NOVEL CLASS-D AUDIO AMPLIFIER FOR WOOFER APPLICATIONS

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Abstract— **This paper presents a new high power Class-D audio amplifier for woofer applications. A regulated DC voltage supply is not needed as well as a low pass output filter overcoming the disadvantages of ordinary audio amplifiers structures. A 1kW laboratory prototype was implemented and it was found that a 94% efficiency and 1% of THD could be achieved. A detailed design guide line, principle of operation analysis, control strategy, are also included in this paper.**

***Keywords* – Audio Amplifiers, Class-D Amplifiers.**

I. INTRODUCTION

Recent advances in semiconductor technology have attracted great interest in developing new topologies of Class-D audio amplifiers due to high efficiency levels (above 90%) that can be achieved with this structure. In this context, Class-D audio amplifiers present some advantages over ordinary linear amplifiers (Class A, B, and AB) [1-2].

The first advantage is the reduction of the required supply current, which means that it provides reduced power supply requirements (reduced cost, weight, and size). Hence, one can conclude that Class-D audio amplifiers are very attractive to battery power equipments such as Hearing Aids, Wireless Speakers, and Notebooks, for example.

The second advantage is the reduction of heat generation and, hence, extremely reduced heat sinks are needed which translates into more output power available in small structures.

The ordinary Class-D amplifiers, depicted in Fig. 1, are composed by a pulse width modulation (PWM) stage, a power stage, and a low-pass output filter. In the PWM stage, the reference signal is compared with a high frequency saw tooth signal (carrier) in order to obtain digital pulses whose width is proportional to the instantaneous input signal level.

The power stage is often composed by a full-bridge structure so that higher output power levels can be achieved, in low voltage levels applications mainly.

The output low-pass filter is used in order to remove the harmonic components of the PWM signal composing the amplified reference signal delivered to the load.

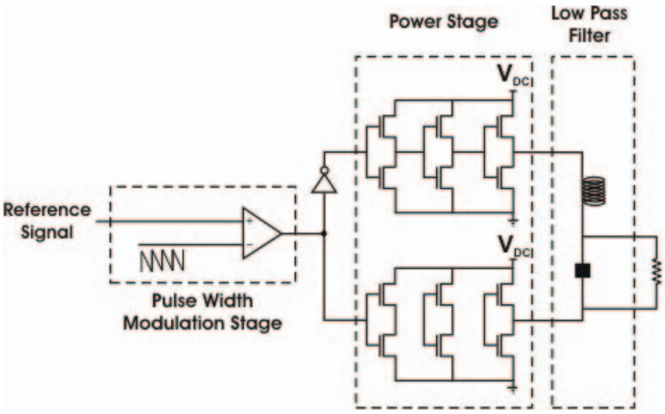

Fig. 1. Ordinary Class-D amplifier

It must be emphasized that the generated PWM signal depends on the power supply voltage level of the power circuit. Therefore, any oscillation in the supply voltage level appears in the amplified PWM signal distorting the audio signal. In order to solve this problem, a feedback circuit must be implemented, as one can see in [2-3].

However, despite of many well known advantages of Class-D amplifiers, this structure is hardly used in high power applications. In other words, it is very difficult to find technical papers reporting the use of Class-D amplifier to power subwoofers for multimedia, automotive, home component stereo systems, and home theater systems.

In this kind of application, in general, a three-way amplification system is required and the input signal frequencies are divided as it follows:

- 10 – 700 Hz for subwoofer;
- 700 – 4 kHz for woofer;
- above 4 kHz for tweeter.

As depicted in Fig. 2 [3], one can observe that 45% of the audio amplifier total output power is dedicated to the woofer, 45% to subwoofer, and just 10% of the nominal power is dedicated to the tweeter. Thus, in general, Class-AB audio amplifier is the most suitable structure for tweeters because, in low power applications, it provides good efficiency, low distortion, low weight, reduced size, and low price mainly.

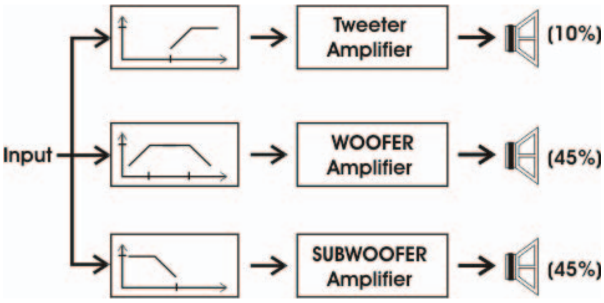

Fig. 2. Active loudspeaker system (three-way) based on separate amplifiers for each band

On the other hand, audio amplifiers for woofer and midrange used in automotive and home audio applications (high power audio applications - above 1kW), must be able to process a large amount of active power with high efficiency and therefore switched converters (Class-D) are more suitable and should be preferred for this application.

In this context, this paper presents a new proposal of Class-D audio amplifier structure for woofer and midrange application that presents significant advantages over ordinary Class-D amplifiers.

In a previous work [4-5], the first topology of a new Class-D audio amplifier for woofer and midrange application was presented. This new structure, shown in Fig. 3, provided a significant innovation eliminating the additional low pass output filter commonly used in ordinary Class-D amplifiers. In addition, a feedback circuit was implemented using a simplified control circuit.

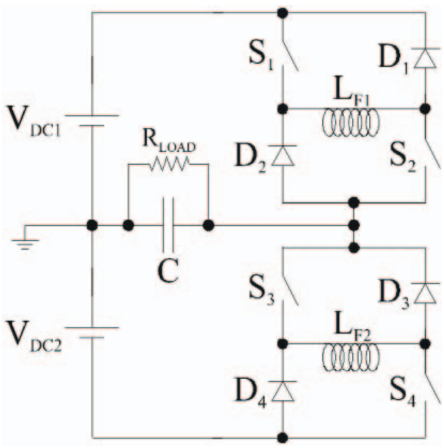

Fig. 3. 4-switches Class-D audio amplifier

However, in order to achieve soft-commutation and reduced EMI, snubber circuits are needed. Besides, four switches are used, which increases the cost and the circuit complexity.

Therefore, in order to overcome these disadvantages and to improve the performance of the 4-switches Class-D audio amplifier depicted in Fig. 3, a new topology was developed and it is presented in this work. Thus, the main focus of this paper is to evaluate this new arrangement.

The proposed converter is shown in Fig. 4 and it was designed to power a woofer amplifier with cutoff frequency of 2 kHz, which is suitable for this application.

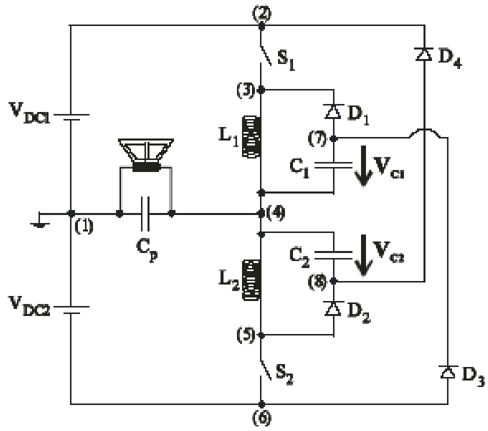

Fig. 4. Proposed Class-D audio amplifier for woofer application

The main advantages of this structure in relation to the one presented in [4-5] is described as it follows:

- In this new arrangement just two switches are used, hence, just two isolated gate drive circuits are needed, providing low cost;
- Soft-commutation is naturally obtained and snubber circuits are not needed;
- Reduced EMI;
- Higher efficiency and good performance;
- Low THD (below 1%).

II. Principle of Operation

Complementary drive commands for switches S_1 and S_2 are obtained through hysteresis loop comparison between a sample of the output voltage signal (voltage across capacitor Cp) and the reference voltage signal. Therefore, the output voltage waveform follows the reference signal through a very simple control strategy.

In order to introduce the principles of operation of the proposed Class-D audio amplifier, the stages of operation are briefly described as it follows. First, three assumptions must be taken into account:

a) The capacitor C_1 constitutes a voltage supply, in the direction illustrated in Fig. 4 ($V_{C1} = V_{Cp} + V_{cc2}$);
b) The capacitor C_2 constitutes a voltage supply, in the direction indicted in Fig. 4 ($V_{C2} = V_{Cp} + V_{cc1}$);
c) In any time instant, the sum of the voltages across capacitors C_1 and C_2 is equal to the voltages V_{cc1} and V_{cc2} ($V_{C1} + V_{C2} = V_{cc1} + V_{cc2}$).

Thus, during the positive semi-cycle of voltage V_{Cp}, whose polarity is indicated in Fig. 5, the load is powered by the DC voltage supply V_{cc1} through inductor L_1. Meanwhile, the DC voltage supply V_{cc2} together with the load helps to modulate the output voltage waveform.

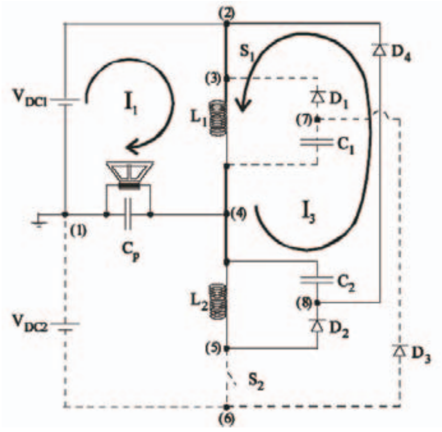

Fig. 5. First operation stage.

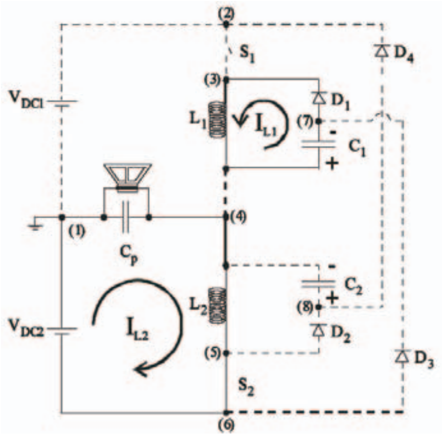

Fig. 6. Second operation stage.

III. Design Guide Line

The maximum slew rate must be taken into account in order to achieve an accurate design of the proposed Class-D audio amplifier. The maximum slew-rate is determined considering the maximum frequency of the sinusoidal or triangular waveform to be amplified. Higher frequency values require higher slew-rates in order to reproduce a sinusoidal or triangular waveform. The square waveform can not be considered to calculate the maximum slew-rate since its value is infinite, theoretically.

The mathematical analysis is based on sinusoidal input signal instead of triangular input signal in order to simplify the design guide line. Therefore, the instantaneous input signal is presented in equation (1).

$$v(t) = V_{pk}.\sin(\omega.t) \tag{1}$$

where:

V_{pk} - peak value of the sinusoidal output signal;

ω - angular frequency $2.\pi.f$;

Thus, the desired slew-rate can be calculate by

$$\frac{dv(t)}{dt} = \omega.V_{pk}.\cos(\omega.t) \tag{2}$$

The maximum voltage variation occurs during the zero crossing for the maximum frequency to be amplified, so cos(0) = 1, as depicted in Fig. 7. It means that cos(ωt) presented in equation (2) can be eliminated resulting in (3).

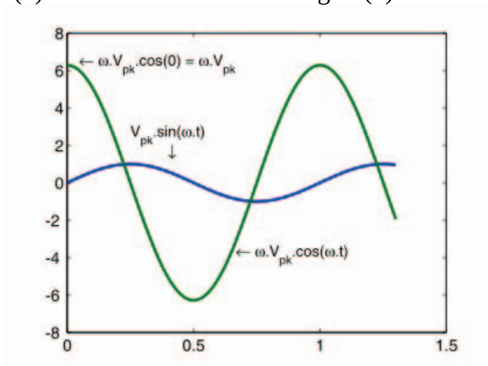

Fig. 7. Sinusoidal waveform and its derivative used in the mathematical analysis.

$$\frac{dv(t)}{dt} = \omega.V_{pk} \tag{3}$$

Equation (4) relates current and capacitance and it is extremely important to calculate the necessary current to produce the desired slew-rate in the output filter capacitor.

$$I_{pk} = C.\frac{dv(t)}{dt} \tag{4}$$

Through the combination of (3) and (4) results

$$I_{pk} = 2.\pi.f_{max}.C.V_{pk} \tag{5}$$

Where:

f_{max} - maximum frequency to be amplified.

Considering a positive slew-rate in capacitor C_p depicted in Figs. 5 and 6, one can observe that inductor L_1 charges capacitors C_p and C_1 and, at the same time, discharges capacitor C_2. This charging and discharging process occurs basically at the same time due to the high switching frequency.

Therefore, the circuit shown in Fig. 8 can be used to find the current equation that produces the maximum slew-rate.

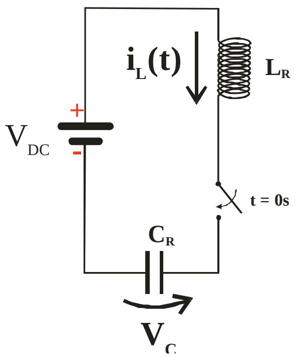

Fig. 8. Equivalent LC circuit (Positive slew-rate).

Based on the series LC circuit depicted in Fig. 7 one can obtained the peak value of current $i_L(t)$. The maximum current through the inductor causes the maximum voltage variation across capacitor C_T. The initial conditions are indicated with the subscript 0, for example V_{C0} and I_{C0}. Therefore, the across the inductor is

$$V_L(s) = s \cdot L \cdot I_{L(s)} - L \cdot I_{L0} \tag{6}$$

If $V_{C0} = q_0/C$, then

$$V_C(s) = \frac{I_{L(s)}}{s \cdot C} + \frac{V_{C0}}{s} \tag{7}$$

If $V_{DC} = V_L + V_C$, then

$$\frac{V_{DC}}{s} = V_L(s) + V_C(s) \tag{8}$$

Substituting (6) and (7) in (8), we have

$$I_L(s) = \frac{V_{DC} - V_{C0}}{L(s^2 + 1/L \cdot C)} + \frac{s \cdot I_{L0}}{(s^2 + 1/L \cdot C)} \tag{9}$$

If the angular frequency is

$$\omega_0 = 2 \cdot \pi \cdot f_0 = \frac{1}{\sqrt{L_R \cdot C_R}} \tag{10}$$

Therefore,

$$I_L(s) = \frac{V_{DC} - V_{C0}}{L \cdot \omega_0} \cdot \frac{\omega_0}{(s^2 + \omega_0)} + I_{L0} \frac{s}{(s^2 + \omega_0)} \tag{11}$$

If the characteristic impedance of the resonant circuit is

$$Z_0 = \sqrt{\frac{L}{C}} \tag{12}$$

And applying the inverse *Laplace* transform, the instantaneous current through the inductor is

$$i_L(t) = I_{L0} \cdot \cos \omega_0 (t - t_0) + \frac{V_{DC} - V_{C0}}{Z_0} \cdot \sin \omega_0 (t - t_0) \tag{13}$$

For $I_{L0} = V_{C0} = 0$, we have

$$i_L(t) = \frac{V_{DC}}{\sqrt{L/C}} \cdot \sin \omega_0 (t - t_0) \tag{14}$$

Equation shows that the maximum inductor current occurs when $\sin\omega_0(t\text{-}t_0) = 1$. Thus, making (5) equal to (14), one can obtain (15) which relates the inductance and the capacitance in order to obtain the desired maximum slew-rate.

$$L \cdot C = \frac{V_{DC}{}^2}{4 \cdot \pi^2 \cdot f_{\max}{}^2 \cdot V_{pk}{}^2} \tag{15}$$

It is important to notice that the load impedance was not taken into account, this is because the load is not related with the slew-rate. However, the load impedance is relevant to the analysis of frequency response and/or filter design.

The sum capacitances C_p, C_1, and C_2 is equal to the resonant capacitance C_R. The suitable values for C_1 and C_2 are

$$C_p \le \left(C_1 = C_2\right) \le 2.C_p \tag{16}$$

IV. Control Strategy

The control technique is based on hysteresis control. Hence, the switching frequency rate depends on the control feedback dynamic. In the proposed converter, the switching frequency is around 50 kHz.

The switching frequency of ordinary Class-D amplifiers is constant, providing design facilities of the output filter. On the other hand, the proposed topology operates with two current sources in the modulation of the amplified signal across the filter capacitor C_p, in the output stage. Thus, low THD can be achieved using hysteresis control technique.

The hysteresis is implemented using a comparator that receives in its inverter input a sample of the modulated signal, as shown in Fig. 9.

The signal that is going to be reproduced is applied to the non-inverter input and the result of this comparison is used to command the switches S_1 and S_2 in a complementary way.

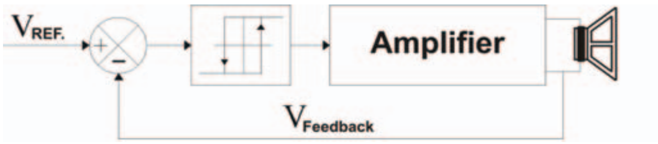

Fig. 9. Block diagram of the control strategy.

V. Experimental Results

The efficiency of the proposed audio amplifier is depicted in Fig. 10. One can observe that almost 94% of efficiency was achieved at rated power (1kW).

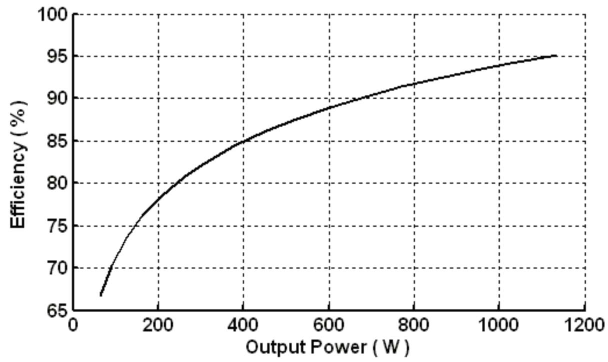

Fig. 10. Efficiency of the proposed audio amplifier in relation to the output power.

The Bode diagram is depicted in Fig. 11 illustrating the voltage gain response of the proposed converter and in Fig. 12 the output voltage or the voltage across capacitor Cp (Ch. A) and the reference input signal (Ch. B) are depicted. One can observe that the peak value of the sinusoidal reference signal is 3V and the output signal is also sinusoidal, in phase, and the peak value is 100V (gain equal to 33.33). These signals were obtained using FLUKE oscilloscope model 199C.

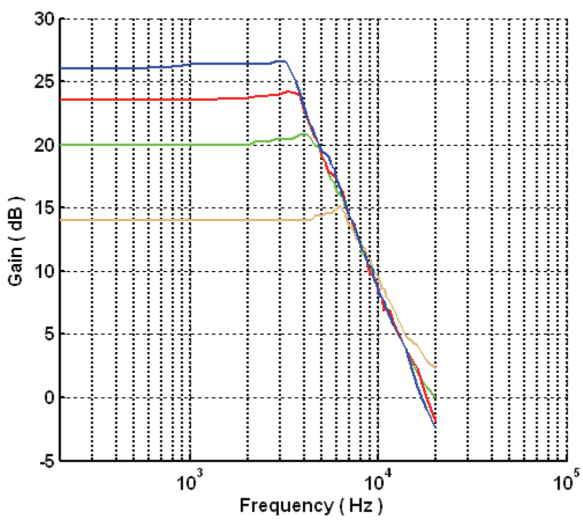

Fig. 11. Voltage gain response.

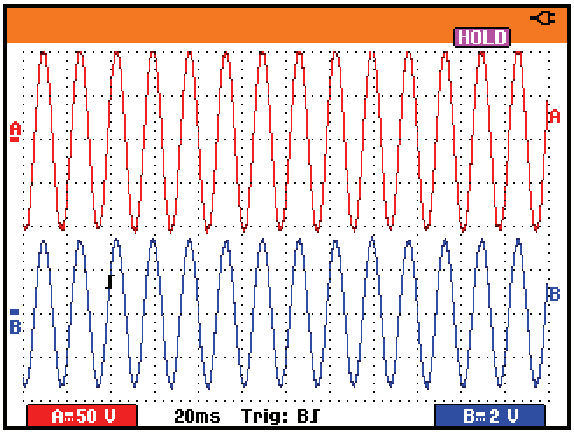

Fig. 12. Ch.A - Output voltage (Across Cp) Ch. B – Reference input signal.

In order to verify the performance of the proposed converter, the software *FLUKEVIEW®* was used to obtain the harmonic spectrum of the input and the output signals. The harmonic spectrum of the reference signal is depicted in Fig. 13(a) with the fundamental amplitude and in Fig. 13(b) without the fundamental amplitude. The harmonic spectrum of output signal is depicted in Fig. 14(a) with the fundamental amplitude and in Fig. 14(b) without the fundamental amplitude. Therefore, one can observe that the THD of the reference signal is 0.6% and the THD of the output signal is 0.97%. Hence, one can conclude that the THD caused by the proposed Class-D audio amplifier is around 0.37%.

The total harmonic distortion of the output voltage signal for different load conditions is depicted in Fig. 15.

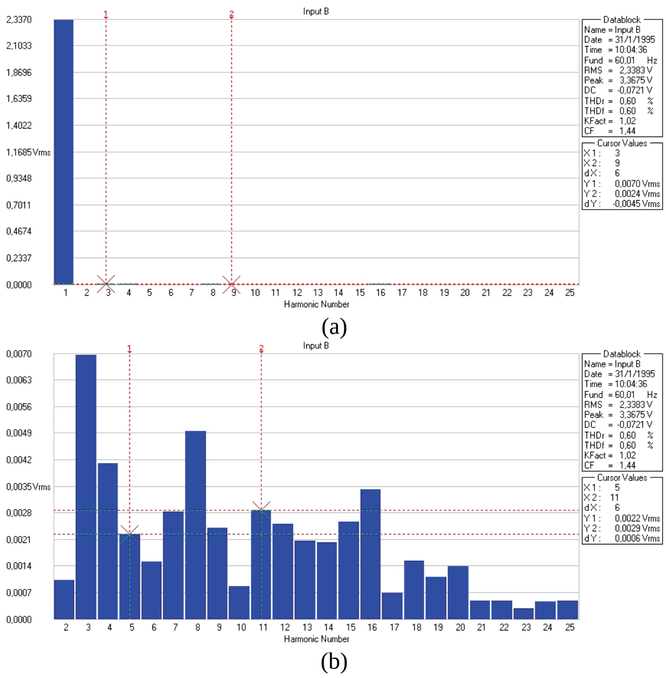

Fig. 13. Harmonic spectrum of the reference signal (a) with the fundamental amplitude (b) without the fundamental amplitude.

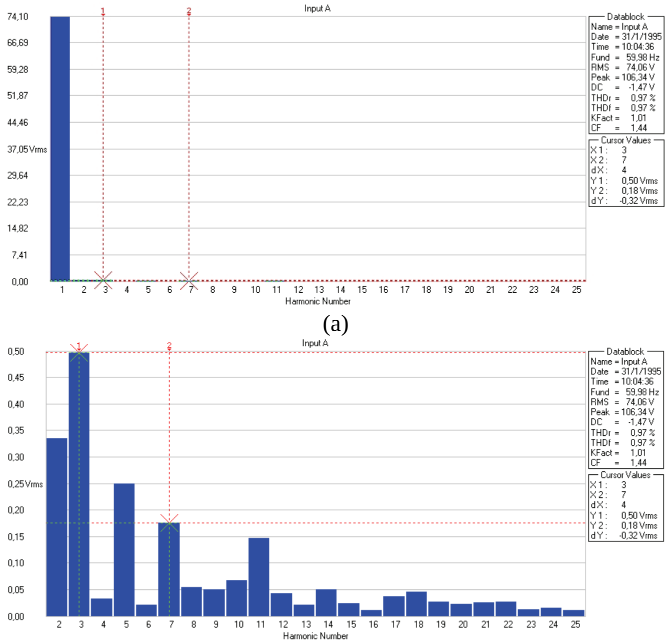

Fig. 14. Harmonic spectrum of the output signal (a) with the fundamental amplitude (b) without the fundamental amplitude.

Finally, a 1 kW prototype implemented in laboratory is portrayed in Fig. 15.

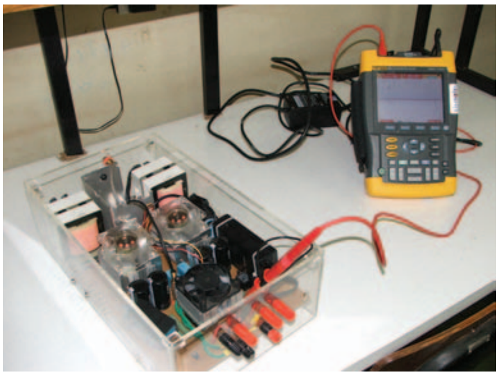

Fig. 15. Prototype implemented in laboratory.

VI. Conclusions

This paper presented a new high power Class-D audio amplifier for woofer applications. A regulated DC voltage supply is not needed as well as low pass output filter, overcoming the disadvantages of ordinary Class-D audio amplifiers structures. 1kW laboratory prototype was implemented and it was found that 94% efficiency and less than 1% of THD could be achieved.

The main advantages of this structure in relation to previous works are: just two switches are used, hence, just two isolated gate drive circuits are needed, providing low cost; soft-commutation is naturally obtained and snubber circuits are not needed; reduced EMI; higher efficiency and good performance; and low THD (below 1%).

A detailed design guide line, principle of operation analysis, control strategy discussion, is also included in this paper.

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