

# A Strategy for Duty Cycle Limitation of PWM Magnetic Bearing Power Amplifier

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## Abstract

Multi-phase bridge power amplifiers can meet the multi-degree-of-freedom control requirements of magnetic levitation systems, but the problem of large current ripple restricts the improvement of control accuracy. Therefore, a four-phase bridge converter for active magnetic suspension bearings is proposed, and a reverse shared winding driving path is constructed. At the same time, opposite carrier modulation technology is adopted, making the converter operate in continuous conduction mode for most of the time during normal operation, effectively reducing current ripple. To verify the effectiveness of the scheme, simulation and experimental platforms are built. The results show that this four-phase bridge converter has the advantages of small current ripple and fewer power devices.

## Keywords

**Magnetic Bearing; Power Amplifier; Four-phase Bridge Arm; Current Control.**

## 1. Introduction

Magnetic levitation bearings, as core supporting components in the field of high-speed rotating machinery, have become key enabling elements for high-end equipment such as flywheel energy storage, high-speed motors, and aero-engines due to their characteristics of no mechanical contact, no friction and wear, no lubrication, and active controllability [1, 2].

Their working principle involves converting the low-level control signals output by the controller into the current required to drive the electromagnetic coils through power amplifiers, thereby achieving real-time control of the rotor's levitation position [3]. As the core execution component of magnetic levitation bearing systems, the topology and control strategy selection of switching-mode power amplifiers directly determine the regulation accuracy of electromagnetic forces, dynamic response speed, and system operational stability [4].

Switching-mode power amplifiers are mainly divided into half-bridge and full-bridge types. The half-bridge consists of two power switching devices and diodes [5], outputting uni-polar current, and is suitable for simplified scenarios where the direction of electromagnetic force does not require dynamic switching; the full-bridge achieves bipolar current output through a bridge configuration of four power switching devices [6], allowing flexible regulation of current amplitude and direction. Amplifiers can be further divided into two-level and three-level topologies based on modulation strategies. The two-level topology has a simple structure but its current ripple is constrained by bus voltage and switching frequency [7]; the three-level topology achieves -1, 0, and three-level outputs, improving current ripple suppression

capability and bus voltage decoupling, resulting in a total harmonic distortion reduction of over 30% compared to the two-level under the same operating conditions [8].

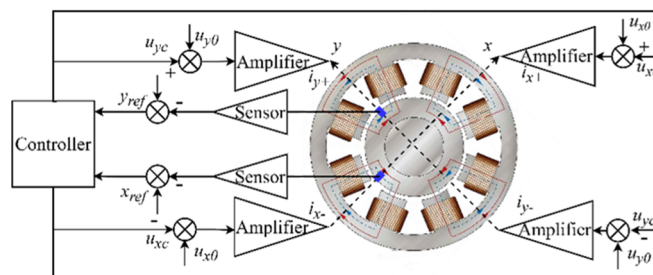
Currently, Liu Zeyuan [9] and others have proposed a spatial vector pulse width modulation (SVPWM) technology based on hybrid magnetic bearings and a current-type single-cycle control method [10], which results in low current ripple and high tracking accuracy for each load coil. Additionally, current ripple can be reduced by increasing the switching frequency, such as using gallium nitride devices with higher switching frequencies [11], but this method requires balancing the reduction of inductor current ripple with the increase in switching frequency losses. Wang Chunyi [12] and others proposed a duty cycle strategy for improved three-bridge-arm power amplifiers, analyzed the tracking range, and eliminated distortion in one coil. LI [13] and others proposed an embedded mutual inductance circuit model to model power amplifiers, quantifying the eddy current effects caused by the inherent high-frequency switching of PWM. Additionally, combining modern control theories such as model predictive control (MPC) [14], sliding mode control [15], and multi-phase modulation strategies [16] can achieve a leap in control performance.

The power amplifier proposed in this paper adopts a four-phase reverse shared bridge topology, where each coil operates based on a half-H bridge driving mode. The optimization of the topology structure reduces the use of power electronic devices; furthermore, an opposite carrier modulation is proposed to further reduce current ripple and mixed operating modes, reducing 16 modes to 4. To verify the effectiveness and reliability of the proposed method, this paper conducts verification work through a combination of Matlab/Simulink simulation analysis and physical experiment testing, fully ensuring the engineering applicability of the technical solution.

## 2. Working Principle

### 2.1. Four-Phase Bridge Working Principle

An active magnetic levitation bearing system mainly includes position sensors, controllers, power amplifiers, and electromagnetic coils. A simplified four-phase magnetic levitation bearing control system is shown in Figure 1.



**Fig 1.** Block diagram of the four-phase control system of magnetic levitation bearing

When the rotor deviates from the equilibrium position, the sensor detects the displacement change and transmits it to the controller via the regulating circuit. The controller sets the current set point in real time based on the rotor's position. The power amplifier monitors the current and generates electromagnetic force to move the rotor back to the equilibrium position. A four-phase bridge power amplifier is a high-performance driving topology used to control the multi-phase winding's of a magnetic bearing. Each H-bridge consists of two high-side and two low-side power switching devices. By regulating the turn-on and turn-off of the switching devices, the current flowing through the electromagnetic coils is controlled, thereby precisely

adjusting the electromagnetic force generated by the magnetic levitation bearing to achieve stable levitation of the rotor.

As shown in Fig.2, the four-phase shared bridge consists of four half-bridge arm winding parts and one full-bridge arm common part. It is composed of 6 switching tubes (Q1~Q6) and flyback diodes. Q5 and Q6 form the common bridge arm, serving as the shared current path for the four-line coils, while the winding bridge formed by Q1-Q4 constitutes the independent bridge arms, respectively responsible for the independent control paths of the corresponding coils. Among them, L1 and L2 control the coils in the x-direction, and L3 and L4 control the coils in the y-direction.

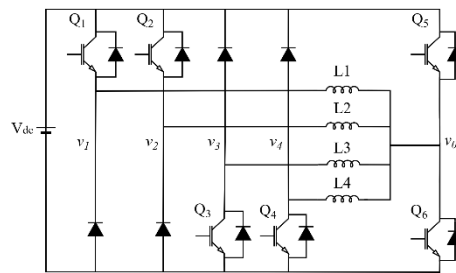


Fig 2. Four-phase bridge topology

The coil current expression is:

$$\begin{aligned}
 i_{L1} &= I_0 + i_{xref} \\
 i_{L2} &= I_0 - i_{xref} \\
 i_{L3} &= I_0 + i_{yref} \\
 i_{L4} &= I_0 - i_{yref}
 \end{aligned} \tag{1}$$

For the two sets of coils of the same degree of freedom, current differential control is adopted. To minimize the current stress on the common bridge arm under steady-state operating conditions, the winding currents corresponding to one degree of freedom are injected into the common bridge arm through the non-common bridge arms, while the winding currents of the other degree of freedom flow out from the common bridge arm to the non-common bridge arms. The expression is:

$$\begin{aligned}
 i_{L1} + i_{L2} &= i_{L3} + i_{L4} = 2I_0 \\
 i_{L1} + i_{L2} - i_{L3} - i_{L4} &= 0
 \end{aligned} \tag{2}$$

This amplifier can provide bidirectional current flow to the coil. Based on the operation of the switching tubes controlling the same coil, the circuit can be divided into: charging state, freewheeling state, and discharging state. Assuming the bias current is constant, the current waveform from 0 to T/2 is as follows:

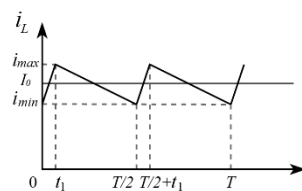


Fig 3. Amplifier output current waveform

The change in coil current can be represented as follows:

$$\begin{cases} L \frac{di_L(t)}{dt} + Ri_L(t) + 2V_{ON} = V_{dc} & 0 < t < t_1 \\ L \frac{di_L(t)}{dt} + Ri_L(t) + V_D + V_{ON} = 0 & t_1 \leq t < \frac{T}{2} \end{cases} \quad (3)$$

0 to T/2, there are two states: charging and freewheeling, with current expressions as follows:

$$\begin{aligned} i(t) &= \frac{V_{dc} - 2V_{ON}}{R} \left( 1 - e^{-\frac{t}{\tau}} \right) + I_0 e^{-\frac{t}{\tau}} & 0 < t < t_1 \\ i(t) &= -\frac{V_D + V_{ON}}{R} \left( 1 - e^{-\frac{t}{\tau}} \right) + I_0 e^{-\frac{t}{\tau}} & t_1 \leq t < \frac{T}{2} \end{aligned} \quad (4)$$

Where T is the carrier period, the conduction voltage drop of the switching transistor is  $V_{ON}$ , the forward conduction voltage drop of the freewheeling diode is  $V_D$ , and the current ripple is approximately:

$$\Delta i \approx \frac{U_D + U_{ON} + RI_0}{2fL} \quad (5)$$

The two groups of coils for controlling two degrees of freedom have opposite current directions, and the voltages at both ends of the coils are also opposite. The voltage at both ends of the coil is expressed as follows:

$$\begin{aligned} v_{L1} &= v_1 - v_0 \\ v_{L2} &= v_2 - v_0 \\ v_{L3} &= v_0 - v_3 \\ v_{L4} &= v_0 - v_4 \end{aligned} \quad (6)$$

In the equation  $v_1, v_2, v_3$  and  $v_4$  represent the potential at the midpoints of the winding bridges, while  $v_0$  denotes the common bridge midpoint voltage.

## 2.2. Operating Modes

During the startup phase of the magnetic levitation bearing, the current of the four-line coils must follow a synchronous rise pattern, gradually transitioning from an initial zero value to a preset bias current level. Subsequently, it stabilizes into a steady-state working condition. The four-phase bridge topology employs opposite carrier modulation: the carrier of switching transistors Q1 and Q2 is the same, while the carrier of switching transistors Q3 and Q4 is opposite, complementary driving the upper and lower transistors of the common bridge arm.

$$\begin{aligned} d_1 &= d_2 = d_x \\ d_3 &= d_4 = d_y \\ d_5 + d_6 &= 1 \end{aligned} \quad (7)$$

$d_1 - d_6$  represent the duty cycles of windings Q1 to Q4.

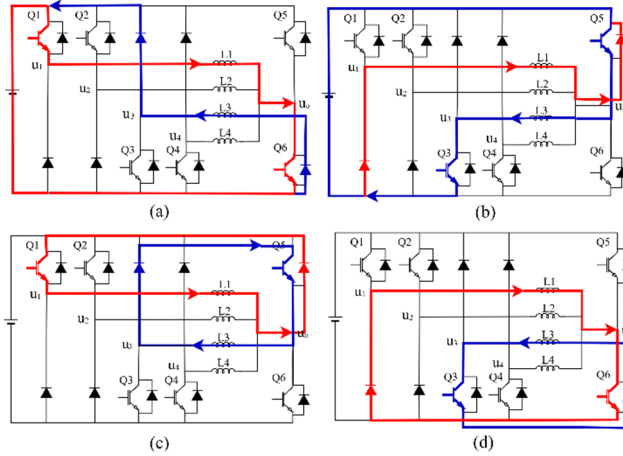
Based on the above, controlling the switching of a coil using one winding bridge switch and one common bridge switch will produce three voltage states, among which the charging state voltage is denoted as  $+$ , the discharging state voltage is denoted as  $-$ , and the freewheeling state voltage is denoted as  $\times$ . The freewheeling state involving the common bridge switch is denoted as  $\times_c$ , and the state involving the winding bridge switch is denoted as  $\times_w$ . The different switching combinations in the x and y directions are represented as follows:

$$\begin{bmatrix} +1 \\ +a \\ -a \\ -1 \end{bmatrix}_y [-1 \ -a \ +a \ +1]_x = \begin{bmatrix} -1 & -a & \times_w & \times_w \\ -a & -a^2 & \times_w & \times_w \\ \times_w & \times_w & -a^2 & -a \\ \times_w & \times_w & -a & -1 \end{bmatrix}, \quad (8)$$

Taking coils L1 and L3 as an example, the working states are shown in the table below:

**Table 1. Work status**

Work status	Corresponding to the legend
Charging state	(a)
Discharge state	(b)
Free-running state	(c)
Free-running state	(d)



**Fig 4. Four-phase bridge work status**

During the start-up phase of the magnetic levitation bearing, the currents of the four coils need to work together to gradually increase from an initial zero value to a preset bias current, as shown in the dynamic transition process in Fig. 4(a). In the working state, as shown in (b), the winding coils are more in the freewheeling operating state, and the current ripple on the four coils is further reduced.

When the four-phase shared bridge is in the freewheeling working state, as shown in Figure 5: Q1, Q2, and Q5 form two current loops, respectively controlling the operation of coils Coil1 and Coil2; Q3, Q4, and Q6 form two current loops, respectively controlling the operation of coils Coil3 and Coil4. At this time, turning on the switching tubes of the same coil power amplifier causes the electromagnetic bearing coil current to rise rapidly, quickly reaching the set command current value.

Under a fixed common bridge duty cycle, the average voltage at the center point of the winding bridge arm can also be controlled by the winding bridge duty cycle:

$$V_n = d_n V_{dc} \quad (n = 1, 2, 3, 4) \tag{9}$$

An analysis of the midpoint voltages of each bridge arm in the four-phase bridge is conducted.  $V_w$  is the midpoint voltage of the winding bridge,  $V_{cb}$  is the midpoint voltage of the common bridge, and  $Z$  is the winding coil impedance. The relationship between the coil current and the bridge arm midpoint voltage within one cycle can be expressed as follows:

$$\begin{bmatrix} i_{L1} \\ i_{L2} \\ i_{L3} \\ i_{L4} \end{bmatrix} = \frac{1}{Z} \begin{bmatrix} 1 & 0 & 0 & 0 & -1 \\ 0 & 1 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 & 1 \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_o \end{bmatrix} \tag{10}$$

The average midpoint voltage of the common bridge can be simplified to:

$$u_o = \left( \frac{u_1 + u_2 + u_3 + u_4}{4} \right) V_{dc} + \frac{(i_{L3} + i_{L4} - i_{L1} - i_{L2})}{4} Z \tag{11}$$

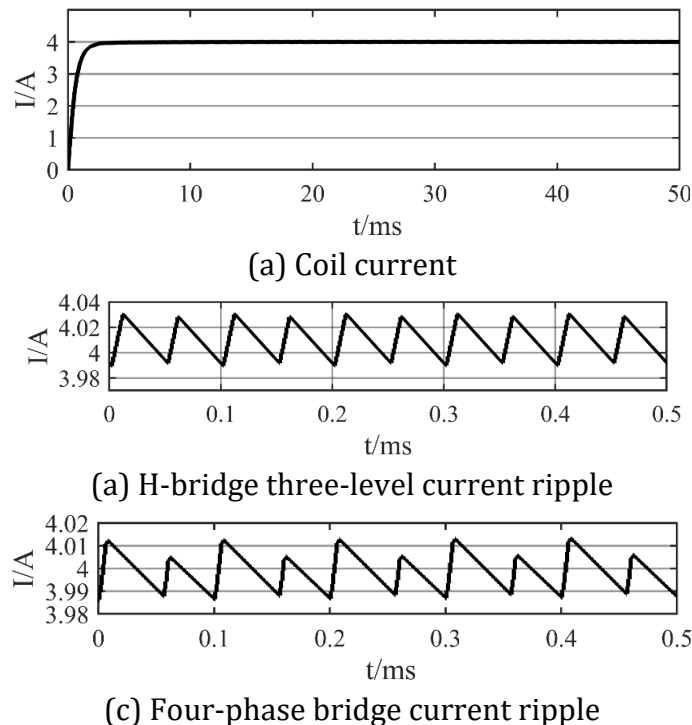
### 3. Modeling and Simulation Verification

To verify the proposed novel improved four-phase bridge topology, a radial four-degree-of-freedom magnetic bearing control system was built using Matlab/Simulink for simulation verification of Chapter 2. The simulation parameters adopted the experimental platform parameters, as shown in Table 2.

**Table 2.** Simulation Experimental Platform Parameters

Parameter	Value
Coil inductance L/mH	10
Wire resistance value R/ $\Omega$	1
Bus voltage/V	50
Switching frequency/kHz	20
Bias current/A	4

Figure 7 shows the working current variation process of the four-phase reverse shared power amplifier: In the initial stage, the current rapidly rises from 0 to a stable level of about 4A, then enters the steady-state working region, with a four-phase bridge current ripple of about 25mA. The overall current response is rapid and the steady-state ripple is small, reflecting the power amplifier's fast dynamic response characteristics and good current stability. At the same time, a simulation of the H-bridge three-level circuit was conducted, with the result showing a current ripple of about 35mA.



**Fig 5.** Coil current analysis

The above simulation results show that the current ripple of the four-phase bridge is about 25% lower than that of the H-bridge circuit.

## 4. Summary

To address issues such as component redundancy, large current ripple, and complex control modes in traditional magnetic levitation bearing power amplifiers, this paper proposes a four-quadrant reverse shared bridge topology along with a corresponding modulation strategy. This topology employs a bridge arm sharing architecture, where each coil is driven by a half-H bridge, reducing the number of IGBT/MOSFET through component reuse. The reverse carrier modulation strategy can cancel high-frequency harmonics, reducing current ripple by more than 25%, while simplifying 16 working modes to 4, thereby streamlining control logic. Experimental validation confirms the advantages of the proposed scheme in ripple suppression and operational stability.

## Acknowledgments

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