

Research on Switching Power Amplifier of Magnetic Bearing

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Abstract

The working principle of the half-bridge switching power amplifier used in the magnetic bearing is introduced, and the three-level switching power amplifier is improved from the following aspects: A three-level modulation strategy without phase shifting and external logic circuits. A DC isolated power supply for isolating drive modules is developed, and soft switching technology is applied to switching power amplifiers. The static performance of the switching power amplifier was tested, and the magnetic bearing test platform was built, and the static suspension test of the rotor was carried out. The test results show that the improved magnetic bearing power amplifier has stable performance, low current ripple and practical performance.

Keywords

Power Amplifier; Magnetic Bearing; Soft Switch; Isolated Drive.

1. Introduction

Magnetic bearing is a mechatronic product that uses electromagnetic force to suspend the rotor in the air. It has the advantages of no mechanical wear, high precision, long service life and no pollution. It has broad application prospects in high-speed motors, flywheel energy storage, aerospace and other fields [1,2]. The magnetic bearing system includes the rotor, electromagnetic coil, power amplifier, controller and displacement sensor. The power amplifier is the executive part of the magnetic bearing, and its performance will directly affect the control effect of the entire system.

At present, the switching power amplifier in the magnetic bearing system generally uses the pulse width modulation (PWM) technology [3]. According to different pulse width modulation strategies, it can be divided into two-level switching power amplifiers and three-level switching power amplifiers. Compared with two-level power amplifiers, three-level power amplifiers have smaller current ripple and the ripple does not vary with the bus voltage [4]. Traditional three-level pulse width modulation requires phase shifting of PWM or adding external logic circuits, and the circuit structure is complicated [5]. This paper proposes a three-level modulation strategy based on a half-bridge switching power amplifier without phase shift processing. Select TMS320F28335 DSP to generate PWM waveform. It has high precision and reliable performance.

In the working process of the switching power amplifier, the voltage and current are not 0 when the switching component is turned on and off. The voltage and current overlap to produce switching loss and high noise. In order to improve the efficiency of the power amplifier, the soft switching technology is applied to the power amplifier, which improves the efficiency of the power amplifier and reduces the switching noise and current spikes.

2. Three-level switching power amplifier modulation strategy

According to the topological structure of the main circuit, three-level switching power amplifiers can be divided into full-bridge and half-bridge. The electromagnetic coil current in

the magnetic bearing is unipolar. Considering the cost and control method, a half-bridge switching power amplifier is selected.

The traditional three-level modulation strategy uses two PWMs with the same frequency to drive Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) separately, which requires the addition of logic circuits and phase shifting of PWM [5]. This paper uses two PWM waves with different frequencies to achieve three-level modulation. The frequency of the Q_2 drive waveform is much higher than that of Q_1 . This method does not require phase shift processing and is simple to modulate.

The modulation principle of the three-level switching power amplifier is shown in Figure 1, and the coil current of the half-bridge main circuit in the four switching states is shown in Figure 2. Q_1 and Q_2 are MOSFETs, D_1 and D_2 are schottky diodes, R and L represent the equivalent resistance and inductance of the electromagnetic coil, and U_d is the DC bus voltage.

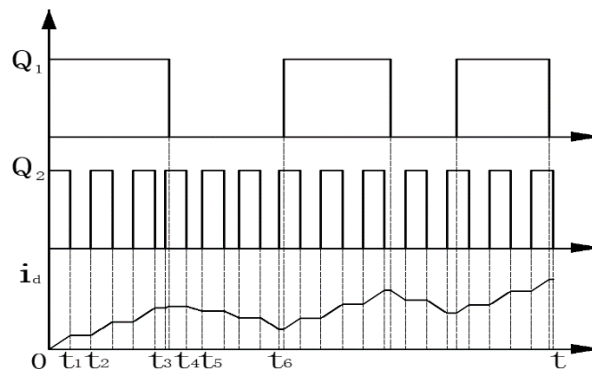


Fig. 1 Modulation principle of the three-level switching power amplifier

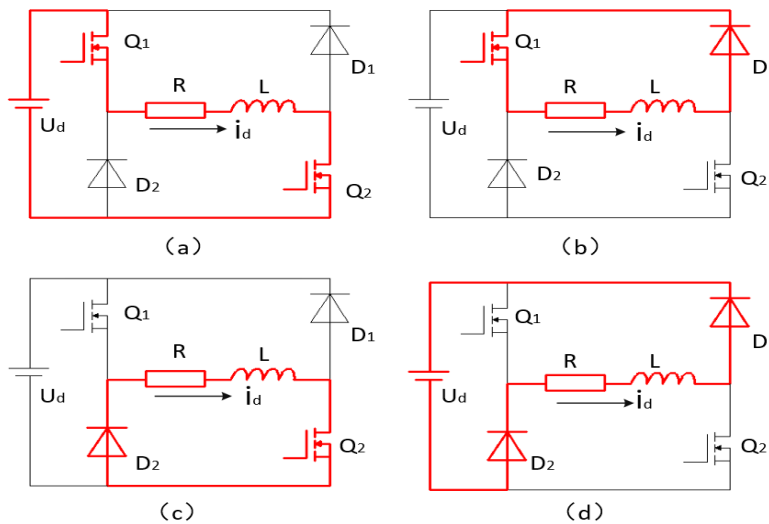


Fig. 2 Coil current in four switching states

When $t \in [0, t_1]$, Q_1 is turned on, Q_2 is turned on, the DC bus voltage U_d is applied to the electromagnetic coil through Q_1 and Q_2 . The current rises rapidly, the power amplifier works in the charging state, and the current loop corresponds to Figure 2 (a).

When $t \in [t_1, t_2]$, Q_1 is turned on, Q_2 is turned off, the coil current forms a follow-current loop through Q_1 and D_1 , and the current decreases slowly. In the follow-current state, it can be considered that the coil terminal voltage is 0, and the current loop corresponds to Figure 2(b).

In the period of $0 \sim t_3$, the power amplifier continuously switches under the two working states of charging and follow-current, and the coil current continues to rise.

When $t \in [t_3, t_4]$, Q_1 is turned off, Q_2 is turned on, and the coil current forms a follow-current loop through Q_2 and D_2 . The current loop corresponds to Figure 2(c).

When $t \in [t_4, t_5]$, Q_1 is turned off, Q_2 is turned off. Ignoring the voltage drop of transistor, the terminal voltage of the electromagnetic coil is $-U_d$. The coil discharges, and the current decreases rapidly. The current loop corresponds to Figure 2(d).

During the period of $t_3 \sim t_6$, the power amplifier continuously switches under the two working states of discharge and follow-current, and the coil current continues to drop.

3. Circuit design

3.1. Isolated drive module

The PWM signal output by the DSP is a weak current signal, which is not enough to directly drive the MOSFET. The main circuit of the power amplifier bears relatively high voltage and current, which is likely to cause interference to the weak current signal. Therefore, an isolated drive circuit needs to be added between the DSP and the main circuit of the power amplifier.

Connecting the photoelectric isolator to the output of the DSP can effectively avoid the interference of strong current. This paper selects 6N137 as the opto-isolator. When the input signal voltage is greater than 1.7V and the current is greater than 6.5mA, 6N137 starts to work. DSP meets this requirement and can directly drive the opto-isolator.

The topological structure of the isolated drive module is shown in Figure 3. The model of the MOSFET to be driven is IRF540N. The lowest gate-source voltage (V_{gs}) for the MOSFET to turn on is only 4V, and the output voltage of the 6N137 can reach 5V. In theory, the 6N137 can directly drive the MOSFET. In the actual test, it is found that when V_{gs} is 5V, the MOSFET is in an incomplete conduction state, the turn-on and turn-off process is slow, and the heat is severe. To solve this problem, a triode amplifier circuit is added to improve the driving capability. The triode amplifier circuit adopts a two-stage amplifying structure. The first-stage amplifier is a common-emitter amplifying circuit built by T_1 , which can amplify both voltage and current. After the first-stage amplification, the test found that the driving voltage has reached the requirements but the driving current is still insufficient, so a push-pull amplifier circuit is added as the second-stage amplification. The push-pull amplifier circuit is composed of one NPN transistor T_2 and one PNP transistor T_3 with the same parameters. It has strong current sourcing and sinking capabilities, small output impedance, strong driving capability, and can meet the driving requirements.

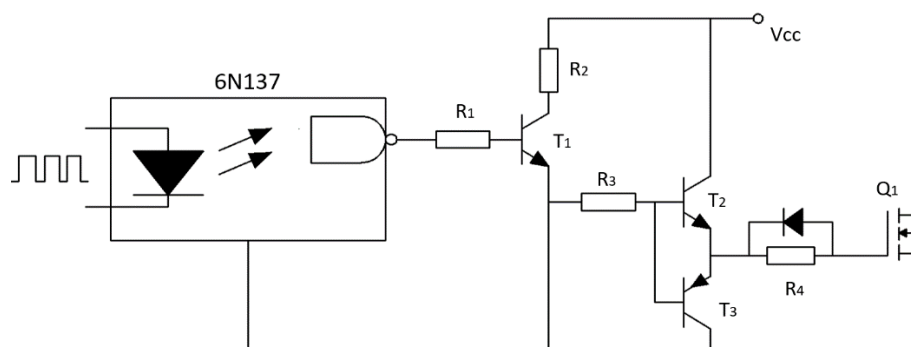


Fig. 3 Topological structure of the isolated drive module

According to the principle of full-bridge DC/DC converter, this paper has designed a DC isolated power supply, its circuit schematic diagram is shown as in Figure 4. The DC isolation power supply adopts an electromagnetic isolation scheme, and a pulse-driven isolation transformer with a tap on the secondary side is selected as the isolation component. The transformer's ratio

is 1:1:1. The primary side of the transformer is driven by the dedicated chip VPS8701 for isolated power supply. The VPS701 integrates two N-channel power MOSFETs and two P-channel power MOSFETs, which are connected in a full-bridge structure. The secondary side of the transformer is connected to a full-wave rectifier circuit, and the two diodes are turned on alternately to provide a stable DC voltage to the load.

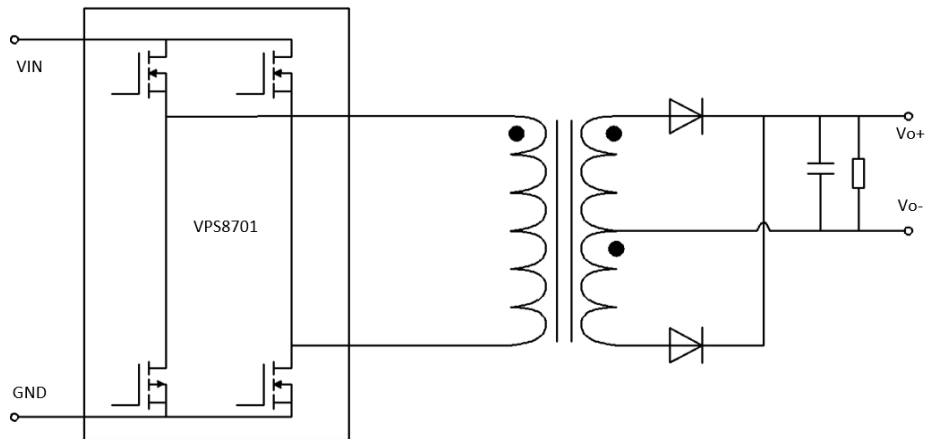


Fig. 4 DC isolated power supply circuit

Supply power to the isolation drive module, input the PWM signal, and use an oscilloscope to measure the gate-source voltage (V_{gs}) of the MOSFET. The input and output waveforms are shown in Figure 5. It can be seen from Figure 5 that the isolated drive module has good performance and can meet the drive requirements.

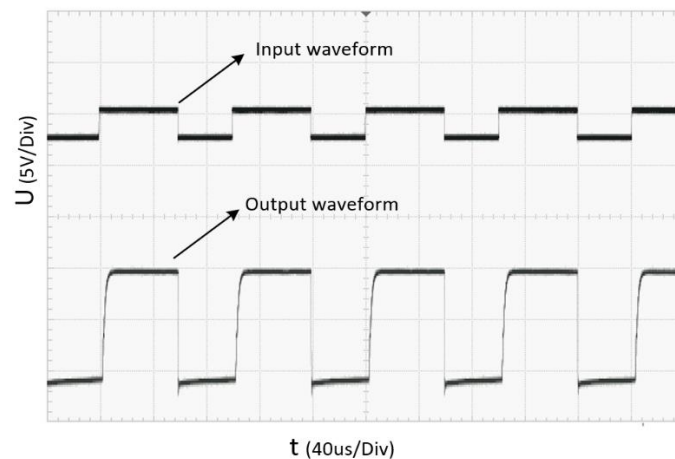


Fig. 5 Isolation drive module input and output waveforms

3.2. Application of soft switching technology

In the magnetic bearing, the switching component of the traditional switching power amplifier works in the hard-switching state. In the hard switching circuit, the switch can not be turned on and off instantaneously. The terminal voltage and current of the switch overlap, resulting in power loss. Excessive du/dt and di/dt and parasitic circuit oscillations during the switching process will cause serious electromagnetic interference, which will affect the efficiency of the circuit and the reliability of the device [6].

To solve this problem, this paper applies soft switching technology to the switching power amplifier. Soft switching technology can significantly improve the working conditions of the

switching components and improve the reliability of the MOSFET. The switch is turned on and off under the condition of zero voltage or zero current, so the switching loss is zero in theory. Based on the principle of the zero-transition PWM circuit, this paper designs a zero-voltage-transition (ZVT) PWM converter for the magnetic bearing power amplifier. The voltage of the switching component is 0 during the turn-on and turn-off process. The basic circuit and working mode of the soft-switching power amplifier are shown in Figure 6. Q_1 , Q_2 , M_1 , and M_2 are all MOSFETs, Q_1 and Q_2 are the main switching components, M_1 and M_2 are auxiliary switching components, L_1 and L_2 are resonant inductors, C_1 and C_2 are resonant capacitors, D_1 , D_2 , D_3 , and D_4 are follow-current diodes.

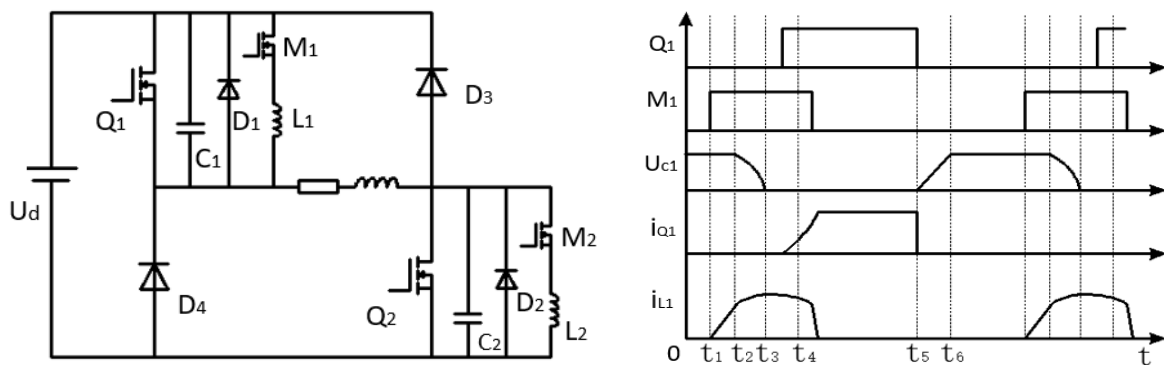


Fig. 6 Basic circuit and working mode of soft-switching power amplifier

Assuming that all diodes, capacitors, and inductors are ideal devices, the working conditions of each switch state are described as follows.

$t \in [0, t_1]$, the main switch Q_1 and the auxiliary switch M_1 are in the off state. Q_1 is turned off, then D_4 must be turned on. The voltage across Q_1 and its parallel branch is the power supply voltage.

$t \in [t_1, t_2]$, M_1 is turned on, the voltage across L_1 is the power supply voltage, the auxiliary inductor current i_{L1} rises linearly from 0. M_1 is connected in series with inductor L_1 , the inductor current cannot change suddenly, and its initial value is 0, so M_1 is zero current open.

$t \in [t_2, t_3]$, the auxiliary inductor current i_{L1} rises to a certain value, L_1 starts to resonate with C_1 , i_{L1} continues to rise, and the terminal voltage of C_1 starts to drop.

$t \in [t_3, t_4]$, the voltage of C_1 drops to 0, the resonance continues. The voltage starts to become negative, the diode D_1 turns on. L_1 and D_1 form a follow-current loop, which clamps the terminal voltage of C_1 at zero potential. Then Q_1 is turned on at zero voltage.

$t \in [t_4, t_5]$, turn off the auxiliary switch M_1 , and wait for the next turn-on of the main switch Q_1 .

$t \in [t_5, t_6]$, turn off the main switch Q_1 , since Q_1 is connected in parallel with C_1 , the terminal voltage is 0, and the capacitor voltage cannot change suddenly, so Q_1 is turned off at zero voltage.

At this point, the main switch Q_1 has completed a zero voltage turn-on and zero voltage turn-off, and waits for the next switching cycle. The turn-on and turn-off process of Q_2 is the same as that of Q_1 .

4. Experimental Results

In order to verify the performance of the magnetic bearing power amplifier designed in this paper, the static performance test of the power amplifier was carried out. Take a set of electromagnetic coils of the radial magnetic bearing as the load, the equivalent resistance of the electromagnetic coil is 1.2Ω , the equivalent inductance is 2.2mH , the DC bus voltage of the main

circuit of the power amplifier is 30V. The switching frequencies of the two power MOSFETs are 5kHz and 25kHz respectively and their duty ratio are both 65%. The electric current waveform of the electromagnetic coil is shown as in Figure 7.

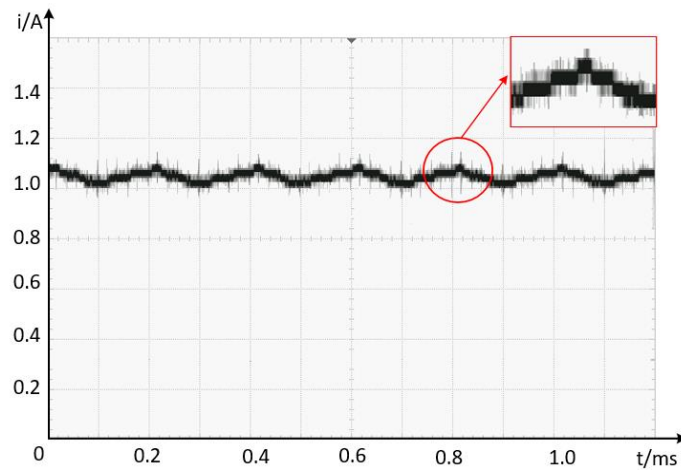


Fig. 7 Electromagnetic coil current waveform

It can be seen from Figure 7 that the output current of the power amplifier is stable around 1.05A, the current ripple is about 50mA, the static performance is stable, and the current spike is small.

In order to further verify the dynamic performance of the magnetic bearing power amplifier, a DSP-based magnetic bearing test platform was built, as shown in Figure 8. The position information of the rotor is collected by the displacement sensor, and the proximator converts the position information into a voltage signal, then inputs the voltage signal into the DSP. The DSP is the controller of the magnetic bearing. It adopts the PID control algorithm to calculate the frequency and duty of the PWM signal. The power amplifier receives the signal of the DSP, changes the current of the electromagnetic coil, and realizes the stable suspension of the rotor.

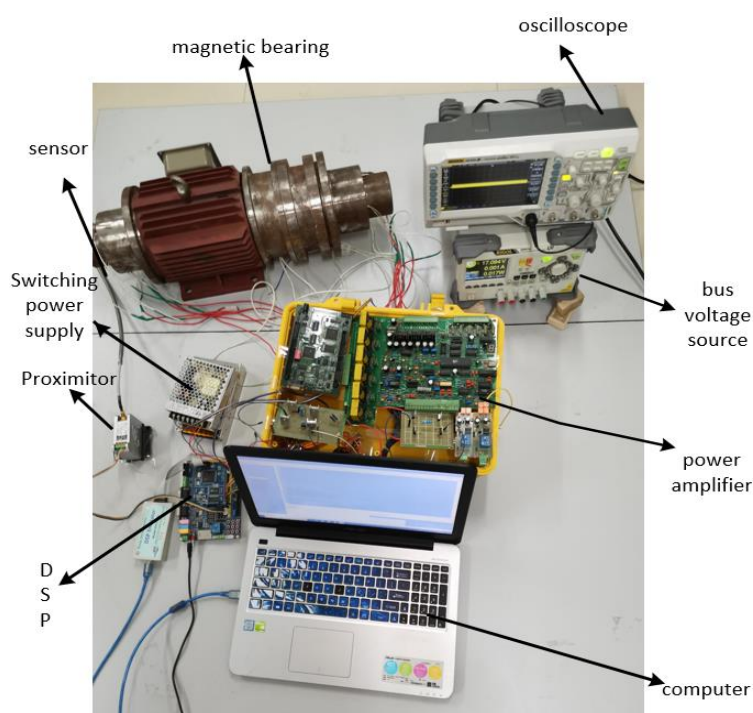


Fig. 8 Magnetic bearing test platform

The static suspension test is carried out on the motor rotor, and the voltage signal of the displacement sensor on the single degree of freedom of the rotor is shown in Figure 9.

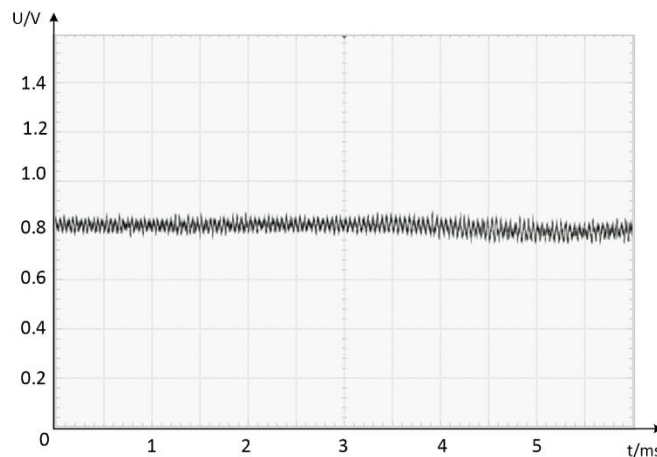


Fig. 9 Voltage signal of displacement sensor on single degree of freedom

It can be seen from Figure 9 that the magnetic bearing power amplifier designed in this paper can realize the static and stable suspension. It has practical performance.

5. Conclusion

Based on the half-bridge switching power amplifier, this paper improves the traditional three-level switching power amplifier and changes the PWM phase-shift modulation strategy. According to the principle of the full-bridge DC/DC converter, designed a DC isolated power supply for the isolation drive module. In order to reduce switching loss and current interference, soft switching technology is applied to switching power amplifiers. The test results show that the control of the improved switch power amplifier is simple, the performance is stable, and it meets the practical requirements of magnetic bearing.

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