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A NOVEL HYSTERESIS CURRENT CONTROL STRATEGY FOR SWITCHING POWER AMPLIFIERS IN ACTIVE MAGNETIC BEARINGS*

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ABSTRACT
A switching power amplifier with hysteresis current control strategy in active magnetic bearings has the characters of a simple implementation, a high dynamic response and a good performance on small signal sensitivity. However, for the frequency limit of switch element, the hysteresis band can't be too small. In this paper, a novel double band hysteresis current control strategy is proposed, where an additional hysteresis band is brought in the conventional hysteresis band current control strategy. The proposed method can realize tri-state modulation, and reduce the switching frequency at the same hysteresis band. Theoretical analysis, simulations and experiments have verified that the switching power amplifier with double band hysteresis current control strategy has lower switching frequency and smaller current error.

INTRODUCTION
The principle of an active magnetic bearing is based on current or voltage controlled electromagnets by which attractive magnetic forces are exerted to the rotor to be supported. The power amplifier has to supply the coil current to the solenoid to generate the required magnetic field density. It is highly desired to transform the controller output signals without any significant distortion into the required magnetic field forces with a sufficiently high frequency range. A highly undistorted transformation of the controller signals under dynamic conditions requires considerable effort in the power amplifier design.

There are two types of the power amplifiers in the active magnetic bearings, which are analog power amplifier and switching power amplifier. For the analog power amplifiers, they cause substantial losses at static or quasi-static operating conditions. In order to reduce the losses of the analog power amplifiers, the switching power amplifiers are often used. In the switching power amplifiers, high voltage and high current are present in power-switching element only during the switching periodic. The comparatively small switching losses are proportional to the supply voltage, and the switching-transition frequency. There is practically no current flow for the power-switching element at OFF-state conditions, and the power loss for the ON-state conditions is proportional to the resistance of the switching element and the square of the current. So the power losses of the switching power amplifiers are small and the efficiency of switching power amplifier could be high more than 95%. However there is a big disadvantage of the switching power amplifiers. Because of the periodic switching process, the control current is superimposed with a considerable number of higher harmonics (current ripple). The higher harmonics of the control current both cause undesirable forces exerted to the rotor, and generate additional eddy current and hysteresis losses that may lead to thermal problems of the active magnetic bearings[1].

Pulse width modulation (PWM), sample/hold and hysteresis type are the most important configurations of the switching power amplifiers[2-4]. To the first two configurations, a few methods[5,6] have been proposed which are used to minimize the harmonics of the control current. But there are few methods proposed about the hysteresis type [7,8] to minimize the harmonics. Further more, the switching power amplifiers with the hysteresis current control strategy in the active

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magnetic bearings have the advantages of a simple implementation, a high dynamic response and a good performance on insensitive to load parameter variation. Especially the circuit required to implement the hysteresis control is even simpler than that required for fixed sampling rate control pulse width modulation (PWM), at the expense of only a few resisters needed to produce the desired hysteresis. So, there is a need to research the harmonics problem of hysteresis configuration.

Two kinds of modulations are used to control the switches to allow the current to track the reference signal: bi-state switching and tri-state switching. Compared with the bi-state switching, the tri-state switching has several advantages. The tri-state amplifier makes only two switches during a switching cycle instead of four. A tri-state switching amplifier therefore has only half the switching losses of the same bi-state switching amplifier. The current on the electrolytic capacitor in the tri-state switching is also greatly reduced. The low current in the capacitor will reduce heating and extend the capacitor life. What's more, the current ripples reduce significantly in the tri-state switching power amplifiers, which mean lower harmonics, better control precision that are very desirable.

A novel hysteresis current control strategy, named double band hysteresis current control strategy, is proposed in this paper, which combines the hysteresis current control and the tri-state modulation. This method realizes the tri-state modulation by introducing an additional hysteresis band in the traditional hysteresis current control, and reduces the switching frequency to a large extent at the same width of hysteresis. On the basis of analyzing the principle, the double band hysteresis current control method is introduced in detail, and verified by the results of simulations and experiments.

TRI-STATE DOUBLE BAND HYSTERESIS CURRENT CONTROL

The Scheme of Hysteresis Current Control

The scheme of the switching power amplifiers used traditional hysteresis current control strategy is shown in Figure 1. The error signal for the amplifier, between the reference signal and the current feedback signal, is compared to the hysteresis band. When the error signal is above the superior hysteresis band, the driving signal to the H-bridge is in high level and the switches are on which result in the coil current increasing. Conversely, when the error signal is below the inferior hysteresis band, the driving signal is in low level and the switches are off which results in the coil current decreasing. When the error signal is between the superior hysteresis band and inferior hysteresis band, the driving signal doesn't change. The output voltage and current waveforms of the power amplifier with traditional hysteresis current control are shown in Figure 2. The coil current i fluctuates around the reference current i_r between superior and inferior hysteresis bands (band width is $2h$).

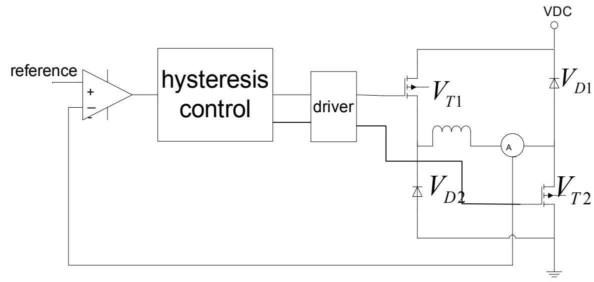


FIGURE 1: Power amplifier with traditional hysteresis band current control system diagram

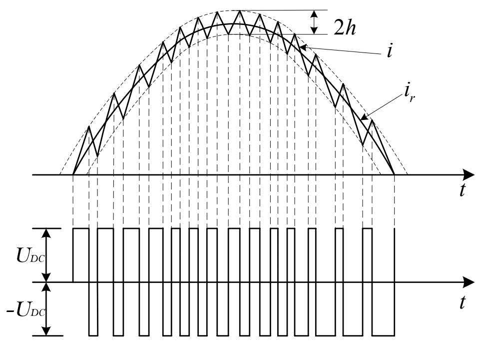


FIGURE 2: Output voltage and current waveforms of the power amplifier with traditional hysteresis current control

The tri-state hysteresis current control has one more state compared with the traditional hysteresis current control, which is called current-circulate process. For a given reference signal i_r, the coil current waveform of the amplifier with the tri-state hysteresis current control is shown in Figure 3.

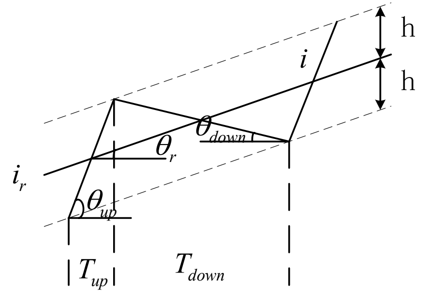


FIGURE 3: tri-state hysteresis band current control

When $(i - i_r) > h$, there are two possible conditions. If the slope of reference signal k_r is greater than the slope of circulate current k_{cir}, V_{T1} remains on and V_{T2} off, so the current flows through V_{T1} and V_{D1} to form the current-circulate circuit. Then, the current decreases as k_{cir}; if the slope of reference signal k_{r} smaller than k_{cir}, V_{T1} and V_{T2} are both off. The current decreases as k_{down} (the slope of decreasing current when the voltage of coil is U-). Conversely, when $(i-i_r)<h$, there are also two possible conditions. If the slope of reference signal k_{r} greater than k_{cir}, V_{T1} and V_{T2} are both on. The current increases as k_{up} (the slope of increasing current when the voltage of coil is U+). If the slope of reference signal k_{r} is smaller than k_{cir}, V_{T1} becomes on, and V_{T2} off, so the current flows through V_{T1} and V_{D1} to form the current-circulate circuit. The coil current decreases as k_{cir}.

Relationship between the Switching Frequency and Hysteresis Band

When the current increases, the periodic can be written as

$$T = T_{up} + T_{\text{cir}} = \frac{2h}{(k_{up}-k_r)} + \frac{2h}{(k_r - k_{\text{cir}})} \qquad (1)$$

The voltage equations of power transistor are

$$\left.\begin{aligned} L\frac{di(t)}{dt} &= U_{DC} - 2U_{ON} - U_R, \text{ when } V_{T1} \text{ and } V_{T2}\ on \\ L\frac{di(t)}{dt} &= -U_{ON} - U_D - U_R, \quad \text{when } V_{T1} \text{ and } V_{T2}\ off \end{aligned}\right\} \qquad (2)$$

where L is the coil inductance, U_{DC} is the power supply for H-bridge, U_{ON} is drain-to-source voltage of MOSFET, U_D is diode forward voltage, U_R is voltage on resistance of magnetic coils.

The linearization solution of differential equation (2) is

$$\left.\begin{aligned} i(t) &= i_{\min} + \frac{U_{DC} - 2U_{ON} - U_R}{L}t, \text{ when } V_{T1}V_{T2}on \\ i(t) &= i_{\max} - \frac{U_{ON} + U_D + U_R}{L}t, \quad \text{when } V_{T1}V_{T2}off \end{aligned}\right\} \qquad (3)$$

So, the slopes of currents are

$$k_{up} = \frac{U_{DC} - 2U_{ON} - U_R}{L} \qquad (4)$$

$$k_{\text{cir}} = -\frac{U_{ON} + U_D + U_R}{L} \qquad (5)$$

When U_{ON}, U_D and U_R are much smaller than U_{DC}, so $2U_{ON} + U_R \approx U_{ON} + U_D + U_R \square U_0$, and substituting equations (4) and (5) into equation (1), we have:

$$\begin{aligned} T &= \frac{2hL(U_{DC} - U_0 - k_r L + U_0 + k_r L)}{[U_{\text{DC}}(U_0 + k_r L) - (U_0 + k_r L)^2]} \qquad (6) \\ &= \frac{2hLU_{DC}}{[U_{\text{DC}}(U_0 + k_r L) - (U_0 + k_r L)^2]} \end{aligned}$$

The switching frequency is given by

$$f = \frac{[U_{\text{DC}}(U_0 + k_r L) - (U_0 + k_r L)^2]}{2hLU_{DC}} \qquad (7)$$

For the amplifiers with the traditional hysteresis current control, the switching frequency is

$$f = \frac{[U_{DC}^2 - (U_0 + k_r L)^2]}{4hLU_{DC}} \qquad (8)$$

When $2(U_0 + k_r L)$ is much smaller than the power supply voltage U_{DC}, the switching frequency of the tri-state modulation amplifier is much smaller than that in the bi-state modulation at the same hysteresis band.

Implementation of the Tri-state Hysteresis Current Control

There are some difficulties in implementation of the tri-state hysteresis current control by comparing the slope of feedback current to the slope of reference signal. First, current slope in an analog circuit is very difficult to accurately measure in real time. Second, the current-circulate slope is difficult to confirm and moreover it varies along with the amplitude of coil current. In order to overcome these problems, a novel tri-state hysteresis current control method, i.e., tri-state double band hysteresis current control method, is proposed here. The scheme diagram of the power amplifiers with the double band hysteresis current control is shown in Figure 4.

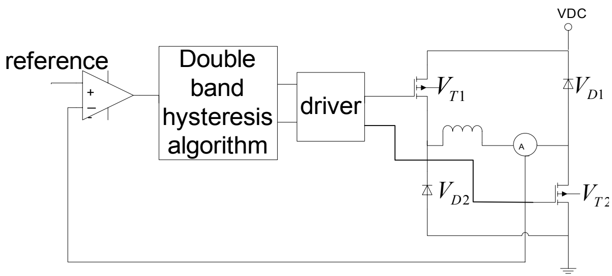


FIGURE 4: Power amplifier with hysteresis band current control system diagram

On the basis of the traditional hysteresis current control, the double band hysteresis current control adds another hysteresis band, consisted of an inner band and an outer band shown in Figure 5. The work conditions of H-bridge depend upon the relation between feedback current signal and two hysteresis band. Firstly, the current was compared with the inner band. If the current got to the inner band (point C, D, G, J in Figure 5), the H-bridge would turn into the current-circulating state and the current in the coil would decrease very slowly. Secondly, the current was compared with the outer band. If the current got to the outer band (point A, E, H in Figure 5), the H-bridge would turn into high-voltage state or low-voltage state, the current in the coil would increase or decrease very quickly. The double band hysteresis current control method realizes current mode tri-state modulation, in which the switching frequency is much lower at the same hysteresis band compared with the conventional hysteresis current control method, and makes the amplifiers with higher efficiency, lower harmonics and better control precision. The H-bridge state transition is shown in Table 1.

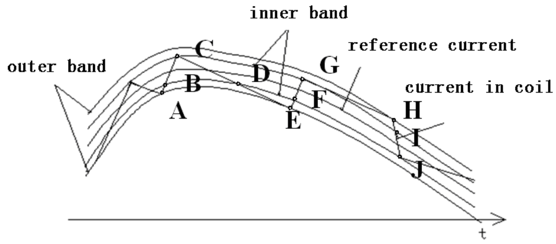


FIGURE 5: The scheme double band hysteresis current control

TABLE 1: H-bridge state transition

Before			After			Touched band
Current state	Vt1	Vt2	Vt1	Vt2	Current state	
U+ increase	on	on	off	off	U- decrease	Superior outer band
			off	on	circulate	Superior inner band
circulate	off	on	off	off	U- decrease	Superior outer band
			off	on	circulate	Superior inner band
U- decrease	off	off	on	on	U+ increase	Inferior outer band
			off	on	circulate	Inferior inner band
circulate	off	on	on	on	U+ increase	Inferior outer band
			off	on	circulate	Inferior inner band

SIMULATION RESULTS

The scheme of the tri-state double band hysteresis current control is shown in Figure 6, which is composed of a control circuit, a power converter, a current feedback loop and a power supply. The control circuit includes two hysteresis comparators, two analogue multiplexers and one error comparator. System parameters are: inner band is 0.1 V, outer is 0.12 V, coil resistance is 2 Ω , coil inductance is 10 mH .

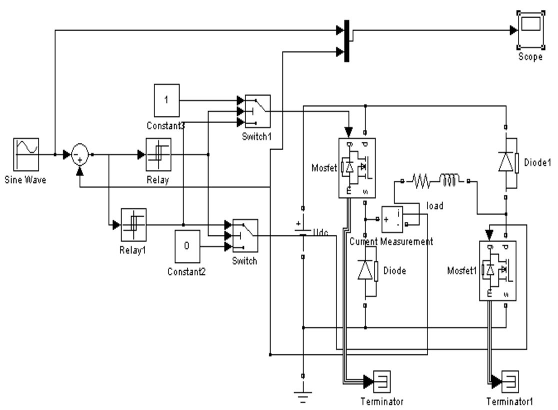


FIGURE 6: Tri-state power amplifier simulation system

Tracking Characteristic

Given a sinusoidal signal with an amplitude of 2.5 A and frequency of 1000 Hz, the output current waveform of tri-state power amplifier is shown in Figure 7. The output current tracks sinusoidal wave signal accurately almost without any phase shift.

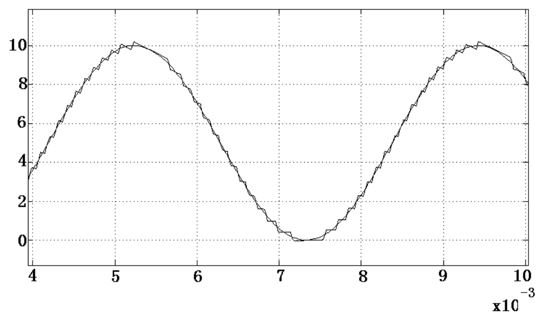


FIGURE 7: Output current waveform of tri-state power amplifier

Step Response

When a step signal of amplitude 5 V is applied, the output current waveforms of the tri-state power amplifier with power supply U_{DC} of 300 V and 150 V, respectively, are shown in Figure 8. Obviously, along with the increase of power supply voltage, the rate of current response raises. However, U_{DC} has very small effect on frequency of the tri-state power amplifiers.

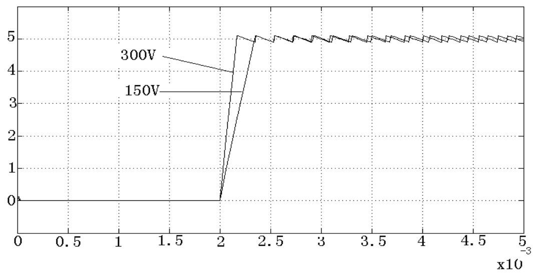
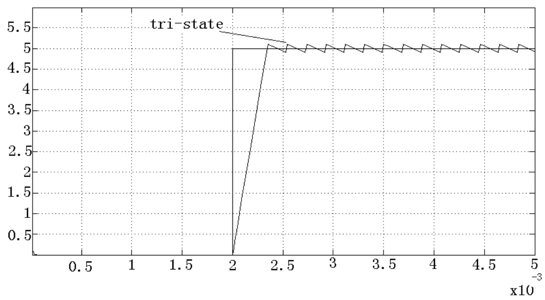


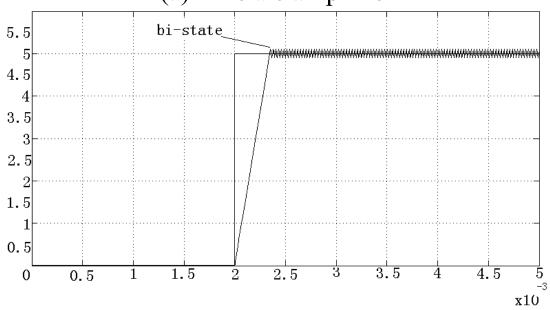
FIGURE 8: Step response of tri-state current control power amplifier

Switching Frequency

Use of a switching power amplifier normally causes the distortion in the bearing current, which generates more heat in the bearing than the linear one. In order to reduce the current ripple (for the hysteresis current control, the current ripple equals the hysteresis band), the switching frequency has to be increased. However, the switching frequency cannot be increased indefinitely due to the dynamic loss, which results from the fact that the MOSFET switches do not start and stop conducting current instantaneously. Another reason is that some parasitic parameters associated with the H-bridge will cause severe voltage spikes, or even circuit oscillations, if the switching frequency is too high.



(a) Tri-state amplifier



(b) Bi-state amplifier

FIGURE 9: The frequency comparison between tri-state and bi-state

Compared to the bi-state modulation amplifier, the tri-state modulation amplifier has a great advantage that the switching frequency of the tri-state modulation amplifier is much smaller than that in the bi-state modulation amplifier at the same hysteresis band. Some simulations are made to compare the switching frequency of two modulations, and results are shown in Figure 9.

EXPERIMENTAL RESULTS

An experimental validation for the proposed method can be obtained by measuring the currents in the magnetic coils. A number of experimental results are shown to validate the operation principle of the amplifier when connected to a magnetic bearing coil load (R=0.6 Ω, and L=13.2 mh) and subject to some special reference signal.

For the AMB systems, the function of power amplifier is to make an undistorted output current tracking input reference signal. The experimental input-output characteristic curve is shown in Figure 10. It is noted that input and output signal have a good linear relationship.

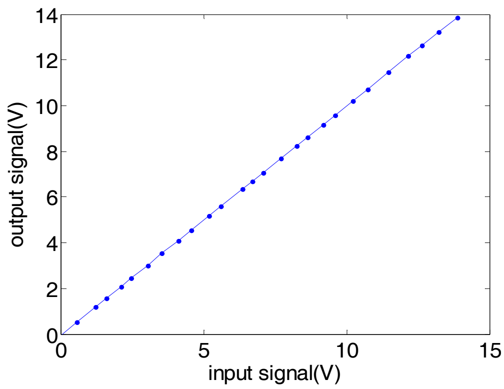
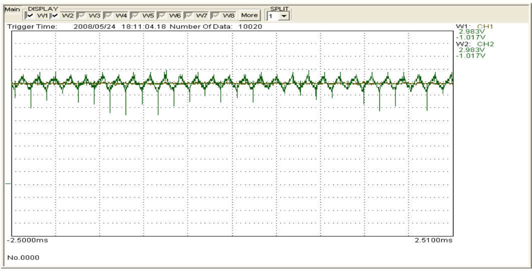


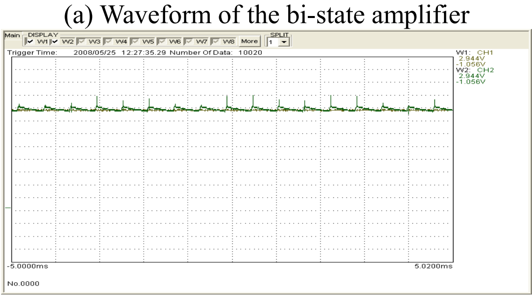
FIGURE 10: Relationship between input and output

Figure 11 shows the output waveforms of two modulations when the input is constant value and Figure 12 shows the output waveforms when the input is a sinusoidal signal (f=150 Hz, Amp=2 V). It is noted that the current ripples of the tri-state amplifier are much smaller than the bi-state amplifier's at the same switching frequency.

The frequency response performances of the power amplifiers for active magnetic bearings, such as bandwidth, have a greatly effect in the dynamic behavior of the AMB rotor system. The performances of the power amplifiers are quite different under different test conditions. Even if the previously developed power amplifiers for active magnetic bearings have very wide bandwidth. We often find the test was undertaken with the random input of small amplitude and the small load, without mentioning the supply voltage and amplifier gain.

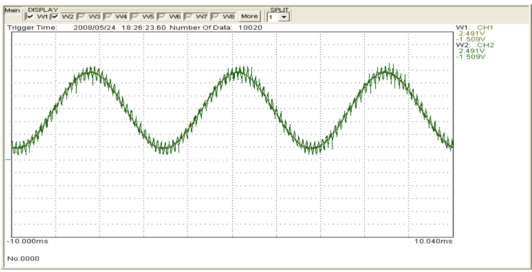


(a) Waveform of the bi-state amplifier

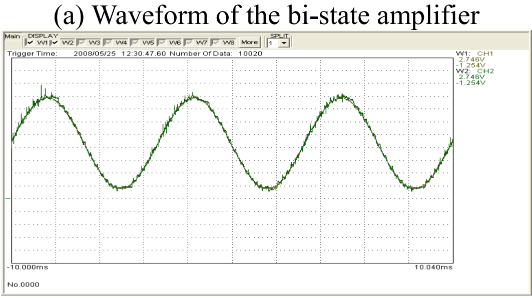


(b) Waveform of the tri-state amplifier

FIGURE 11: Output waveforms comparison under step signal input



(a) Waveform of the bi-state amplifier



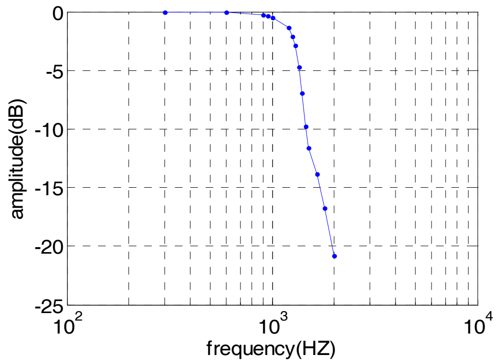
(b) Waveform of the tri-state amplifier

FIGURE 12: Output waveforms comparison under sine signal input

The current slew rate limits the force slew rate. For most cases, it is very important to know the maximum sinusoidal dynamic range of current, which limits the practical control force.

So the sinusoidal signal input with maximum excitation amplitude (sinusoidal sweep) should be employed to test and obtain the bandwidth of the power amplifier. In addition, the practical load, the supply voltage and amplifier gain should be cited as well.

In this experiment, the sinusoidal signal amplitude is 2V and frequency ranges from 100-2000 Hz, supply voltage is 30V, the amplifier gain set as 1. The frequency response function is shown in Figure 13. It is shown that the frequency at -3dB-point is about 1300 Hz.



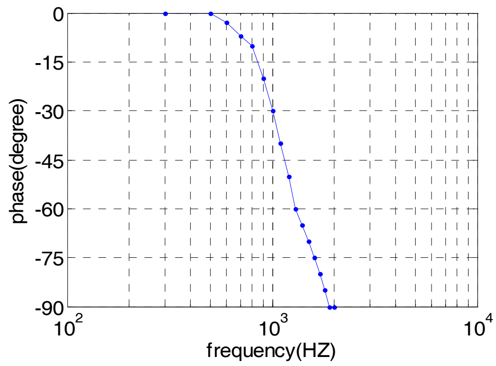


FIGURE 13: The frequency response of the tri-state amplifier

CONCLUTION

A power amplifier with a novel current control method has been presented. This method realizes tri-state modulation by introducing an additional hysteresis band to the traditional hysteresis current control. The results of simulations and experiments validate that this power amplifier has advantages as follows:

(1) The circuit required to implement the tri-state hysteresis current control is very simple.

(2) The tri-state modulation reduces the switching frequency to a large extent at the same width of hysteresis band.

(3) It has a good linear relationship and a wide bandwidth.

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