The Twelfth International Symposium on Magnetic Bearings (ISMB 12)
Wuhan, China, August 22-25, 2010

Failure Mechanism of Improved Three-Level Power Amplifier for Active Magnetic Bearings

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Abstract: In switching power amplifiers used in active magnetic bearings, three-level modulation technique is commonly used to reduce the current ripple of switching power amplifiers, so as to improve the performance of active magnetic bearing system. In our research, it is found that when a modified three-level PWM modulation technique was used in the switching power amplifiers, the output current waveform of the three-level PWM power amplifier was inconsistent with the theoretical waveform sometimes. At the same switching frequency, the current ripple of the modified three-level PWM power amplifier was much bigger than the theoretical value. The failure phenomenon is introduced and the failure mechanism of the modified three-level PWM power amplifier is theoretically analyzed for different carrier waves based on the analysis of the modified three-level PWM modulation technology in this paper. It is found that the deviation of bias voltage setting in the modified three-level PWM circuit results in its failure, and the failure mechanism is different for different carrier waves. Simulation and experimental results are in good agreement with the theoretical analyses. Finally, some suggestions about avoiding the failure of the modified three-level PWM power amplifier are proposed.

Keywords: Failure Mechanism,Three-Level PWM,Power Amplifier, Active Magnetic Bearings,Current Ripple

Introduction

Active magnetic bearings (AMB) are a very promising technology and are now being employed for a variety of industrial rotating machineries. These non-contacting bearings use magnetic forces to firmly hold the rotor and to maintain separation between rotating rotor and the machine’s stationary components. The power amplifier supplies the coil current to the solenoid to generate the required electromagnetic force. It is highly desired to transform the controller output signals without any significant distortion into the required electromagnetic force within a sufficiently high frequency range. A highly undistorted transformation of the controller signals under dynamic conditions requires considerable effort in the amplifier design.

Switching power amplifiers[1-3] are used in most AMB systems for their high efficiency. However, there are some problems in the switching power amplifiers due to the periodic switching process. In fact, the control current in the switching power amplifiers is superimposed with a considerable number of higher harmonics[4-7]. The higher harmonics of the control current cause undesirable forces exerted to the structure, generate eddy current and hysteresis losses within the material that may lead to thermal problems of the magnetic bearings. To overcome these drawbacks, a current mode three-level PWM modulation technology for the switching power amplifier of the active magnetic bearings was proposed. The current ripples of three-level PWM modulation are significantly smaller than that of two-level PWM modulation at the same switching frequency.

Figure 1 shows the principle of general three-level PWM switching power amplifier. Based on the traditional two-level PWM switching power amplifier, a zero level of output voltage is introduced to produce an output current circulating stage. The general three-level PWM switching power amplifier's shortcoming is that a phase-shifting circuit is necessary and the circuit structure is complicated.

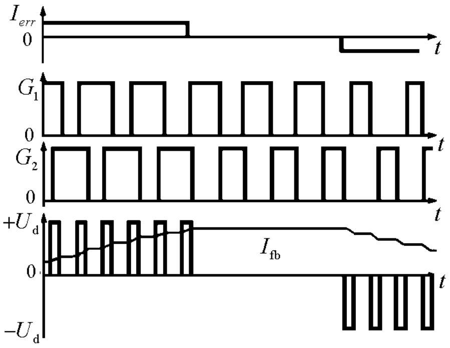


Fig. 1 Principle of general three-level PWM modulation

papers [16-18] proposed an improved three-level PWM switching power amplifier which doesn't need phase-shifting circuit and simplifies the circuit structure. However, in some experiments, the improved three-level PWM switching power amplifier's output current waveform was not the same as the theoretical one. In order to improve the improved three-level PWM switching power amplifier reliability, it is necessary to study the failure mechanism in depth.

In this paper, the failure mode and the failure mechanism of the improved three-level PWM modulation switching power amplifiers are studied. Meanwhile, the methods for reducing the failure of the improved three-level switching power amplifiers are suggested.

Principle of Improved Three-level PWM Switching Power Amplifier

The main circuit of switching power amplifier usually has two types, i.e., half bridge (unipolar) and full bridge (bipolar). When the bias magnetic windings and the control windings share a coil, the active magnetic bearing system requires only unipolar output current of the power amplifier, the half-bridge structure can just meet this requirement. Compared with the full-bridge structure, besides simple and economic, the half-bridge structure needs only half the switches and driving circuits, and there is no issue of the same leg straight on, so the switching power amplifiers in most magnetic bearings adopted the half-bridge structure. The structure of improved three-level PWM switching power amplifier with the half-bridge main circuit was shown in Figure 2. The main circuit consists of two switches T_1 and T_2, two diodes D_1 and D_2. R is the coil resistance, L is the inductance, U_d is the DC bus voltage, I_{ref} is the current reference signal, and I_{fb} is the feedback signal of the current in coil.

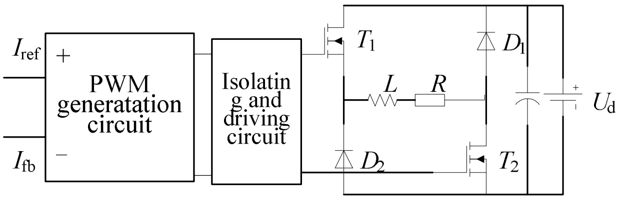
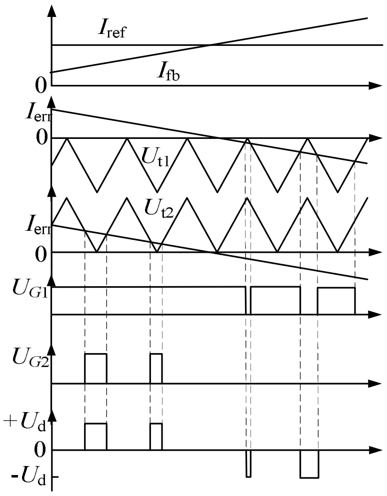


Fig. 2 Structure of three-level PWM switching power amplifier

The improved three-level PWM switching power amplifier modulation principle is shown in Figure 3. $I_{err}=I_{ref}-I_{fb}$ is current error signal, U_{t1} and U_{t2} are triangular carriers, output range of U_{t1} is $-A$ to 0, output range of U_{t2} is 0 to A, A is the amplitude of U_{t1} and U_{t2}, U_{G1} and U_{G2} is driving signal for the switch T_1 and T_2, respectively. Clearly, when the current error signal is bigger than the current reference signal, U_{G1}'s duty cycle is 100%, T_1 is on, U_{G2}'s duty cycle is 0-100%, T_2 works in PWM mode; When the current error signal is less than the current reference signal, U_{G1}'s duty cycle is 0-100%, T_1 works in PWM mode, U_{G2}'s duty cycle is 0, T_2 keeps off. Using this modulation, the power amplifier's output voltage has three levels of $+U_d$, 0, and $-U_d$.



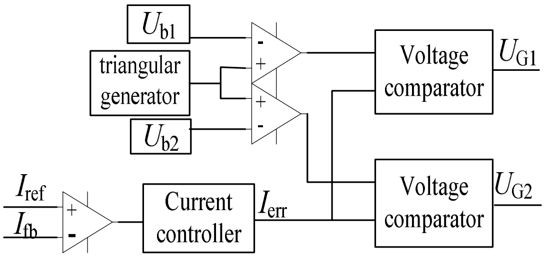


Fig. 3 Improved three-level PWM modulation schema Fig. 4 Improved three-level PWM generating circuit

The improved three-level PWM generation circuit is shown in Figure 4. The PWM generation circuit mainly consists of error comparator, current controller, triangular wave generation circuit, voltage offset circuit and voltage comparator. The error comparator compares the current reference signal I_{ref} with the current feedback signal I_{fb} to get the current error signal I_{err}. The current controller can used various control algorithms to improve the control performance of the power amplifiers. The triangular wave generator generates the triangle wave signal. Offset voltage circuit superimpose offset voltage U_{b1} and U_{b2} to the triangle wave signal and obtains the triangular carriers U_{t1} and U_{t2}. I_{err} and two triangular carriers were compared by the voltage comparator and generate two driving signal—U_{G1} and U_{G2}. Currently, most power amplifiers are used PWM chip (such as TL494) to replace the triangular wave generator and the voltage comparator.

Three-level Waveform and the Failure Waveform

When the current reference signal I_{ref} is constant, the theoretical output current waveform of the improved three-level PWM switching power amplifier is shown in Figure 5, and its expression is

$$Ldi/dt + Ri + 2U_{on} = U_d \qquad 0<t<t_1 \tag{1}$$

$$Ldi/dt + Ri + U_{VD} + U_{on} = 0 \qquad t_1<t<T \tag{2}$$

where i is the coil current, U_{on} is the forward voltage of switches, U_{VD} is the forward voltage of diodes.

For the resistance exists in the circulating circuit, the value of current will decrease slowly when output voltage of power amplifier is 0V. So in each cycle, there is a very short period of current rising stage, and the current would present saw-tooth waveform.

Figure 5(b) is the actual current waveforms of the improved three-level PWM switching power amplifier using TL494. The actual current waveform is obviously different from the theoretical current waveform, which is approximately trapezoidal wave. Besides the waveform distortion, the actual value of current ripple is much bigger than the theoretical value. This phenomenon is called "modulation failure".

(a) Theoretical current waveform (b) Actual current waveforms

Fig. 5 Theoretical waveform and distortional waveform

Failure Mechanism

Results of research by a lot of simulations and experiments revealed that the modulation failure was due to inaccurate setting of the offset voltage U_{b1} and U_{b2}. The detail analysis is given as follows:

The input voltages corresponding to 0% and 100% duty cycle of PWM waveform is denoted as $U_{0\%}$ and $U_{100\%}$, then triangular carrier amplitude $A=U_{100\%}-U_{0\%}$. In accordance with the improved three-level PWM modulation requirements in Figure 4, the offset voltage U_{b1} should be set to $U_{100\%}$, the offset voltage U_{b2} should be set to $U_{0\%}$. However, there are certain difficulties in the practical realization of the above offset voltage settings due to following reasons. (a) The input voltages corresponding to the 0% and 100% duty cycle of PWM waveform is difficult to accurately determine. In particular, the difference between the $U_{100\%}$ and $U_{0\%}$ of the PWM integrated chip is very small. (b) Difficult to set the offset voltage accurately. So in reality, the offset voltage settings will always have some deviations.

In order to facilitate the theoretical analysis, assuming that the deviation of U_{b1} is α, and the deviation of U_{b2} is 0.

$$U_{100\%}=U_{b1}+\alpha \tag{3}$$

$$U_{0\%}=U_{b2} \tag{4}$$

When the offset voltage U_{b1} and U_{b2} were superimposed with the current error signal, the current error signal corresponding to the 0% to 100% duty cycle of two driving signal U_{G1} and U_{G2} are respectively $(-A+\alpha, \alpha)$ and $(0, A)$.

According to α, the offset voltage settings can be divided into four types.

1) $\alpha=0$，ideal condition

According to different work modes, the current error signal I_{err} can be divided into four intervals, namely:

A. $0<I_{err}<A$

Duty cycle of U_{G1} corresponding to I_{err} is 100%, U_{G2}'s duty cycle is 0 to 100%, then T_1 keeps on, T_2 works in PWM mode, the power amplifier output voltage is $+U_d$ or 0, and the coil current is in rising stage or circulating stage.

B. $-A<I_{err}<0$

Duty cycle of U_{G1} corresponding to I_{err} is 0~100%, U_{G2}'s duty cycle is 0, then T_1 works in PWM mode, T_2 keeps off, the power amplifier output voltage is $-U_d$ or 0, and the coil current is in falling stage or circulating stage.

C. $I_{err}>A$

Duty cycle of U_{G1} and U_{G2} both are 100%, then T_1 and T_2 are both on, the power amplifier output voltage is $+U_d$, and the coil current is in rising stage.

D. $I_{err}<-A$

Duty cycle of UG1 and U_{G2} both are 0%, then T_1 and T_2 are both off, the power amplifier output voltage is $-U_d$, and the coil current is in falling stage.

As can be inferred combining the above analysis and Figure 3, when $I_{err}> 0$, output voltages could be $+U_d$ and 0, when $I_{err} <0$, output voltages could be $-U_d$ and 0. This is theoretical improved three-level PWM modulation.

2) $\alpha<0$

According to different work modes, the current error signal I_{err} can be divided into five intervals, namely

A. $0<I_{err}<A$

Duty cycle of U_{G1} corresponding to I_{err} is 100%, U_{G2}'s duty cycle is 0 to 100%, then T_1 is on, T_2 works in PWM mode, the power amplifier output voltage is $+U_d$ or 0 , and the coil current is in rising stage or circulating stage.

B. $\alpha<I_{err}<0$

Duty cycle of U_{G1} corresponding to I_{err} is 100%, U_{G2}'s duty cycle is 0, then T_1 is on, T_2 is off, the power amplifier output voltage is 0, and the coil current is in circulating stage.

C. $-A+\alpha<I_{err}<\alpha$

Duty cycle of U_{G1} corresponding to I_{err} is 0%, U_{G2}'s duty cycle is 0 to 100%, then T_1 is off, T_2 works in PWM mode, the power amplifier output voltage is $-U_d$ or 0 , and the coil current is in falling stage or circulating stage.

D. $I_{err}>A$

Duty cycle of U_{G1} and U_{G2} both are 100%, then T_1 and T_2 are both on, the power amplifier output voltage is $+U_d$, and the coil current is in rising stage.

E. $I_{err}<-A+\alpha$

Duty cycle of U_{G1} and U_{G2} both are 0%, then T_1 and T_2 are both off, the power amplifier output voltage is $-U_d$, and the coil current is in falling stage.

Under this condition, a new work mode—T_1 is on and T_2 is off—appeared, but when $I_{err}>0$, output voltages is $+U_d$ and 0, when $I_{err}<0$, output voltages is $-U_d$ and 0, which is the same as $\alpha=0$.

3) $0<\alpha<A$

According to different work modes, the current error signal I_{err} can also be divided into five intervals, namely

A. $\alpha<I_{err}<A$

Duty cycle of U_{G1} corresponding to I_{err} is 100%, U_{G2}'s duty cycle is (α/A)%~100%, then T_1 is on, T_2 works in PWM mode, the power amplifier output voltage is $+U_d$ or 0 , and the coil current is in rising stage or circulating stage.

B. $0<I_{err}<\alpha$

Duty cycle of U_{G1} corresponding to I_{err} is $(1-\alpha/A)$%~100%, U_{G2}'s duty cycle is 0%~(α/A)%, then T_1 and T_2 both work in PWM mode, the power amplifier output voltage is $+U_d$, 0 and $-U_d$, and the coil current is in rising stage, circulating stage or falling stage.

C. $-A+\alpha<I_{err}<0$

Duty cycle of U_{G1} corresponding to I_{err} is 0~ $(1-\alpha/A)$%, U_{G2}'s duty cycle is 0, then T_1 works in PWM mode, T_2 is off, the power amplifier output voltage is $-U_d$ or 0 , and the coil current is in falling stage or circulating stage.

D. $I_{err}>A$

Duty cycle of U_{G1} and U_{G2} both are 100%, then T_1 and T_2 are both on, the power amplifier output voltage is $+U_d$, and the coil current is in rising stage.

E. $I_{err}<-A+\alpha$

Duty cycle of U_{G1} and U_{G2} both are 0%, then T_1 and T_2 are both off, the power amplifier output voltage is $-U_d$, and the coil current is in falling stage.

Under this condition, another new work mode—T_1 and $T2$ both work in PWM mode—appeared, and moreover, when $I_{err}>0$, output voltages is $+U_d$, 0 and $-U_d$, when $I_{err}<0$, output voltages is $-U_d$ and 0, which is different from $\alpha=0$. This is the direct reason for the current waveform distortion in Figure 4.

4) $\alpha>A$

The work condition of $\alpha>A$ and the work condition of $\alpha<A$ is symmetrical, so the work condition of $\alpha>A$ is no longer introduced.

In summary, when the offset voltage is set to $0<\alpha<A$, the improved three-level PWM modulation generates some significant changes, so the following analysis is mainly to consider $0<\alpha<A$.

Influence of Carriers

The above discussion and analysis just made a qualitative analysis for the improved three-level PWM modulation failure, and the actual failure process and failure range need to further consider the effect of the carriers.

Currently, the modulation of PWM integrated chip mostly used triangular comparison method, but the carriers are not the same forms. The main forms of carriers are divided into symmetric and asymmetric triangle. Asymmetric triangular waveform contains more species, and this paper selected the saw-tooth wave. The analysis was made as follows when the carrier used symmetric triangle and saw-tooth wave.

a. Symmetric Triangle

When the carrier is the symmetric triangle, the range of α which would result in the failure of improved three-level PWM modulation is

$$\alpha_1 < \alpha < A \tag{5}$$

where $\alpha_1 = \dfrac{k_2 T(b_1^2 + k_1 k_2)}{2b_1(k_1 + k_2)}$, T is the switching cycle, k_1 is the product of the current slope of rising stage and the proportional gain k_P of current controller, k_2 is the product of the current slope of circulating stage and k_p, b_1 is the slope of the triangular carrier.

When α satisfies Eq. (5), the current error signal I_{err} and the carrier U_{t1} would intersect, and the output current waveform presents "~" shape shown in Figure 6. Its work process can be divided into four stages, i.e., the current rising stage(ab), the circulating stage(bc), the currents falling stage(cd), and the circulating stage(de).

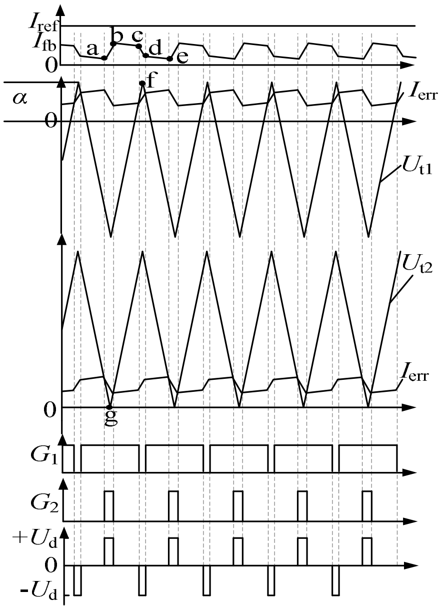


Fig. 6 Failure analysis for symmetrical triangle carrier

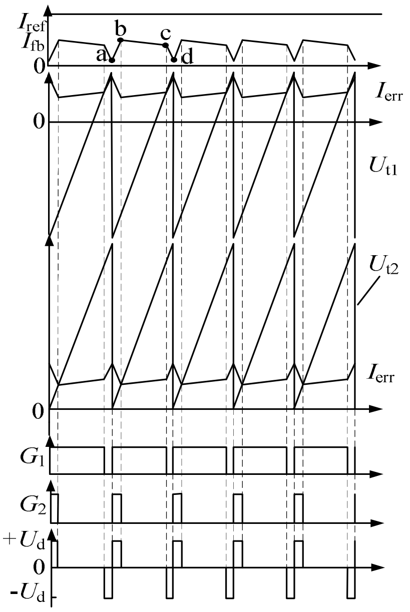


Fig. 7 Failure analysis for saw-tooth wave carrier

The failure process shown in Figure 6 can make use of 5 intersections of the current error signal and triangular carrier a, b, c, d, e and f, g corresponding to the points of triangular carrier peak and valley to obtain the following equations

$$\begin{cases} i(t_2) = -k_1(t_2 - t_0) + i(t_0) \\ i(t_2) = b_1(t_2 - t_1) \end{cases} \tag{6}$$

$$\begin{cases} i(t_3) = k_2(t_3 - t_2) + i(t_2) = k_2(t_3 - t_2) + b_1(t_2 - t_1) \\ i(t_3) = \alpha - b_1(t_4 - t_3) \end{cases} \tag{7}$$

$$\begin{cases} i(t_5) = k_1(t_5 - t_3) + i(t_3) = k_1(t_5 - t_3) + \alpha - b_1(t_4 - t_3) \\ i(t_5) = \alpha - b_1(t_5 - t_4) \end{cases} \tag{8}$$

$$\begin{cases} i(T) = k_2(T - t_5) + i(t_5) = k_2(T - t_5) + \alpha - b_1(t_5 - t_4) \\ i(T) = i(t_0) = b_1 t_1 \end{cases} \tag{9}$$

$$t_1 + T/2 = t_4 \tag{10}$$

where t_0, t_1, t_2, t_3, t_4, t_5 are respectively the time points of a, g, b, c, f and d.

Solved Eqs. (6)-(10), and obtained

$$\begin{aligned} t_2 - t_0 &= \frac{\frac{b_1 + k_1}{b_1 + k_2}\left(k_2 T + \frac{b_1 T}{2} + \alpha\right) + \frac{b_1 - k_1}{b_1 - k_2}\left(\frac{b_1 T}{2} - \alpha\right) - b_1 T}{2k_1} \\ &= \frac{(b_1^2 - k_1 k_2) k_2 T + 2b_1(k_1 - k_2)\alpha}{2k_1(b_1^2 - k_2^2)} \end{aligned} \tag{11}$$

Seen from Figure 6, the current ripple is the current changes during t_0 to t_2.

$$\Delta i = k_1(t_2 - t_0) = \frac{(b_1^2 - k_1 k_2) k_2 T + 2b_1(k_1 - k_2)\alpha}{2(b_1^2 - k_2^2)} \tag{12}$$

When $\alpha = \alpha_1$ in Eq. (12), the power amplifier works in state of critical failure, and the current ripple is

$$\Delta i = \frac{k_1 k_2 T}{k_1 + k_2} \tag{13}$$

When $\alpha = A = b_1 T/2$ in Eq. (12), the improved three-level PWM switching power amplifier turns to be a two-level PWM switching power amplifier, and the current ripple becomes

$$\Delta i = k_1 t_2 = \frac{(b_1^2 - k_1 k_2) k_2 T + b_1(k_1 - k_2) b_1 T}{2(b_1^2 - k_2^2)} = \frac{k_1 T}{2} \tag{14}$$

b. Saw-tooth Wave

When the carrier used the saw-tooth wave, the range of α which would result in the failure of the improved three-level PWM modulation is

$$\alpha_1 < \alpha < A \tag{15}$$

Where $\alpha_2 = \dfrac{k_2 T(k_1 + b_2)}{k_1 + k_2}$, b_2 is the slope of saw-tooth wave. When the frequency of saw-tooth wave is the same as the symmetric triangle's, then $b_2 = b_1/2$.

When α satisfies Eq. (15), the current error signal and the carrier U_{t1} will intersect, resulting in the output current waveform presents "/‾\" shape shown in Figure 7 which is very close to the current waveform shown in Figure 5 (b). Its work process can be divided into three stages, i.e., the current rising stage (ab), the circulating stage(bc), and the current falling stage(cd).

The equations of failure waveform shown in Figure 7 can be expressed as follows:

$$\begin{cases} i(t_1) = -k_1 t_1 + i(t_0) \\ i(t_1) = b_2 t_1 \end{cases} \tag{16}$$

$$\begin{cases} i(t_2) = k_2(t_2 - t_1) + i(t_1) = k_2(t_2 - t_1) + b_2 t_1 \\ i(t_2) = \alpha - b_2(T - t_2) \end{cases} \tag{17}$$

$$\begin{cases} i(T) = k_1(T - t_2) + i(t_2) = k_1(T - t_2) + \alpha - b_2(T - t_2) \\ i(T) = i(t_0) \end{cases} \tag{18}$$

Where t_0, t_1 and t_2 are respectively the time points of a, b and c.

Solved Eqs. (16)~(18), we can obtain that：

$$t_1 - t_0 = \frac{Tk_2(b_2 - k_1) + \alpha(k_1 - k_2)}{2(b_2 - k_2)} \tag{19}$$

It can be seen from Figure 7 that the current ripple is the current changes of t_0-t_1

$$\Delta i = k_1(t_1 - t_0) = \frac{Tk_2(b_2 - k_1) + \alpha(k_1 - k_2)}{2(b_2 - k_2)} \tag{20}$$

When $\alpha = \alpha_2$ in Eq. (20), the power amplifier works in state of critical failure, and the current ripple is

$$\Delta i = k_1 t_1 = \frac{k_1 k_2 T}{k_1 + k_2} \tag{21}$$

When $\alpha = A = b_2 T$ in Eq. (20), the three-level PWM switching power amplifier turns to be a two-level PWM switching power amplifier, and the current ripple is

$$\Delta i = k_1 t_1 = \frac{Tk_2(b_2 - k_1) + b_2 T(k_1 - k_2)}{2(b_2 - k_2)} = \frac{k_1 T}{2} \tag{22}$$

c. Comparison of the Failure Properties of Three-level PWM Switching Power Amplifier with Two Carriers

It is shown from the above analysis that the effects of offset voltage settings deviation α on the three-level PWM modulation with different carriers are different.

In aspect of failure range, the failure range of the improved three-level PWM switching power amplifier with symmetrical triangular carrier is $\alpha_1<\alpha<A$; the failure range of the improved three-level PWM switching power amplifier with symmetrical triangular carrier is $\alpha_2<\alpha<A$. Compared with k_1 and b_1, k_2 is very small, and $b_2=b_1/2$, so

$$\alpha_1 = \frac{k_2 T(b_1^2 + k_1 k_2)}{2b_1(k_1 + k_2)} \approx \frac{k_2 T b_1}{2k_1} \tag{23}$$

$$\alpha_2 = \frac{k_2 T(k_1 + b_2)}{k_1 + k_2} \approx \frac{k_2 T(k_1 + b_2)}{k_1} = k_2 T + \frac{k_2 T b_2}{k_1} \tag{24}$$

Obviously, $\alpha_1=\alpha_2-k_2T$.

In aspect of current waveform, the symmetrical triangular carrier's three-level PWM switching power amplifier output current presents "~" shape, while the saw-tooth wave's presents "/‾\" shape.

In aspect of the effect of α on the current ripple, the effect can used the coefficient of α in Eq. (12) and Eq. (20) to measure, their ratio equals about 1.

In aspect of the effect of controller parameters, k_1 is the product of the current rising slope and k_p, and k_2 is the product of the current circulating slope and k_p, and known from Eq. (23), the molecules containing k_2, the denominator contains k_1, leading to the effects of k_p just offset, so the change of k_p has little influence on the failure range of the symmetric triangular carrier's power amplifier. However, Eq. (24) has an additional item—k_2T, so the change of k_p has an obviously effect on the failure range of saw-tooth wave carrier's power amplifier.

Simulation and Experiment

a. Simulation Analysis

In order to verify the correction of the proposed failure mechanism, according to the above improved three-level PWM switching power amplifier operating principle, a simulation model shown in Figure 8 is established in Matlab/Simulink. Some parameters in Matlab/Simulink are shown in Table 1.

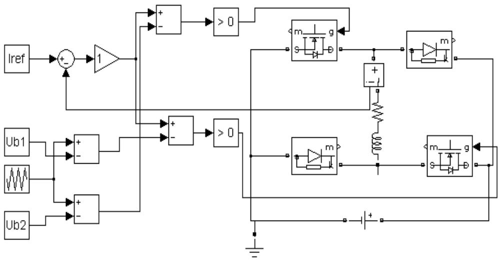


Fig. 8 Simulation model

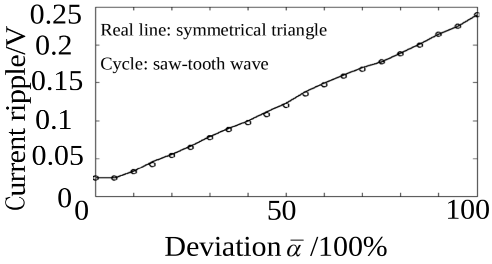


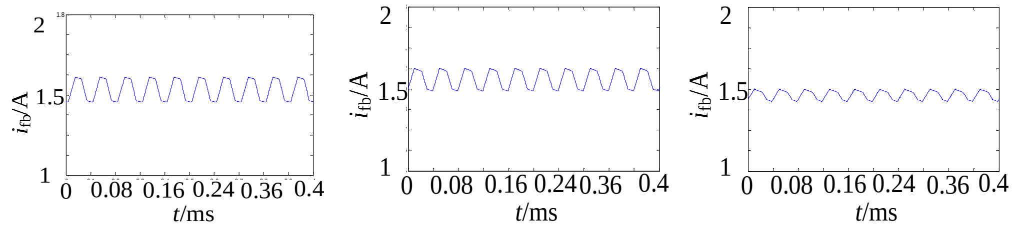
Fig. 9 Relationship between $\bar{\alpha}$ and current ripple

Tab.1 Power amplifier parameters

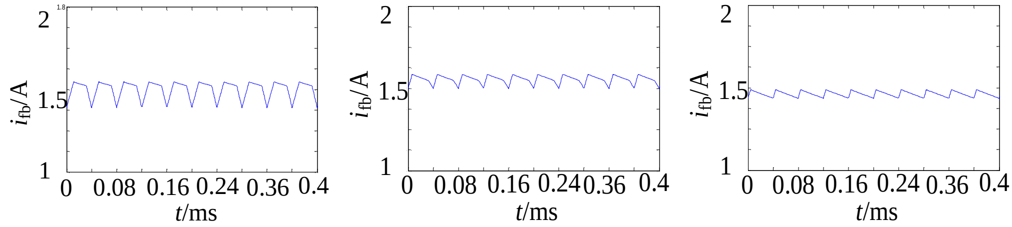
parameters	values
inductance	10.74mH
resistance	1.9Ω
switching frequency	25kHz
voltage source	48V

Figure 9 shows the relationship between offset voltage deviation α and current ripple when k_p= 1, in which x axis adopts the relative deviation $\bar{\alpha}$ that is the ratio of the absolute value of offset voltage deviation and the correct offset voltage. Whatever which carrier is used, the current ripples are proportional with $\bar{\alpha}$. When $\bar{\alpha}$ =0, current ripples are minimum, and when $\bar{\alpha}$ = 100%, current ripples are maximum.

Figure 10 shows the two carriers' improved three-level PWM switching power amplifier output current simulation waveform when $\bar{\alpha}$ is 50%, k_p sets 1, 10 and 20. Seen from Figure 10, increasing k_p can remarkably reduce the failure phenomenon of saw-tooth carrier's three-level PWM switching power amplifier, but to the symmetrical triangle carrier's the effect is not obvious.



Symmetrical triangle



Saw-tooth wave

k_p=1 k_p=10 k_p=20

Fig.10 Effect of k_p on failure

b. Experimental Results and Analysis

To further verify the failure mechanism, an improved three-level PWM switching power amplifier is built based on DSP TMS320LF2812. The main circuit is half-bridge structure consisted of the switch IRF540 and the diodes STPS20100CT. The current feedback signal is obtained by current sensor. The other parameters are shown in Table 1.

Figure 11 shows the output current waveforms and the driving signal waveform of improved three-level PWM switching power amplifier. The results showed that when power amplifier employs improved three-level modulation, the duty cycle U_{G1} is 100%, and the duty cycle of U_{G2} is very small, so the output current presents saw-tooth waveform, and the current ripple is close to the theoretical value.

Figure 12(a) shows the failure phenomenon and the driving signal waveform of the symmetrical triangle carrier's improved three-level PWM switching power amplifier. The current waveform presented "~" shape as the same as shown in Figure 6, and the current ripple was much larger than the one in Figure 11. Figure 12(b) is the failure phenomenon and the driving signal waveform of the saw-tooth wave carrier's improved three-level PWM switching power amplifier. The current waveform presented "/‾\" shape as the same as shown in Figure 7, and the current ripple was much larger than the one in Figure 11 either.

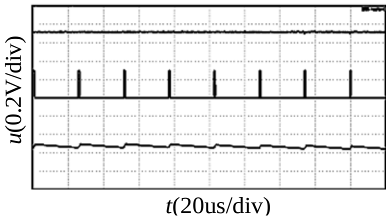
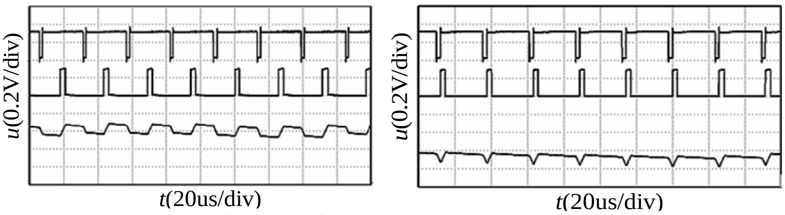


Fig.11 Three-level PWM current waveform



(a) Symmetrical triangle (b) Saw-tooth wave

Fig.12 Three-level PWM failure waveform

Conclusions

The failure phenomenon of the improved three-level PWM switching power amplifier in some experiments is introduced. Through an in-depth analysis of the principle of the improved three-level PWM switching power amplifier, the failure reason and failure mechanism was proposed. The results of simulations and experiments showed that the deviation of offset voltage caused the modulation failure. For different carriers, failure mechanisms and the output current waveforms are different.

Based on the conclusions of this paper, the following measures are proposed to decrease or avoid the failure of the improved three-level PWM switching power amplifier:

(1) Set the offset voltage as $\alpha < 0$. It is easy to implement, but it will bring up great static error;

(2) Use the digital circuit. Digital circuit can achieve accurate offset voltage settings. For the current ripple amplitude of improved three-level PWM switching power amplifier is very small, it will require AD converter with very high precision;

(3) Employ saw-tooth wave carrier. Appropriate increasing k_p can effectively reduce the failure of the improved three-level PWM switching power amplifier, its disadvantage is that k_p can not be too large, otherwise it will cause instability of power amplifier.

Acknowledgment

Project was supported by The National High Technology Research and Development of China(863 Program) (2006AA05Z201) and National Natural Science Foundation of China (10772160).

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