切換式D類音頻放大器之開發

Development of A Switch Mode Class-D Audio Amplifier

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Abstract

This special topic develops a switch-mode class-D audio amplifier. To provide AC output voltage to the loudspeaker, a single-phase full-bridge inverter with proper selected LC low-pass filter is established. Owing to the range of audio frequency being 20Hz to 20kHz, the switching frequency is chosen to be 250kHz to obtain enough switching times. However, traditional metal-oxide-semiconductor field-effect transistor (MOSFET) cannot operate under high switching frequency. Hence the silicon carbon (SiC) MOSFET is adopted to construct the power circuit. Next, the bipolar switching strategy is used to generate the AC output. Through the established shifting approach, the control force is shifted upward and downward, respectively. Then the two resulted signals are compared with the carrier wave, which provides proper dead time to avoid short-circuit between the leg upper and lower switches.

To test the estabilished H-bridge inverter, the input signals containing constant frequencies, white noise and CD player output are used. Under open-loop condition, the inverter powered by a DC source with 48V can provide proper outputs to the loudspeaker. Then the voltage closed-loop control with proportional-integral (PI) controller is adopted to observe the tracking performance. To further enhance the arbitrary waveform tracking closeness, the voltage robust tracking error cancellation controller (VRECC) is added. Although very close voltage command tracking is still not achieved, significant improvement can be observed from the measured results. Further improvement may be feasible by increasing the switching frequency using the suited generator ICs.

Keywords: Class-D audio amplifier, full-bridge inverter, SiC MOSFET, bipolar, PI controller, robust control.

摘 要

本專題旨在開發一切換式 D 類音頻放大器。為提供交流輸出電壓於音箱，建立一單相全橋變頻器，並選擇適當之電感電容低通濾波器。因音頻範圍介 20Hz 至 20kHz，選擇切換頻率為 250kHz 以獲得足夠切換次數。然而，傳統金氧半場效電晶體無法操作於高切換頻率，因此採用碳化矽金氧半場效電晶體建構電力電路。再者，使用雙極性切換策略產生交流輸出電壓，透過所建移位方法，控制力可分別上下移位再與載波進行比較，藉此產生合適之死時以防範上下臂短路發生。

為測試所建全橋變頻器，使用之輸入訊號包含定頻、白噪音及 CD 播放器輸出。於開迴路情形下，可藉 48V 直流電源供給變頻器，提供合適之輸出於音箱。接著採用含比例-積分控制器之電壓閉迴路控制，觀察其追控表現。為更加增進任意波形追控之緊密，加入一電壓強健追控誤差消除器，雖仍無法達成緊密之電

壓命令追控，經量測結果可觀察其明顯改善。而透過適當之產生器積體電路增加切換頻率，亦可進一步改善。

使其於誤差產生下，增加輸入訊號。雖使用比例-積分控制器無法使輸出電壓於全頻下皆具良好追控，由結果顯示其對稱且低失真之波形，因此較不影響於音箱之音訊品質。

關鍵詞： D 類音頻放大器、全橋變頻器、碳化矽金氧半場效電晶體、雙極性、比例-積分控制器、強健控制。

Introduction

Audio amplifiers are used in various plants such as radio wave transmitter, shaker and audio system, which magnifies the audio signals with larger power to supply the load. Depending on the application requirement, the bandwidth should be properly chosen. Basically, it can be classified as linear-mode and switch-mode amplifiers [1-6]. The former is mostly the class-AB amplifier, while the latter is class-D amplifier established by switch-mode inverter. Owing to the comparatively high-efficiency capability of class-D amplifier, the size of power device and even the heatsinks can be reduced. Hence it is widely adopted nowadays.

A class-D amplifier based audio system is composed of a pickup device, a switch-mode (or pulse-width modulation, PWM) inverter, an output low-pass filter and a loudspeaker [7]. The audio signal is compared with the carrier wave to generate switching signal. Then the PWM inverter powered by the DC source produces the amplified audio signal. Through a low-pass filter, the output voltage powers the loudspeaker to yield high-fidelity sound. However, the operating performance of the audio system is influenced by many issues, such as dead time setting [8], distortion caused by junction temperature of switching devices [9], noise of source [10,11], insufficiently high PWM carrier, and switching speed of power device, etc.

To possess a high-performance audio system, the single-phase PWM inverter is a key component affecting the output waveform and hence the audio quality. And the switching strategy applied to the inverter may result in different output performance. Some control and switching strategies for the audio system have been presented including delta-sigma modulator [12], sliding mode control [13], hysteresis control [14], random switching PWM [15] and constant switching frequency PWM [16-18], etc. The hysteresis control has the fastest tracking performance, but the output low-pass filter is hard to design for the PWM inverter. As to the random switching method, the output harmonics can be uniformly distributed. However, the analog circuit realization is complicated. For simplicity, the bipolar switching strategy with voltage-loop direct duty ratio PWM control is adopted. The designed control scheme is first verified under various fixed-frequency signals and white noise with suited frequency range. Then the waveform tracking behavior for the CD player output is observed experimentally. Rather good waveform tracking characteristics by applying the proposed simple robust control are achieved.

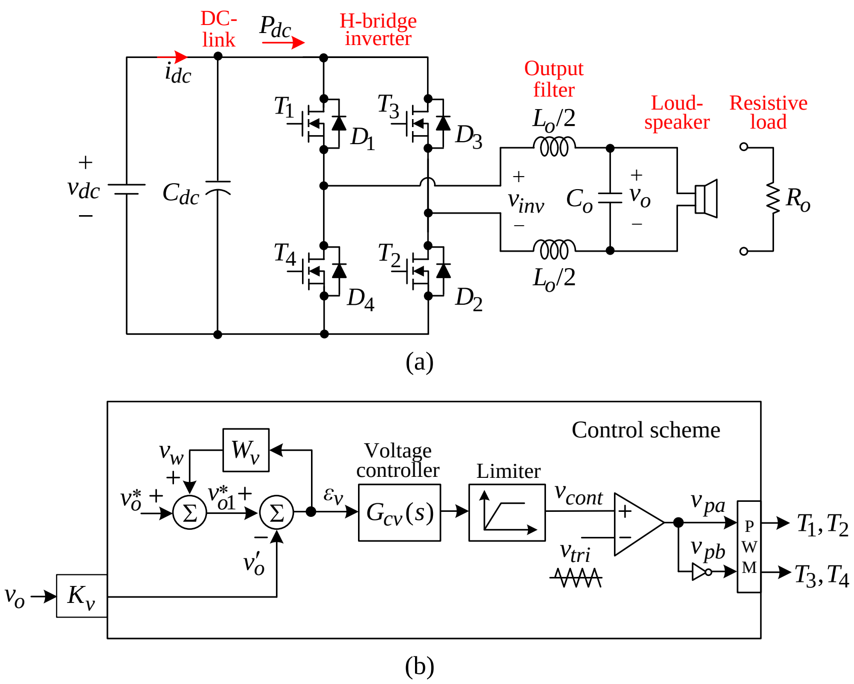


Fig. 1. The established Class-D audio amplifier: (a) power circuit; (b) control scheme.

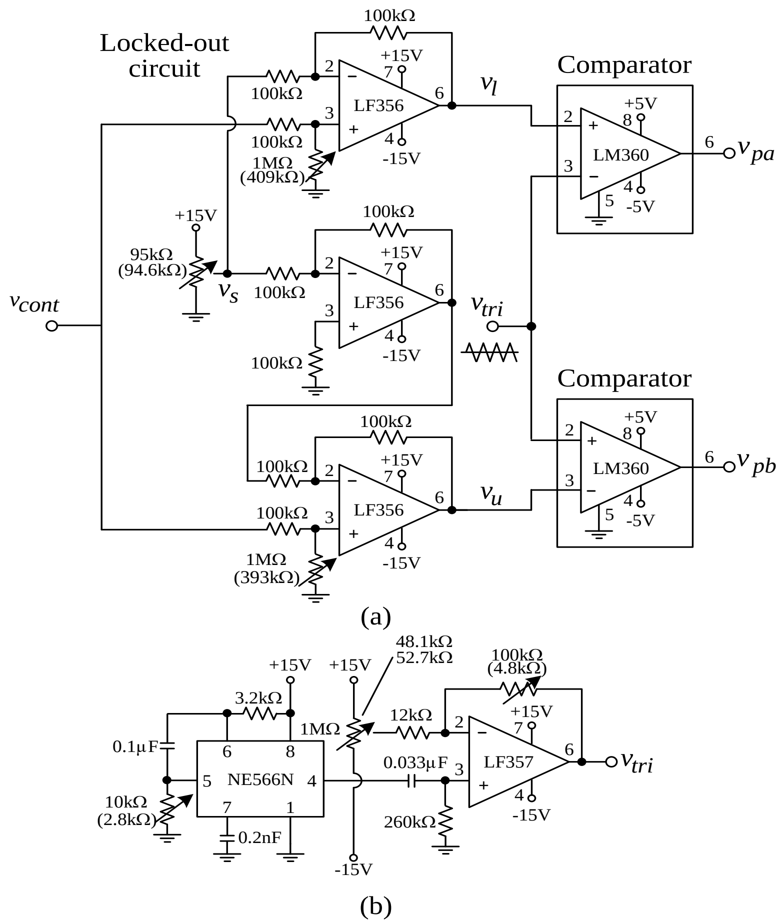


Fig. 2. Analog implementation circuit of open-loop control scheme: (a) dead-time setting; (b) triangular carrier wave generator.

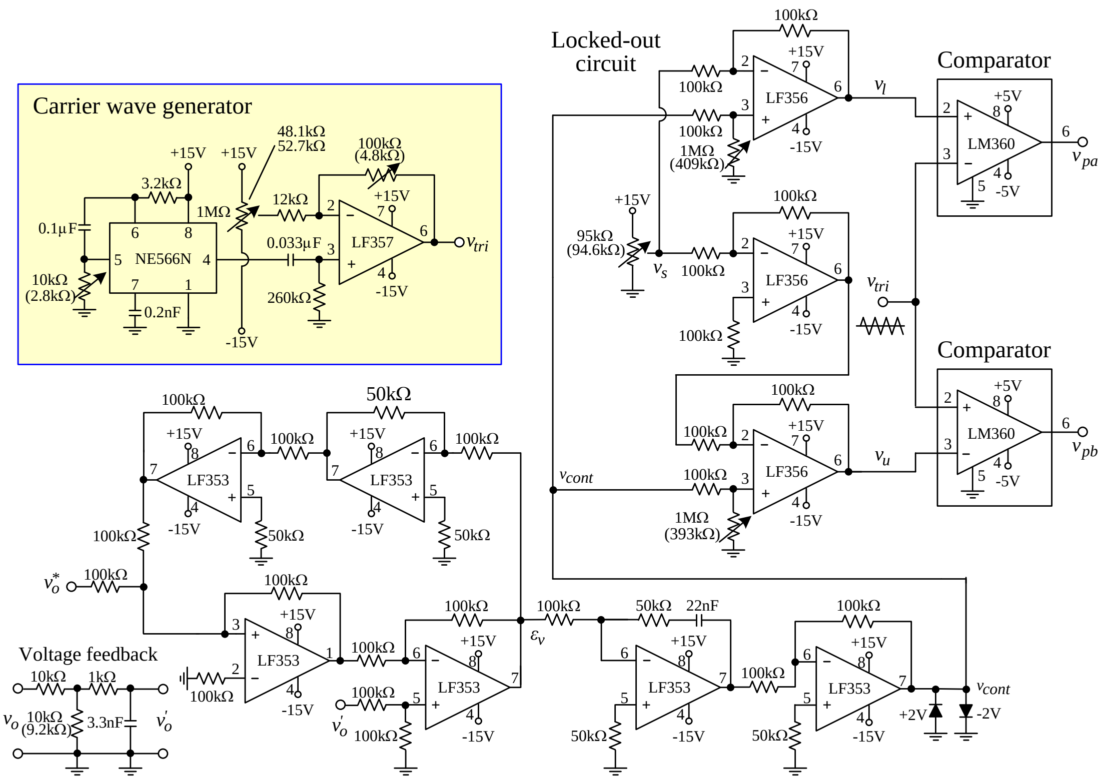
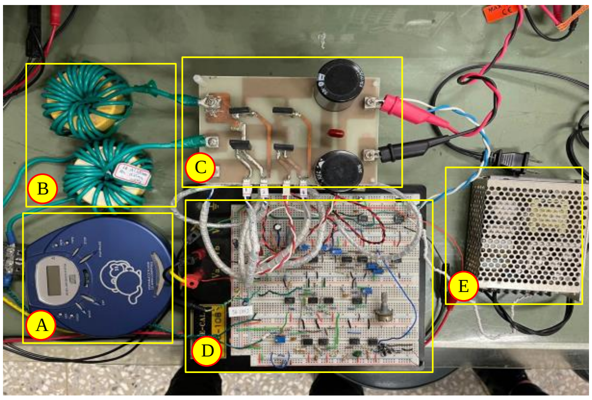
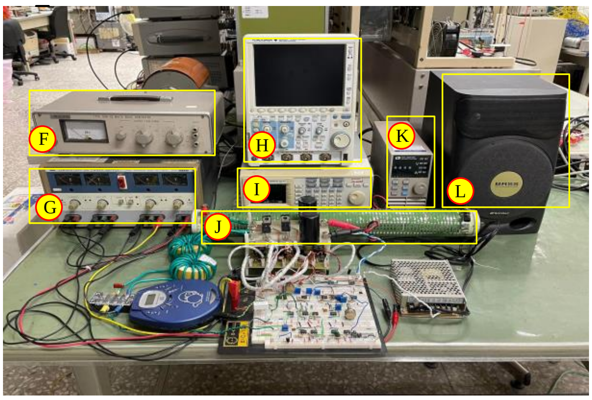


Fig. 3. Analog circuit realization corresponding to Fig. 2(b).



- (A) CD player
- (B) Energy storage inductor (filter)
- (C) Power circuit of full-bridge inverter
- (D) Analog circuit realization of the control scheme to the full-bridge inverter
- (E) Power supply of gate driver



- (F) White signal generator
- (G) Power supply of analog circuit
- (H) Scope for the measurement
- (I) Function generator
- (J) Resistive load
- (K) Power supply to the DC-link voltage
- (L) Loudspeaker

Fig. 4. Photos of the Established Class-D Audio Amplifier

Measured Results

A. Resistive Load

(a) Constant frequencies from function generator

With DC-link voltage of 48V, Fig. 5.1 shows the measured results of the established full-bridge inverter under different constant frequency commands with voltage feedback controller only. Under lower frequency, the voltage is well-tracking. However, as the frequency is increased, the low modulation index makes the output voltage reduced and distorted.

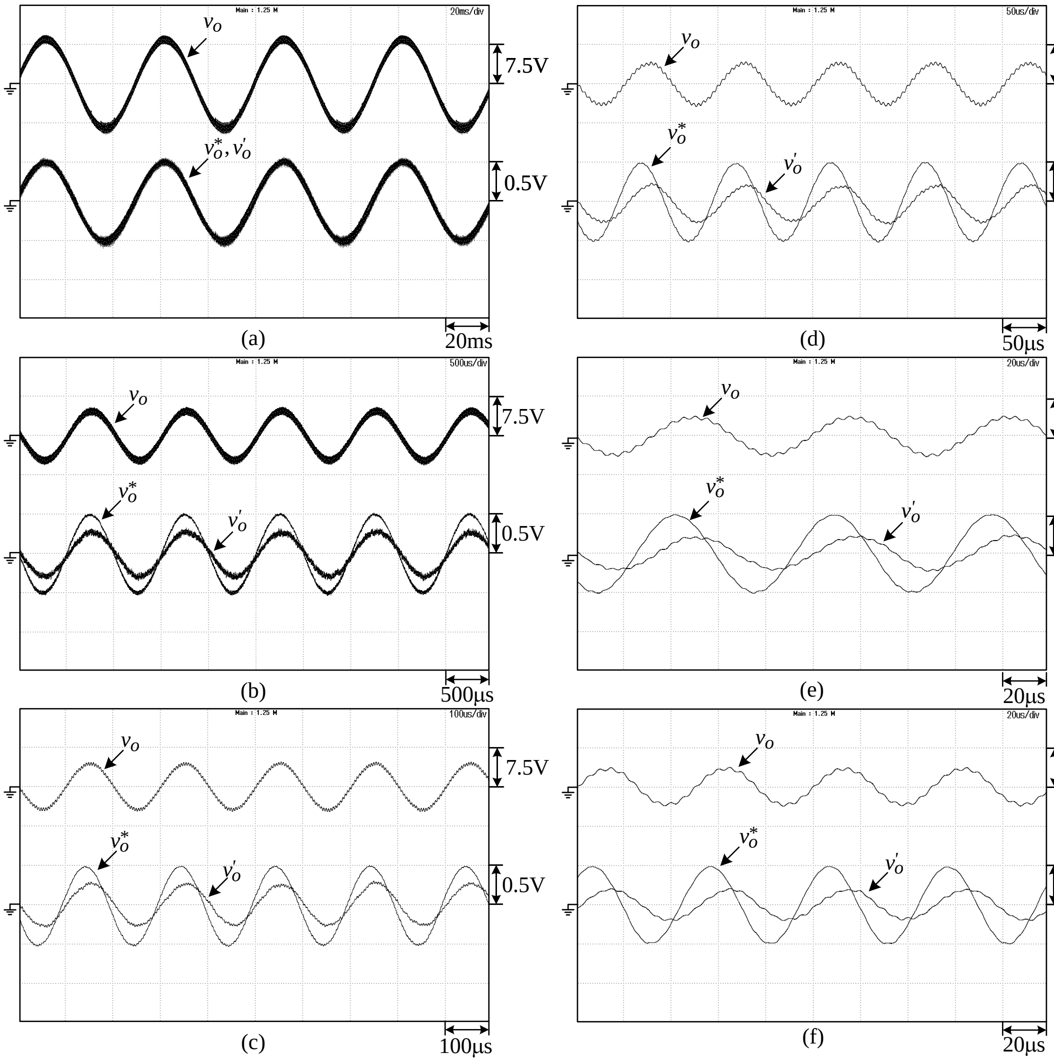


Fig. 5.1. Measured v_o and (v_o^* , v_o') of the established full-bridge inverter under $R_o = 10\Omega$ and $v_{cont} = 0.5\sin(2\pi f_1 t)$ without voltage robust controller: (a) $f_1 = 20\text{Hz}$; (b) $f_1 = 1\text{kHz}$; (c) $f_1 = 5\text{kHz}$; (d) $f_1 = 10\text{kHz}$; (e) $f_1 = 15\text{kHz}$; (f) $f_1 = 20\text{kHz}$

Fig. 5.2 shows the measured results of the established full-bridge inverter under the same cases but with added VRECC. Similar phenomenon can be observed under lower frequency. However, slightly improved output voltage waveforms at higher frequency command can be seen compared to the ones in Fig. 5.1. Notice that the weighting factor of VRECC is properly turned. As the factor is increased more, the system will be diverged, which cannot maintain the waveform shape.

(b) CD player output

Next, the command signal is changed to the one from CD player. Fig. 5.3 shows the measured (v_o^*, v_o') of the established H-bridge inverter without and with the adopted VRECC. Because it is hard to capture the same waveforms, the tracking error (or the empty area between command and feedback) is observed. As the results, the one with VRECC has small tracking error.

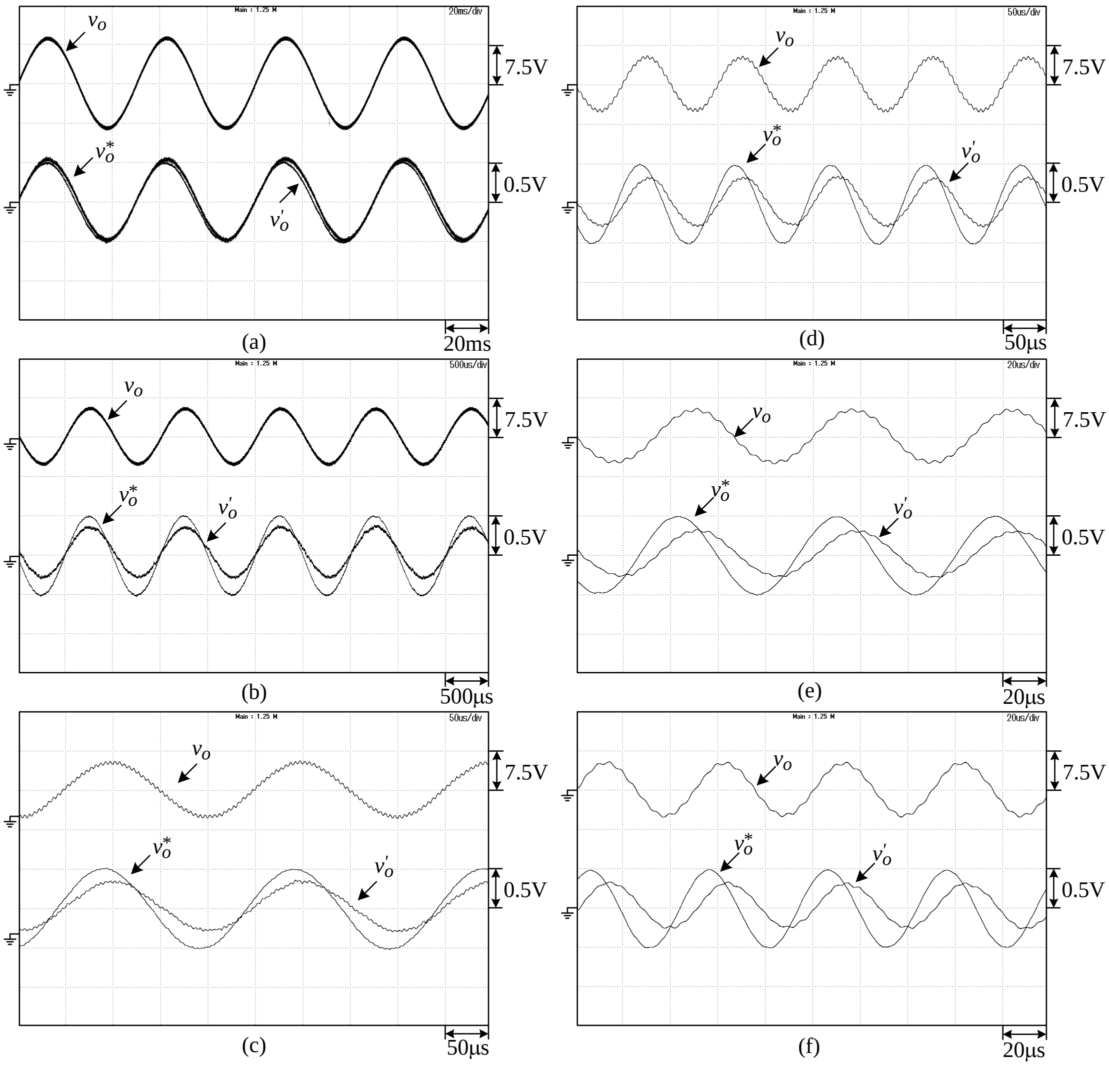


Fig. 5.2. Measured v_o and (v_o^*, v_o') of the established H-bridge inverter under $R_o = 10\Omega$ and $v_{cont} = 0.5\sin(2\pi f_1 t)$ with voltage robust controller: (a) $f_1 = 20\text{Hz}$; (b) $f_1 = 1\text{kHz}$; (c) $f_1 = 5\text{kHz}$; (d) $f_1 = 10\text{kHz}$; (e) $f_1 = 15\text{kHz}$; (f) $f_1 = 20\text{kHz}$.

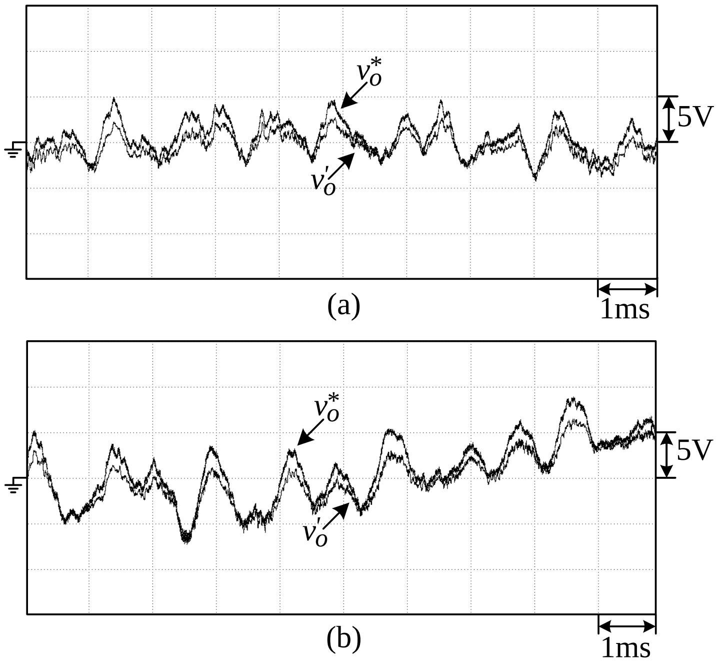


Fig. 5.3. Measured (v_o^*, v_o') of the established H-bridge inverter with audio signal from CD player: (a) without VRECC; (b) with VRECC.

B. Loudspeaker

Here, the output resistive load is changed to the loudspeaker and only the audio signal from CD player is used to see the tracking performance. Fig. 5.4 shows the measured results without and with the VRECC. Similar phenomenon is seen.

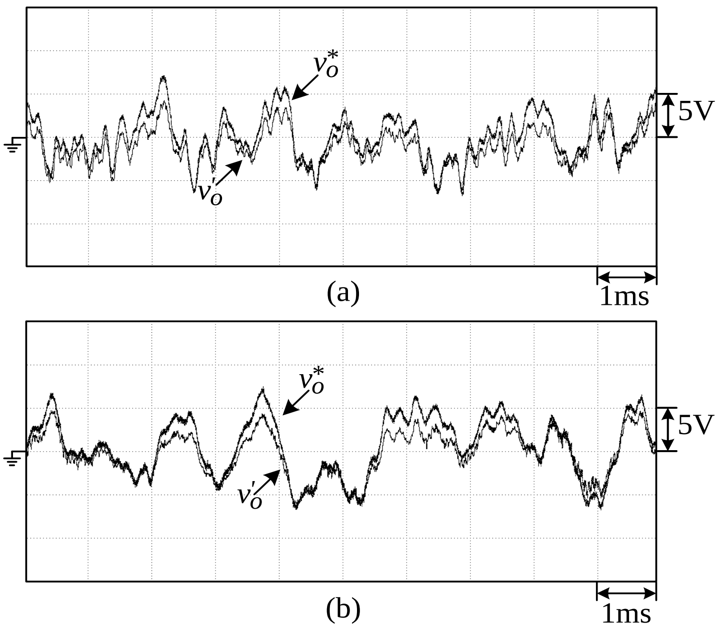


Fig. 5.4. Measured (v_o^*, v_o') of the established H-bridge inverter with audio signal from CD player using loudspeaker: (a) without VRECC; (b) with VRECC.

5. Conclusion

This special topic has developed a Class-D audio amplifier constructed by the full-bridge inverter. Using the adopted bipolar SPWM strategy with proper shifting approach for dead time setting, some measured results under open-loop condition are given to verify the correct operation with different applied audio signals. Then, the voltage feedback loop is added to observe the tracking responses. Furthermore, by adopting the VRECC, the tracking error can be obviously reduced. Despite that the output voltage waveforms are reduced at higher frequency command, they are not distorted, which will not affect the audio quality seriously. Overall speaking, the established full-bridge inverter can supply proper output voltage to the loudspeaker.

Further improvement can be conducted by the following strategies: (i) optimization on dead time setting; (ii) higher switching frequency; (iii) proper selection on switching devices; and (iv) addition of current control loop.

6. 心得

在這次專題中，因為實驗室近幾年沒有做過相關的專題，所以很多時候要靠我們一步一步去摸索。而且剛開始做專題的時候很多事情都不是很熟悉，用了一段時間來學會，所以遇到了很多困難，很多不一樣的情況都發生過，例如：電路接觸不良、元件損壞等等，導致進度很緩慢，不過幸好盧旻澤學長給了很多建議還幫助我們解決了很多問題。

雖然在做專題的時候遇到很多挫折，僅僅是一個三角波產生電路就已經用了差不多四五種方法去做，當中不斷地失敗，不斷地重複嘗試，在專題中一直循環這個過程，盡管這個過程令人很沮喪，但在這些過程中學到了非常多實用的知識與技巧，最大的收獲是學會了發現問題和怎樣找到解決的方案。

最後很感謝廖教授和盧旻澤學長的指導，每當遇到問題時學長都會不厭其煩地給我們解釋和幫我們解決問題。而廖老師在我們卡住的時間一直鼓勵著我們慢慢做，相信著我們一定能夠做出來，同時也給了很多建議和關心我們的前途。