this article, and TMS320F2812 of TI Company is used as the main control chip, the ultrasonic power supply with high performance was studied. The innovation point is the application of advanced digital control chip combining with HPWM control technology, which can reduce the switching losses of high frequency MOSFET and harmonic distortion degree as far as possible, thus to improve the performance of the inverter power supply system.

2. POWER SUPPLY SYSTEM STRUCTURE

The overall design diagram of high-power ultrasonic power is shown in Fig. 1. The output frequency of the ultrasonic power supply is required to 25 kHz; the power is 3 kW. The ultrasonic power supply system includes main control unit of TMS320F2812, sampling circuit of voltage and current, main circuit of inverter, filter, the protection circuit of driver, etc. In terms of inverter main circuit, the invert converts the DC into high-frequency AC by a pair of reverse rectangular pulse with dead zone time which is provided by control circuit, which is consisted by the DSP. At last it can be tuned and filtered by matching network with high-frequency AC approximate to the sine wave and incentive ultrasonic system need.

The output voltage and current are sampled by sampling control circuit, and thus converts them into the reasonable amplitude range of the A/D converters by the modulation circuit, and set the protection circuit. If the system over-load or over-current, the protection signal is produced to shut down the drive output of the four-way switch.

Digital control part is mainly responsible for the operational processing chain. The proper algorithm is used to realize double closed-loop control strategy, and the HPWM is produced to control the on-off of the switch of the inverter bridge, then the closed-loop control of the inverter is realized, which makes the output to meet the performance requirements for the system [3].

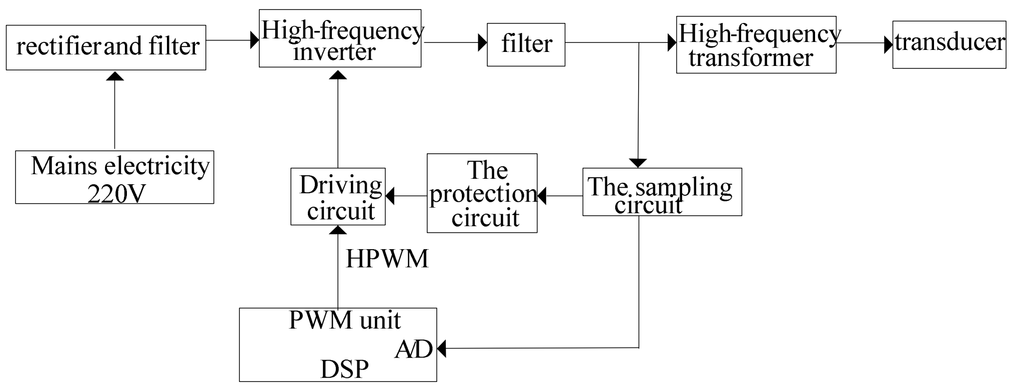


Fig. 1. The overall design diagram of high-power ultrasonic power supply

3. INVERTER MAIN CIRCUIT AND HPWM

3.1 The Structure of ZVS Full Bridge Inverter Main Circuit and THD Analysis

Due to the adoption of advanced PWM control strategy, the inverter operates under the condition of high-frequency. Therefore, switching frequency of MOSFET is the carrier frequency(c). If it takes the carrier ratio for 24, the switching frequency of the switch is 600 kHz, so MOSFET is chosen as the device.

THD [7] is called total harmonic distortion factor. It can be calculated by the equation:

$$THD = \frac{1}{V1}\sqrt{\sum_{n=2}^{\infty}(Vn)^2} \quad (1)$$

But due to the condition of high-frequency, the switching loss of MOSFET is great and the device is easy to damage, so the increase of the power is limited. Moreover, depending on the material properties of the switch, MOSFET is very difficult to achieve high-power output under the condition of high-frequency. So paralleling MOSFET can be used to improve the power, but the switch loss must be reduced as far as possible at the same time, and thus high-frequency inverter is realized.

Therefore, the soft switch technology is applied to the inverter main circuit, which uses topology structure of single-phase full bridge. The control method applies with improved hybrid PWM (HPWM). The whole bridge structure of the zero voltage soft switching (ZVS) technology [4] is shown in Fig. 2. In this circuit, inductor and capacitor are used to shape switching track of the MOSFET for reducing switch loss and improving the switching frequency. Zero voltage on-off (ZVS) of the switch is realized by resonant of the inductor and capacitor of the circuit, and the stress of du/dt and di/dt decreases, combining with the control way of HPWM, which is applied by inverter main circuit, makes the loss of the MOSFET reduce further. At last the high-frequency and high-power inverter can be realized.

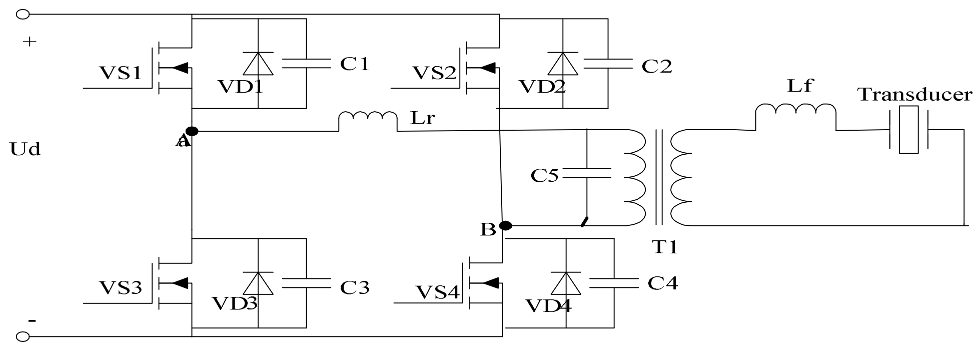
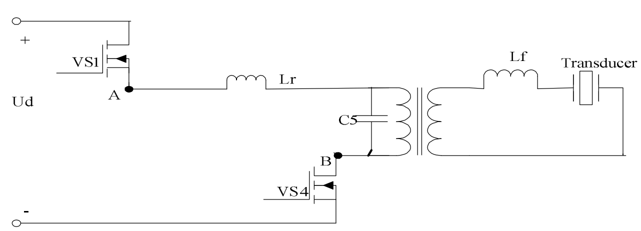


Fig. 2. Topology structure of single-phase full bridge

The operation of this circuit can be briefly described as follows with six operation modes:

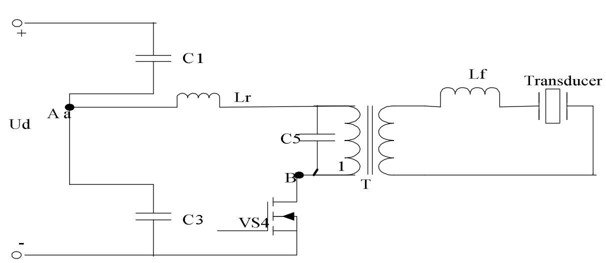
1) Mode 1 [t0, t1]

VS1 and VS4 are conducting during this period, so
uAB=Ud.



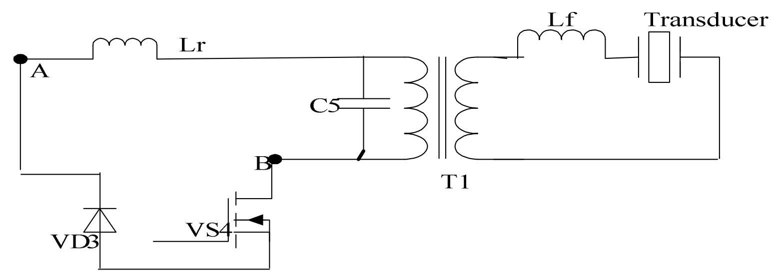
2) Mode 2 [t1, t2]

The input capacitance C1 is initially charged, VS1 turns off and VS4 turns on at t1. C1、C3、Lr resonance,So VS1 turns off at zero voltage.



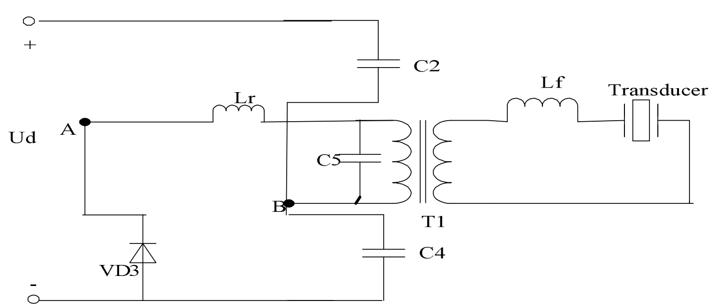
3) Mode 3 [t2, t3]

The voltage of the input capacitance C3 reduced to zero at t2, VD3 is conducting. So VS3 turns on at zero voltage.



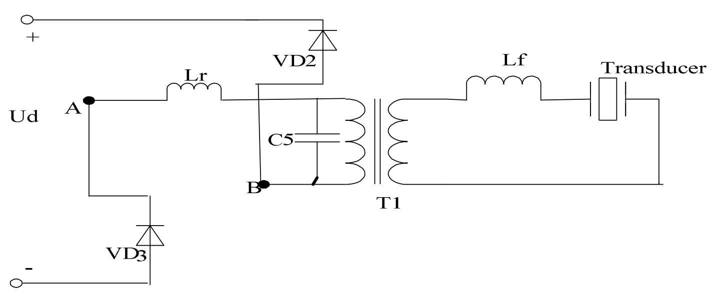
4) Mode 4 [t3, t4]

VS4 turns off at t3. The capacitance C4 is initially charged, while the capacitance C2 is initially discharged. So VS4 turns off at zero voltage.



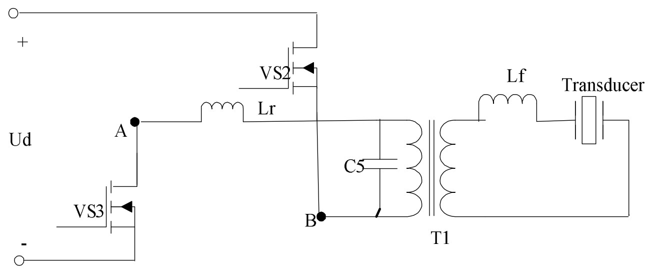
5) Mode 5 [t4, t5]

The voltage of the input capacitance C3 reduced to zero at t4, VD2 is conducting. So VS2 turns on at zero voltage.



6) Mode 6 [t5, t6]

So VS2 and VS3 are conducting at t5,so
uAB=-Ud.



3.2 HPWM Control Technology

Hybrid pulse width modulation is applied to inverter main circuit (HPWM), In terms of its character, HPWM still belongs to the single polarity modulation mode. But the difference is that the two bridge arm alternate to work in low-frequency and high-frequency condition under the HPWM method, which makes these two bridge arm operate symmetrically. So it is called hybrid PWM (HPWM).MOSFET works in the condition of balance, which reduces the switching loss. In addition, it will not only prolong the service life of MOSFET, but also improve the reliability of the whole circuit. It also has the characteristics of high voltage utilization ratio, small harmonic content, low switching loss.

The working process of the HPWM [5]: The four switches are operated alternately at two different frequencies in a cycle, two being commutated at low frequency, the fundamental frequency of the output, while the other two switches are pulse-width-modulated at a high frequency in a half cycle. The modulation and gate signals are illustrated in Fig. 3 respectively. Switching poles T1/T3 are commutated at low frequency while T2/T4 are commutated at high frequency, and vice versa counter. Switching arrangement reduces switching loss.

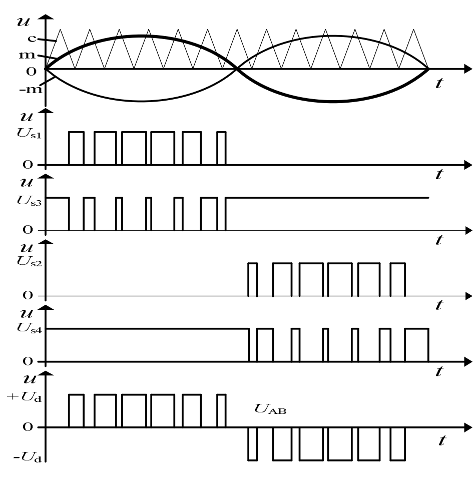


Fig. 3. The waveform of HPWM

Because of adopting HPWM technology, its amplitude and pulse width of the pulse signal is proportional to the modulation sine wave. The high-frequency carrier signal of the pulse signal(c) is filtered by the low-pass filter, and can obtain the sine wave output with the frequency of the modulated wave (m、-m). So it can be easy to realize the adjustable of frequency and amplitude of sine wave output as long as the input of modulation wave is changed.

4. THE DESIGN OF HARDWARE CIRCUIT

4.1 The Analysis of the Sampling Circuit

\In order to realize closed loop control of inverter power supply, it must sample the output voltage of the inverter power supply and the output current through the filter. The sampling signal must be processed by the sampling circuit, making them conform to the requirements of the input of the digital control part.

The device of sampling voltage signal chooses the voltage transformer of KV20A/P, its measurement voltage range can be within 500v. The magnetic balanced current transformer, KT20A/P, is chosen as the device of the sampling current signal. The output current is proportional to the measured current.

TMS320F2812 is used as the main control chip of the system, but internal integration A/D converter of the processor allows the input voltage range of 0～3V, so it need to design appropriate modulation circuit to meet the requirements of A/D input.

4.2 The Analysis of the Drive Protection Circuit

As the switching frequency of the MOSFET can reach about 600 kHz, LM5111 is chosen as the switch tube, which is produced by TI Company. Its two-way drive are Independent, and strong drive ability. In addition, it not only has maximum peak current of 5A, but also can be connected in parallel, and the peak value of output drive current increases to 10A, so that it can drive the power MOSFET with great efficiency and speed of up to 1 MHz. The working frequency of LM5111 is up to 1 MHz, which can meet the design requirements of the inverter power supply completely.

The protection circuit of the inverter power supply is mainly composed of input over-voltage protection and output over-current protection. Their basic principle is that the sampling quantity by the corresponding signal sampling circuit, after the amplitude attenuation, and then compare with the setting threshold value. If it is more than the threshold voltage, the protection happens. If the overload or over current situation happens, the protection signal is produced to shut down driver output of the four way MOSFET.

5. SOFTWARE DESIGN OF INVERTER POWER SUPPLY

5.1 Digital PI Control Principle of the Inverter Power Supply

According to the deviation of proportional (P) and integral (I) to control (PI control), is one of the most widely control law, which is used in control system. The proportional can correct deviation and accelerate the speed of the response while the integral can eliminate the static error and improve the dynamic characteristics. Simultaneously, PID control with simple parameters and easy setting is used widely in engineering applications. Considering two aspects of cost and performance, PI control is adopted as the control strategy of inverter system by this paper. The instantaneous value of the current flowing through the output filter capacitor was introduced into the feedback, combining with the output voltage to form double closed-loop control. Considering that the output of position type PI regulator is related to past state, it will accumulate the errors during the process of calculation, which is hard to realize by digital controller. So an incremental PI controller is used in the regulator.

Digital PI control strategy diagram is shown in Fig. 4. Outer ring is closed-loop control, which output voltage instantaneous value uof compares with the reference voltage uref of the sinusoidal table that produced by the digital controller program, voltage controller adopted the proportion integral (PI) control so as to track the given value. Inner ring is also closed-loop control, which the output current ig of the inductor compared with the output ig of the voltage regulator, current controller adopted the proportional (PI) control, so as to increase the damping coefficient of the Inverter, improve the system's stability and guarantee the robustness of system. Regulator of outer ring can adjust the given value of the inner ring regulator according to the change of load. The full bridge inverter circuit driven by the double closed loop control strategy for HPWM signal has the characteristic of fast dynamic response and small static error.

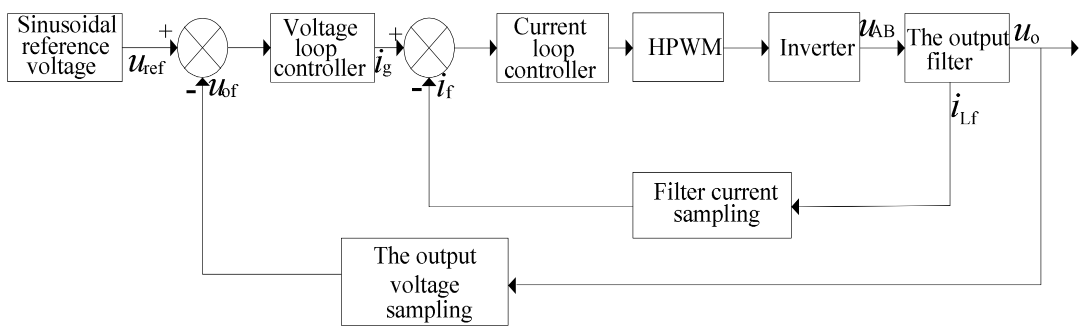


Fig. 4. Digital PI control strategy diagram

5.2 The Generation of HPWM

TMS320F2812, which is produced by TI. Company, provides powerful computing capacity. Its highest running speed can reach 150 MIPS. Take advantage of PWM modules of EV (event management module) in this chip, 6 PWM outputs with programmable dead zone are easily generated. The frequency of the carrier (switching frequency) is determined by timing cycle and counting mode of the timer. Set the timer T1 work as the continuous increase or decrease count mode, can produce symmetrical PWM waveform.

As shown in Fig. 5, the symmetrical regular sampling method, which uses triangle wave as a carrier, is adopted to this system [6]. The calculation method is: through the point of intersection between the symmetry axis of the triangular waveform and sinusoidal waveform, a parallel can be drawn to parallel to time-axis. The point of intersection of the parallel and two waists in the triangular wave are used as "On" and "Off" time of SPWM wave. The symmetrical regular sampling method makes each pulse be center-symmetric with the triangle carrier wave axis.

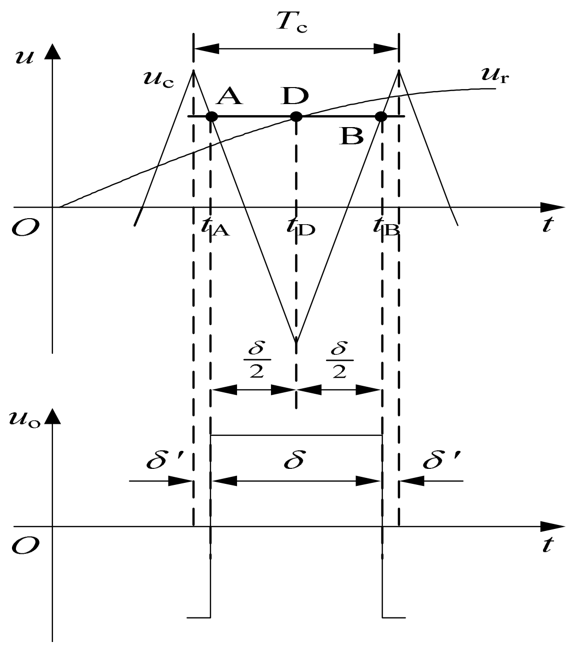


Fig. 5. The Symmetrical regular sampling method

Therefore, a sine wave modulation signal:

$$u_r = a \sin w_r t \tag{2}$$

Where, a is modulation, a =0~1, w_r is Angular frequency sinusoidal signal wave. If it have N rectangular waves in one cycle, and the following formulas, which is expressed as the duty ratio of a square wave can be obtained:

$$D = M \sin(i \times 2\Pi / N) \tag{3}$$

Where, M is the modulation ratio. In order to facilitate the implementation of the program, type (2) can be turned into

$$D = M \sin(w_r i T_c) \tag{4}$$

That is to say, the frequency of the modulation wave and the sampling period (carrier frequency) need only to be determined, so the duty cycle "D" can be determined.

Sinusoidal reference signal are made sine table, which is consisted by a series of discrete points instead of a sine value. It can be easily obtained by the look-up table. In this system, switching frequency fK is 600 kHz, the output of the required sine wave f0 is 25 kHz, So the discrete points of the DSC internal storage, N=600 kHz /25 kHz =24 and then 24 corresponding discrete values are calculated by MATLAB. 24 corresponding discrete values are calculated by MATLAB, and then made a table as the reference voltage signal, which is used to value of look-up table procedures. In the system real-time control, each carrier cycle need to change the duty ratio, which can use the overflow interrupt of the timer to update the value of the compare register CMPRx, that is after overflow interrupt, according to the look-up table pointer, the corresponding sine values are read out by the interrupt service program, and then compared with the corresponding A/D sampling value, which can realize the PI control through the voltage controller. Then P regulation of current loop are realized, and after logic processing, which assigned the computation results to compare register CMP Rx, then resulting in a HPWM signal, and look-up table pointer plus one simultaneously, at the end of the cycle of a sine wave, the look-up table pointer is reset to the first address of the reference sine wave table.

Due to hybrid pulse width modulation (HPWM), the power MOSFET is required to alternate on and off in the low-frequency and high-frequency. In order to realize the mechanism, the upper and lower limits are required on the zero-symmetric in PI regulator limiter. That is to say, the upper limit is set for value of the period Register, the lower limit is set for the corresponding negative. And then PI output compared with zero, the implementation process shown in Fig. 6. According to the following assignment, HPWM output can be realized.

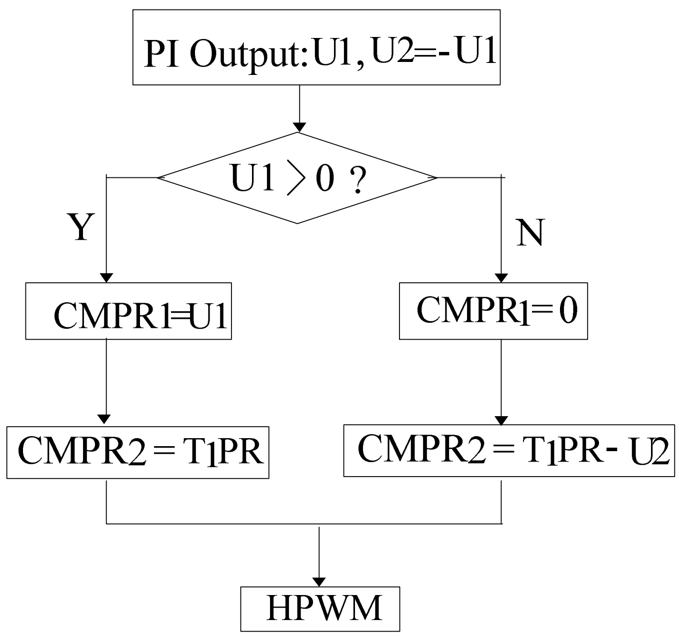


Fig. 6. The process of HPWM output

6. THE EXPERIMENTAL RESULTS

According to the theoretical analysis, a 3KW Ultrasonic power supply is developed and the resonant frequency is 25KHz. Using the hybrid PWM and double closed-loop control strategy proposed in this article. The power is tested. The power experiment shows the system works well and gets high stability, which the waveform of Inverter power supply output voltage (after low-pass filtering) and harmonic analysis, as shown in Fig. 7.

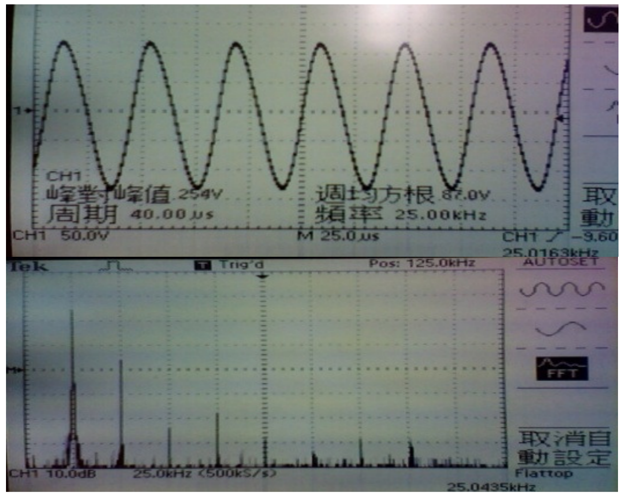


Fig. 7. The waveform of Inverter power supply output voltage and harmonic analysis

7. CONCLUSION

Intelligent high-power ultrasonic power inverter system using HPWM control can realize the frequency regulation of the inverter power, and improving the power factor of the system, reducing the switching losses of the power MOSFET and harmonic distortion of the output waveform, while higher harmonic is suppressed, the loss of the transducer is reduced. The experiments show that the intelligent high-power ultrasonic power inverter system in this method, which TMS320F2812 is used as the main control chip, and ZVS full bridge inverter main circuit is adopted, has a good performance, which provides a good power supply to research and development of the ultrasonic system.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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