A Current Controlled Two Channel Audio Amplifier Using Three Phase Full Bridge Circuit

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Abstract

This paper presents a class-D stereo audio amplifier that controls directly the current of speakers using three phase full bridge circuit. And a new switching method for the current control of the amplifier is proposed. The proposed switching strategy is an improved version of the dead time minimization method, which can reduce current intermittence that commonly occurs with the conventional dead time minimization method whenever the current changes polarity. Dead time is not always adapted in the proposed method, which makes it different from the conventional practice of applying dead time in every current polarity changing point. In this paper, the specific strategy for the stereo operation is discussed. With the experimental results, usefulness of the control strategy is confirmed.

1. Introduction

In the most cases of the audio amplifier that needs wide bandwidth, the linear amplifier is used for the main power amplification. The linear amplifier, however, has a very low efficiency. Nowadays, the class-D amplifier is widely adopted in some audio amplifier applications in order to overcome low efficiency. As the class-D audio amplifier has a discrete switching operation, the high-dynamic characteristics of the switching method are required.[1-3]

For high performance, high order passive filter, multiple control loops and modern control theory are adopted in some cases, such as a sliding mode control. Sometimes, the small linear amplifier is used to fill up the dynamic characteristics added on the class-D amplifier that is a main power amplifier. For some applications of audio amplifier, however, which does not need high fidelity, it is desirable to be able to construct by low cost, compact size and low power consumption.[4, 5]

In this paper, a new switching method for the current control of the class-D amplifier is proposed, and a scheme of stereo operation using three-phase full-bridge circuit configuration is presented, which has a DC source and six switching devices. The proposed amplifier is controlled with only a current control loop and the switching harmonics included in the output current are filtered by a series filter inductance. Since the main circuit configuration and the control circuit are very simple, the proposed amplifier can be constructed in a compact size.

The detailed algorithm of the proposed switching method is discussed in this paper, including the independent actions of the switching devices of the upper arm and lower arm according to the current polarity and the strategy of driving with the three-phase full-bridge circuit as a stereo amplifier.

Finally, experimental results of the proposed class-D stereo audio amplifier are presented and discussed.

2. A Current Controlled Two Channel Audio Amplifier Using Three Phase Full Bridge Circuit

2.1 Configuration of the Main Circuit

Fig. 1 shows the main circuit of the proposed amplifier. It is a conventional three phase full bridge circuit. However, the load configuration is not a normal three phase configuration. Two speakers are connected at channel A-N and channel B-N through the inductors to filter the switching harmonics. Therefore, two switching devices can be reduced in comparison with conventional two channel stereo class-D amplifier, which uses full bridge circuit. Even though two channels produce stereo effects, the sound level of each channel is alike. Therefore, the speakers are connected with the reverse polarity each other to reduce the load of common phase N. In this case, of course, the reference of each channel has each other polarity.

2.2 Direct Current-Control Method of Speaker

In most audio amplifiers, the voltage of speaker is controlled. In the proposed amplifier, however, the current which flows through speaker is controlled. If the speaker is equivalently presented by a series RL circuit with variable back electromotive force, which is generated by the elasticity of speaker, we expect that the proposed method of direct current control of the speaker could amplify the original sound more correctly than the voltage control method. As the main circuit of the proposed amplifier uses three phase full bridge circuit, the reference current of the phase N must be built up and it can be easily generated by a reference generator as shown in Fig. 2. Since one of speaker is connected with reverse polarity, the reference signal is also to be inverted.

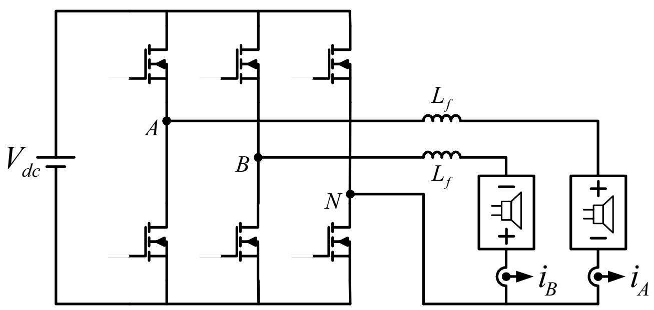


Fig. 1. Configuration of the proposed amplifier

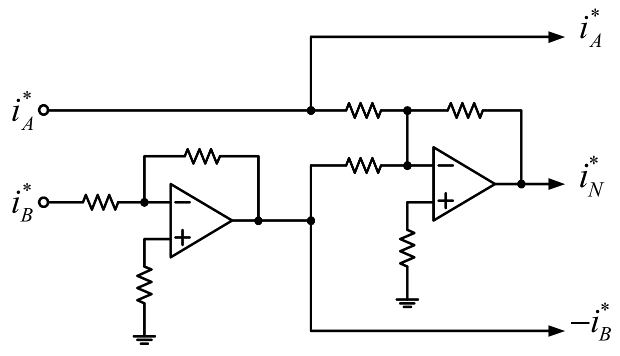


Fig. 2. Reference signal generator

3. A New Switching Strategy for the Current Control

3.1 Proposed Switching Strategy

Fig. 3 shows the basic diagrams of the proposed switching strategy, where I_p and I_n represent current polarities, and G_p and G_n are switching signals of the upper arm and lower arm, respectively. Basically, the gate signal G_p for the upper arm is applied when the current is positive and the gate signal G_n for the lower arm is applied when the current is negative. Thus, we have to know the polarity information of the current. Therefore, the dead time is not needed except instant of current polarity change. In order to prevent the arm short at the instant of current polarity change, dead time is needed. Since the dead time is prepared from the negative edge of the last gate signal G_n instead of the negative edge of the flag signal I_p that means the current is positive, the applied dead time duration should be either less than the prepared dead time or zero. It can be seen that the applied dead time is zero in the case of Fig. 3. Of course, sometimes the dead time will be applied at once in every polarity changing instant of the current. However, at that time the current is almost zero and the dead time effect is negligible. As a result, dead time compensation is no longer required while reducing the possibility of current intermittence and arm short in the proposed switching strategy. And it is very useful for the high frequency application as like class-D amplifiers.

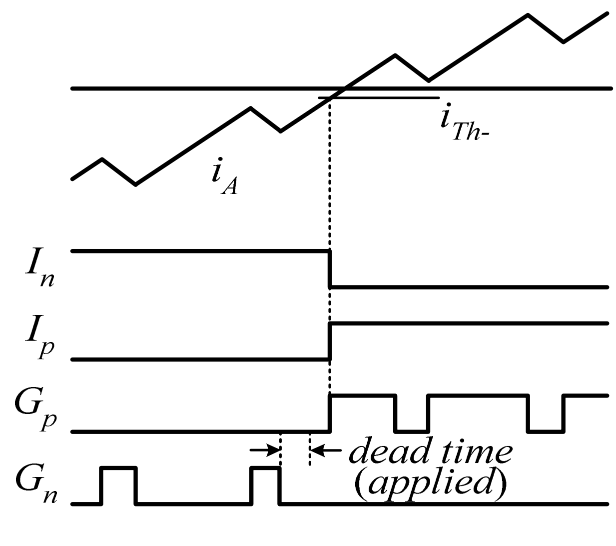


Fig. 3. Diagrams of the proposed method

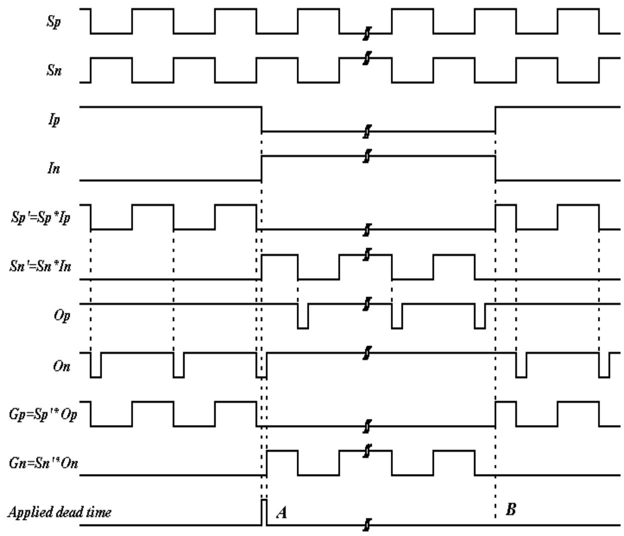


Fig. 4. Specific timing diagrams for the proposed switching strategy.

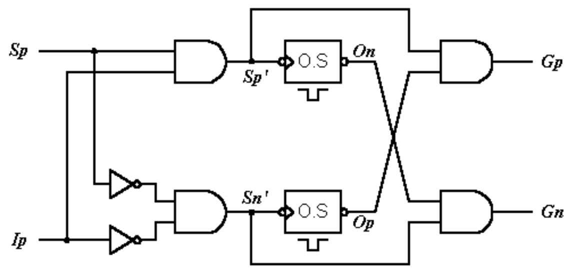


Fig. 5. An example circuit of the signal generation

3.2 Detailed Scheme of the Gating Signal Generation

The specific timing diagram for the generation of the proposed switching signal is presented in Fig. 4. After taking logic AND of $S_{p,n}$ and $I_{p,n}$, S_p' and S_n' can be derived. At every falling edge of these signals, the appropriate dead time O_p and O_n are applied. The gating signals of the upper and lower arms are then given by (1) and (2)

$$G_p = S_p * I_p * O_p \quad (1)$$

$$G_n = S_n * I_n * O_n . \quad (2)$$

In Fig. 4, it can be seen that the actual dead time is applied in Point A. The applied dead time is either the same as the prepared dead time or smaller. In Point B's case, it can be seen that the actual dead time is not applied. In many cases, the dead time has not been applied.

Fig. 5 shows an example circuit generating the gating signals. It can be constructed simply with some additional ICs on the typical gating signal generator of conventional switching method with dead time.

3.3 Characteristics of the Proposed Method

The characteristics of the proposed switching strategy is analyzed for the passive RL loads.

If the increasing ratio and decreasing ratio of the current are similar in the short duration near the polarity changing instant, (3) is satisfied, as shown in Fig. 6.

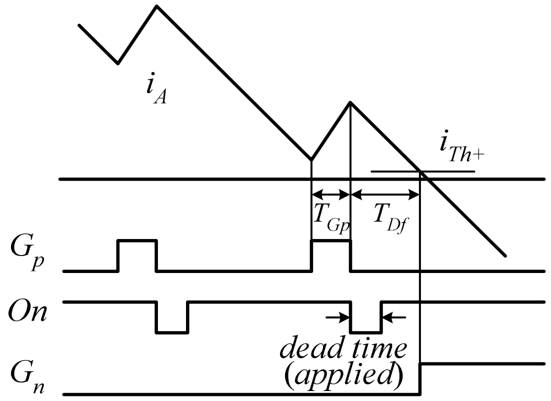


Fig. 6. Diagrams at the polarity changing instant

$$T_{Df} > T_{Gp} \tag{3}$$

where T_{Gp} is the duration of last gating signal for the upper arm and T_{Df} is the free-wheeling duration. At the end of free-wheeling duration, gating signal for the lower arm has to be applied for supplying negative current.

Thus, the sufficient condition that does not require dead time is given by

$$T_{Gp} \geq T_d \tag{4}$$

where T_d denotes the prepared dead time.

When the triangular PWM is adopted, assume that the displacement angle is α, T_{Gp} can be represented by

$$T_{Gp} = \frac{1 - a\sin\alpha}{2} T_s \tag{5}$$

where T_s denotes the sampling period, and a represent the modulation index of the inverter output. Equation (5) is not affected from the back EMF of active load. From (4) and (5) we get

$$a\sin\alpha \leq 1 - \frac{2T_d}{T_s}. \tag{6}$$

Thus, the sufficient condition that satisfy (6) for all range of $0 < a \leq 1$, is given by

$$\alpha \leq \sin^{-1}\left(1 - \frac{2T_d}{T_s}\right) \quad . \tag{7}$$

Finally, (7) is represented using the displacement power factor as follows:

$$\cos\alpha \geq 2\sqrt{\frac{T_d}{T_s}\left(1 - \frac{T_d}{T_s}\right)} \tag{8}$$

Fig. 7 shows the operating region without the adapted dead time, which is evaluated according to the modulation index and load displacement power factor in the case of the single phase inverter, which adopts triangular modulation. It can be seen that the dead time is not applied over the wide region at the instant of current polarity change. Therefore, the dead time compensation is no more needed and the possibility of arm short is almost eliminated.

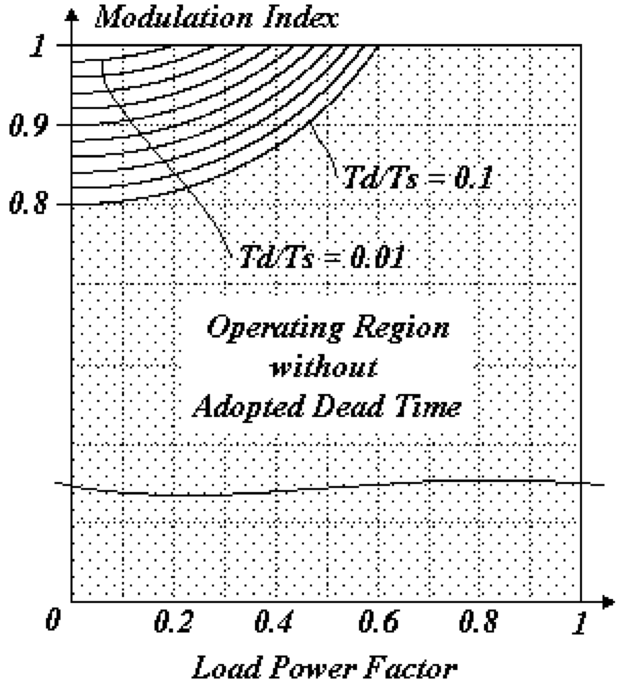


Fig. 7. Operating region without applied dead time

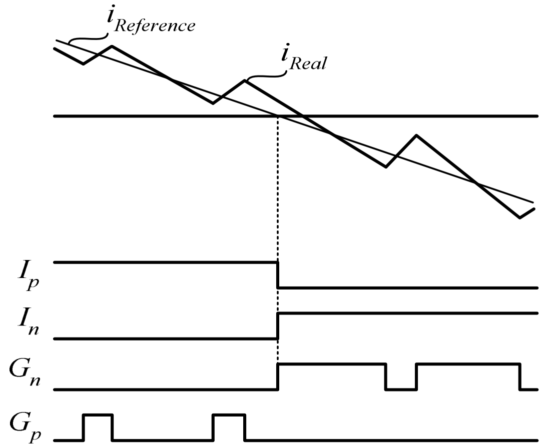


Fig. 8. The reference and real currents with the proposed gating signals in the current control system

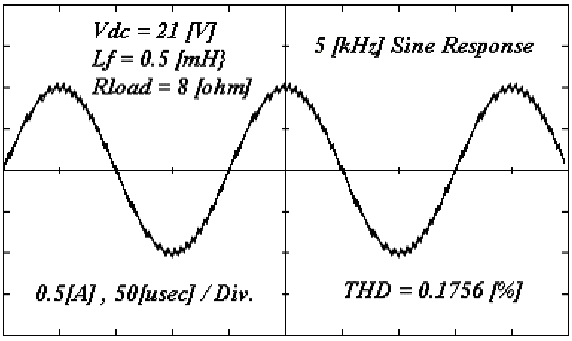
3.4 Usefulness of the Proposed Switching Strategy for the Current Control System

Current control is required in many applications of PWM power converters. Especially in PWM power converters, current control systems are essential for situations that demand the highest performance, such as in the vector control system of ac motor drives, the ac/dc PWM converter system, and in the active power filter system for high-quality source line condition.

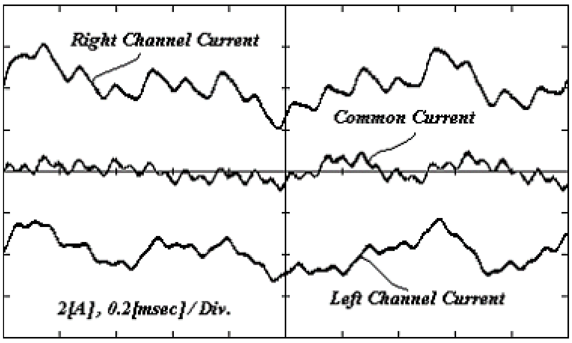
Existing current control systems can easily adopt the proposed switching strategy that uses the polarity information of the reference current instead of the real current. Fig. 8 shows the reference current and real current with gating signals in the case of the proposed switching strategy. It can be seen that current control should be performed correctly and efficiently to eliminate problems arising from real current detection.

4. Experimental Results

At first, simulation results for the proposed class-D amplifier, which is controlled by using the proposed switching strategy, are shown in Fig. 9. Fig. 9 (a) shows 5-kHz sine wave response.



(a) Sine-wave response



(b) Music reproduction response

Fig. 9. Simulation results for the proposed class-D amplifier using a novel switching strategy

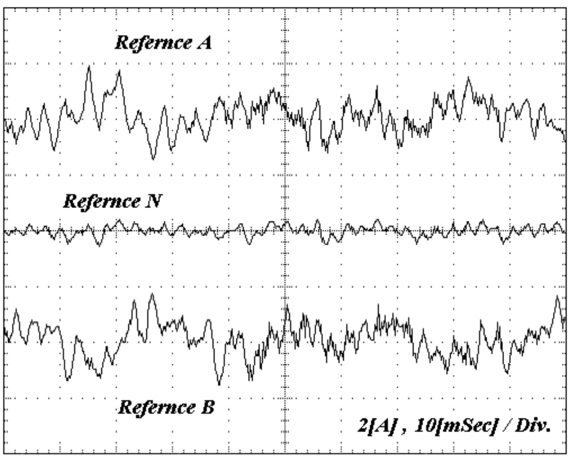


Fig. 10. Three phase reference signal waveforms

The current control is very well done by the proposed switching strategy although the reference frequency is very high. It is confirmed that the output current has only 0.1756-% of THD by the harmonic analysis of the 500-kHz range. And the simulated music reproduction is also well done with the proposed amplifier by using three phase full bridge circuit.

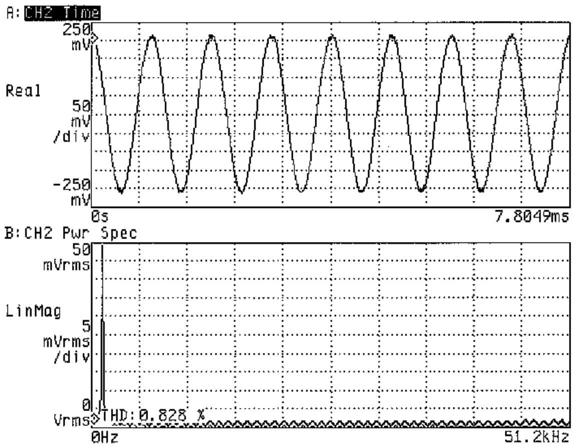
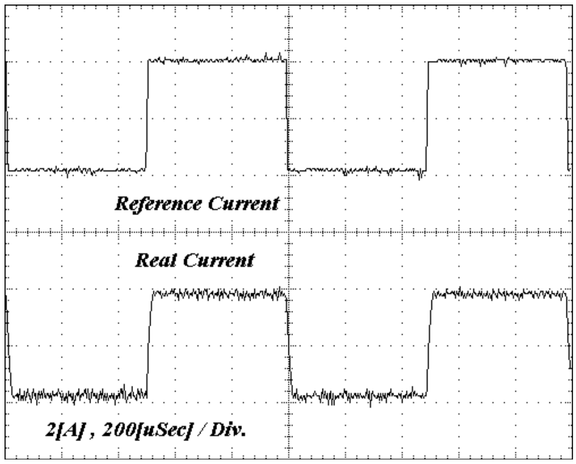
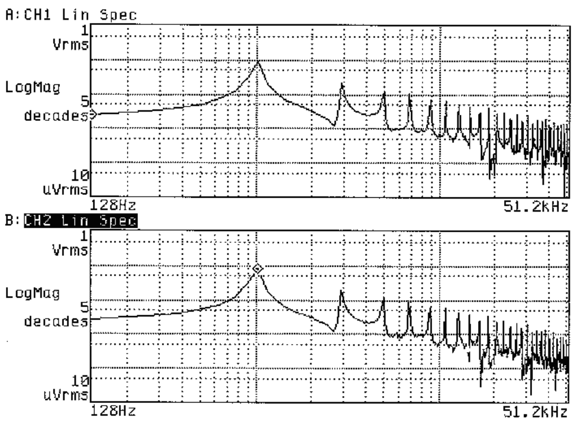


Fig. 11. Measuring result of total harmonic distortion for the 1-kHz sine wave

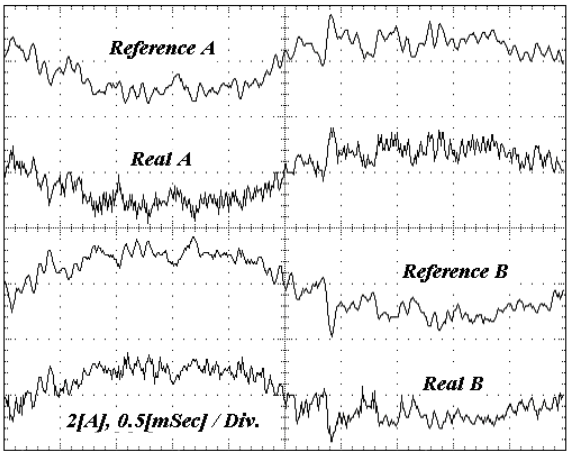


(a) Waveforms of the reference and real currents

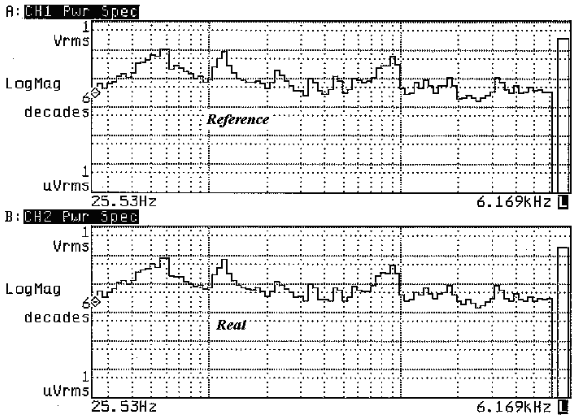


(b) Spectra of the reference and real currents

Fig. 12. Waveforms and spectra of the 1-kHz rectangular response



(a) Waveforms of the reference and real currents



(b) Octave analysis of the reference and real currents

Fig. 13. Waveforms and octave analysis of music sound reproduction

In order to verify the effectiveness of the proposed switching strategy in the application of a current-controlled class-D stereo amplifier using a three-phase full bridge circuit was built and tested.

Fig. 10 shows output waveforms of the reference signal generator presented in Fig 2. It can be seen that the signal level of the common phase N is a relatively small to other main two channels A and B.

Fig. 11 shows measuring result of total harmonic distortion for the 1-kHz sine wave outputs. 0.828-% of THD is measured in the frequency range to 51.2-kHz.

Fig. 12(a) shows the 1-kHz rectangular response and Fig. 12(b) shows the spectra of the reference and real currents, showing an excellent response over the audible frequency band.

Fig. 13(a) represents the music sound reproduction response. The octave analysis of the music sound signals shown in Fig. 13(b) confirmed that original sound was reproduced well, with the reference sound wave matching the real sound wave.

5. Conclusion

In this paper, a novel class-D stereo audio amplifier using three phase full bridge circuit is proposed and a new switching strategy to control directly the output current which flows through the speaker is also proposed. The proposed class-D stereo amplifier can reduce two switching devices compare with the conventional class-D stereo audio amplifier, which is constructed by two full bridge circuits. And the proposed switching strategy is especially efficient in the area of current control system, which uses the polarity information of the reference current without the problems entailed by real current detection. Moreover, even in cases of high frequency switching operation, good switching performance is still possible, underlining the viability of the proposed switching strategy for not only class-D amplifier but also the other wide practical applications. From the experimental results, the validity and viability of the proposed class-D stereo audio amplifier and its switching strategy were confirmed.

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