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Class-D Audio Amplifier using Sigma-Delta (ΣΔ) Modulator

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ABSTRACT

Pulse width modulation and pulse density modulation are deemed to be main modulation techniques, even PDM could not emulate PWM, in terms of, basically, simplicity. PDM bitstream is encoded through sigma-delta modulation. Since sigma-delta modulation, compared to PWM, needs very high switching frequency and more complicated materials to compose circuits, it's more difficult to design one. In this article we design a low-power class-D audio amplifier circuit where the analog signal is encoded into pulse density modulation (PDM) using a first-order sigma-delta (ΣΔ) modulator. The designed circuit is built using Orcad-PSpice and results are analyzed with Matlab. A second-order integrator, a voltage divider as a feedback loop are used to mitigate basically, THD and get high efficiency. The audio signal is passed to the EM speaker through a Butterworth low-pass filter. A low THD of less than 0.2 % is obtained comparing to similar circuits in the literature and a high efficiency of 92 % is achieved.

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1. INTRODUCTION

In recent years, following the rapid development in artificial intelligence, Internet of Things, smart phone, smart speaker and TWS headset based on mainly, class-D audio power amplifiers [1] distinguished by their low-power and high-efficiency. As leaders, CDAs have been swept the market, almost uniquely widely used as audio output units of high-quality portable devices such as smart phones and tablet PCs. [2] Portable devices intensive development of design requires low-power and small complexity. [3] Because they are battery supplied, energy efficiency with low distortion are substantial requirements. Due to all of these features, class-D amplifier is an excellent solution compared to the all other classes. Even, class AB amplifiers are a popular choice, but have a significant drawback in power efficiency. Class-D amplifiers are found to address this problem and to fulfill excellent power efficiency. [4]

Compared to the other linear amplifiers, class-D amplifier suffers from essential drawback: its distortions (non-linearity). To eschew this problem, negative feedback loop is a one perfect solution. Both modulation techniques PWM and PDM are famed and still widely used in class-D amplifiers, but PDM is fewer usually used as it mostly demands much higher switching frequency and more complicated materials to emulate PWM performance.

2. CLASS-D AUDIO AMPLIFIERS

Audio amplifiers are applied to amplify input audio signals and lead output elements (such as speakers) with adequate volume and power levels, fulfill low distortion.

Class-A amplifiers are the most common kind due to their simple design. It literally means "the best class" of amplifier due to its low distortion. Class-B amplifiers were invented as a solution to the efficiency and heating problems associated with the class-A amplifier. The price paid for this efficiency improvement is linearity degradation and crossover problem.The mixture between class-A and class-B produces class-AB. A good compromise in terms of linearity and efficiency, but suffering from a drawback is the limited output swing range due to headroom requirements. [5]

Class-A audio amplifiers could reach maximum efficiency of about 25 % and 50% if inductive coupling is applied, which is extremely very low. Class-B audio amplifiers could accomplish 78.5 % efficiency (in theory), but have one main disadvantage, cross-over distortion. The incorporation of both affords class-AB audio amplifiers which could reach a similar efficiency, whilst removing the cross-over problem.Since class-D amplifiers are switching amplifiers, they are either fully on/off and this drives to low power dissipation and high efficiency (even 90 %). The digital modulated input audio signal manipulates the output stage power devices. Most favorable modulation topologies are pulse-width modulation (PWM) or pulse-density modulation (PDM). The output stage could be performed using half-bridge or full-bridge topologies. Often, class-D amplifiers are bridge configured to raise the output power without raising the power supply voltages. A low-pass filter is used as last stage, to tear out the high PWM/PDM carrier frequency, thus recapturing the audio signal. The modulator and power stage pulses include the desired audio signal but also significant high frequency energy (especially from modulation process). The low-pass filter removes this high frequency, allowing the speaker to be driven without such energy, thus minimizing the electromagnetic interference (EMI). [6]

3. CLASS-D AUDIO AMPLIFIER MAIN STAGES

The main option that makes class-D amplifier an excellent choice and preferable than other classes, is that it uses an output stage consists of transistors operating as switches. [7] So very low power dissipation in the transistors since the current through the transistor is zero when it is off and the resistance is low when it is on. So, high power efficiency is acquired too.The main stages of class-D audio amplifier are integrators and filters, a modulator, a gate driver stage, an output stage, a low-pass filter and a load. [8] Filters and integrator improve total harmonic distortion, in the loop: decrease and get rid of undesirable carrier components and provide steady gain. The modulator provides modulated train by modulating the input signal, which serves as a switch control of the output stage. The power stage provides adequate power to run both load and low pass (LP) filter. [9]

4. PDM-BASED CLASS-D AUDIO AMPLIFIER TECHNIQUE EXPLANATION

4.1 First-order sigma-delta modulation

Sigma-delta modulation: changes (deltas) in voltage at the analog input, are integrated (sigma) into a train of pulses delivered later to the digital signal processing. This modulation is likewise known as PDM “pulse density modulation”, in which the density of pulses determines the digital signal strength and frequency due to the integration functions of the analog to digital converter. [10]

The principle of PDM is, a clock signal with high frequency is applied to sample and hold the compensator output, a quantizer block is applied to convert the voltage information to a pulse density encoding (Figure 1). The quantizer output is amplified in the class-D output stage and applied to the output filter. lately, the switching output is used as the feedback signal and returned to the compensator input. [11]

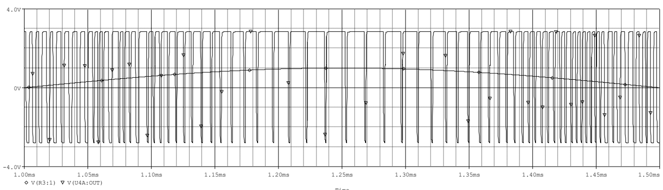

Figure 1. PDM wave form from proposed circuit

Figure 2 shows the functional sigma-delta modulator block diagram. It generates at the output, a digital pulse train signal, where the width of the impulses, is sampled as multiple the period clock. [12]

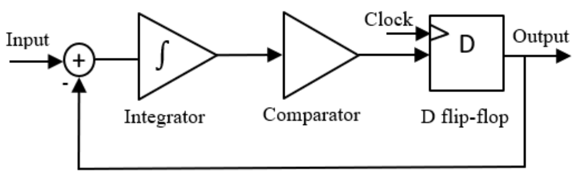

Figure 2. Functional block diagram of a first-order Sigma-delta modulator

The sigma-delta design consists of three successive components: an integrator, a comparator and a buffer (D flip-flop). It has been established that the nonlinearities could be reduced by a higher order modulator or increasing the sampling frequency. These techniques are high cost as hardware complexity and power dissipation increased. [13]

5. PDM-BASED CLASS-D AUDIO AMPLIFIER STAGES EXPLANATION

5.1. Quantizer

It is composite of a D flip-flop and a comparator. The clock frequency is steady and high. The comparator compares the integrator output with grounded signal resulting pulses in the output. These pulses are with constant width and inconstant period. The D latch lifts the comparator output and clears glitches.

5.2. Power stage (switching stage)

The half bridge circuit consists of an upper and lower MOSFETs connected in a cascade arranging PMOS/NMOS as the circuit presented in this paper. This configuration is also called a "totem pole" since the MOSFETs are stacked on top of each other. The high side MOSFET is utilized to switch the positive supply to the load for forward direction while the low side MOSFET is utilized to switch the negative supply to the load for reverse direction. [14] This stage amplifies signal, dissipating less power since it is switches, negligible current circulates in "Off'' state and negligible voltage is present in "On'' state (very small R_{dson} resistors). The MOSFETs are polarized using a gate drive.

5.3. Compensator

To conquer the PDM drawbacks, mainly total harmonic distortion, we use negative feedback loop. A couple of resistors as a negative feedback loop added to a second-order integrator consists of two capacitors, and one resistor, are used to build the compensator.

5.4. Low-pass filter

Since the signal comprises high frequency carrier and its harmonics, a low-pass filter is required to block and eliminate any frequencies higher than 20 kHz. [14] Second-order Butterworth LC filter is the one used as it is simple and highly efficacious. As more, it is designed with the flat response in the audio spectrum pass-band. It is performed by using an inductor and a capacitor in parallel with the load.

6. PROPOSED PDM-BASED CLASS-D AUDIO AMPLIFIER CIRCUIT

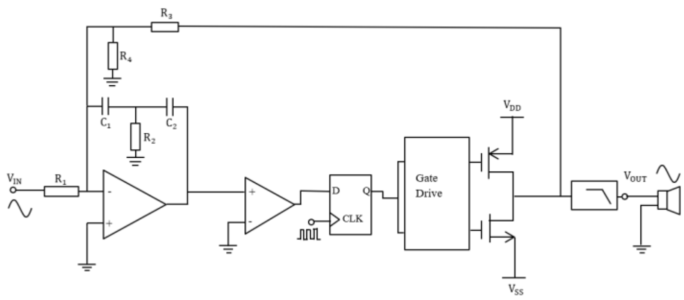

Figure 3. Block diagram of the proposed PDM class-D amplifier

The circuit is fed with ±3 V DC voltage. The output RMS power dissipation of our circuit is 387 mW. Three ICs are used: MAX942 comparator, 74HC74 D latch and TL061 provided with two capacitors and a resistor to build a second-order integrator. We attached to the integrator a negative feedback composite of two resistors. The additive resistor R_4 as depicted in Figure 3, has an important role in removing nonlinearities from output signal as it controls the loop gain, thus it reduces THD. We used IRF520 and IRF9530 MOSFETs as power stage switches, chosen since their small R_{dson}. The output filter is an LC second-order low-pass filter with a cut-off frequency around 20 kHz. The speaker is an 8 Ω resistive load.

7. RESULTS AND DISCUSSION

In this paper, we have built a low-power class-D audio amplifier based on PDM technique.The compensator transfer function of our proposed circuit is,

$$G_C(s) = -\frac{R_2(R_1+R_3//R_4)(C_1+C_2)s+R_1+R_3//R_4}{R_1R_2(R_3//R_4)C_1C_2s^2} \tag{1}$$

The low-pass filter transfer function is,

$$G_F(s) = \frac{1}{LCs^2+\frac{L}{R}s+1} \tag{2}$$

The output signal is 2.5 V V_{max} and the input signal is 1 V V_{max} at 1 kHz frequency. Our proposed circuit fulfills an efficiency of 92%. The obtained THD is 0.2 % with 800 kHz switching frequency.

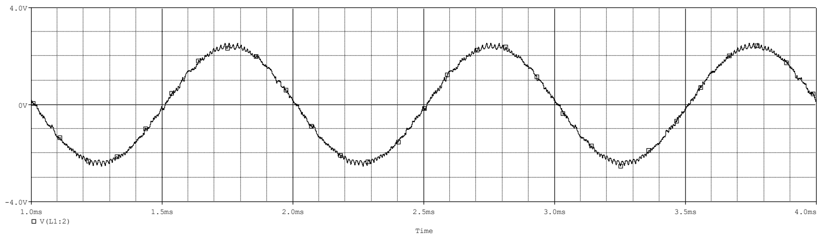

Figure 4. Output filtered PDM signal

In figure 5, the highest harmonic is around -50 dB below the fundamental frequency level (+10 dB). Frequencies higher than 20 kHz could be easily suppressed by the low-pass LC filter.

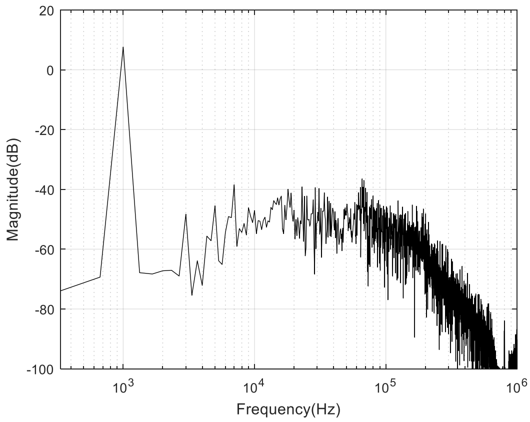

Figure 5. Output spectrum

Figure 6 shows the THD versus switching frequency. Inversely proportional to switching frequency, the higher the switching frequency, the lower the THD.

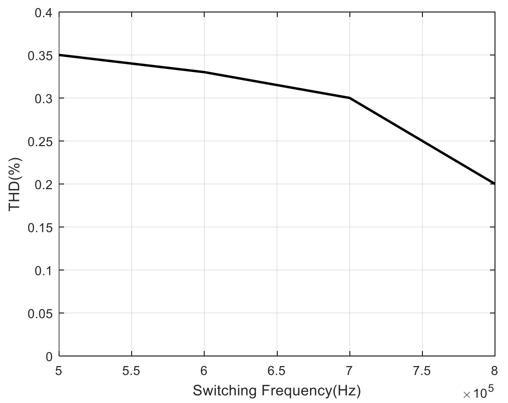

Figure 6. THD vs switching frequency

7.1. Simulink results

The proposed circuit is modeled with a linear model and simulated with Simulink. Figures 7 and 8 present the model and the outcome Bode plot. Where *Rq* and Ki (i=1:5) are functions of circuit elements.

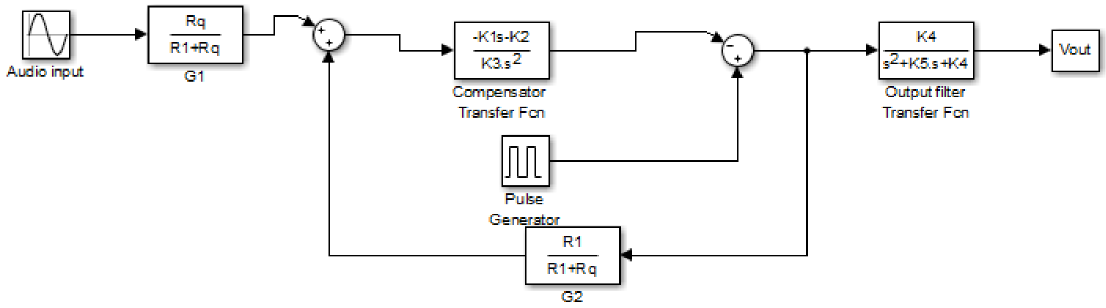

Figure 7. Simulink of proposed circuit

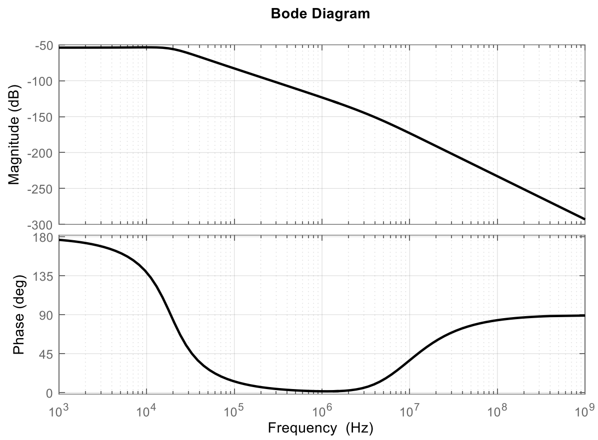

Figure 8. Simulink results of proposed class-D amplifier

The tables below show a comparison between our circuit and state of the art.

Table 1. Comparison of THD

	This work	[3]	[15]	[16]	[17]
THD (%)	0.2	0.872	<0.3	<0.5	<0.1
Technique	ΣΔ	ΣΔ	PWM	PWM	PWM

	This work	[9]	[18]	[1]	[19]
Efficiency (%)	92	90	80	93.3	91
Technique	ΣΔ	PWM	PWM	ΣΔ	PWM

8. CONCLUSION

We have presented a low-power class-D audio amplifier using a first-order sigma-delta modulator as PDM modulator. The benefit of our proposed architecture is that it is more simple, so, mimics traditional classes in terms of simplicity, but overcomes them in terms of efficiency, making huge advantage. Our circuit comprises: an integrator and includes a divider voltage feedback which decreases non-linearity, as compensator, a quantizer combined a comparator and D latch, a switching stage, a low pass filter and a load.The comparison with other designs under similar circumstances shows good result of THD around 0.2 % and high efficiency of 92%.

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