# Class-D Audio Amplifier using Pulse Width Modulation

Jovan Galić, Tatjana Pešić-Brđanin, Lejla Iriškić

*Abstract* - In this paper, a class-D audio amplifier uses MOSFETs in switching mode is designed. The whole system, in addition to amplifiers, contains a pulse width modulator and an output low-pass filter. Either pulse width modulation signal or pulse density modulation signal can be used to drive class-D amplifier stage, and in this paper both techniques are used. The entire system is simulated in PSpice. It is shown that the total harmonic distortion of class-D amplifier is highly influenced by the switching frequency.

*Keywords* – Class-D audio amplifier, Pulse width modulation, Pulse density modulation.

## I. Introduction

Analog power amplifiers have been used for a long time in audio technique [1,2]. There are three classes of audio amplifiers (A, B and AB) which also names as linear power amplifiers. The basic characteristics of linear power amplifier are slightly signal distortion and low power efficiency. The power efficiency of linear amplifier is 30–40% practically in spite of 78.5% theoretically. It, for the desired output power level, means more chip area and additional cooler to reduce heating [2,3].

Class-D power amplifier operates in a switched mode, has high power efficiency and it is able to be digitalized. These characteristics give class-D amplifier significant advantages in many applications because the lower power dissipation produces less heat, saves circuit board space and cost, and extends battery life in battery-powered mobile systems [3,4]. Therefore, class-D amplifiers are becoming preferred in consumer electronic products such as DVD, LCD-TV, MP4, cell phone, hearing instruments, wireless headsets, computer multimedia, etc [2-5].

The modulation techniques commonly applied for the realization of analog/digital class-D amplifiers are either pulse width modulation (PWM) or pulse density modulation (PDM). The choice of modulation techniques (and the parameters of the selected technique) affects the sound quality at the amplifier output. In this paper, we analyze the impact of switching frequency on harmonic distortion of output signal for both techniques of modulation.

## II. Class-D Amplifier Architecture

The class-D amplifier differs from other conventional amplifier classes because it works on a completely different principle. This type of amplifier is called the "digital" amplifier, because of the shape of the output signal, although the digital amplifiers are considered circuits that enhance the digital signals. The operation of the class-D amplifiers is based on pulse width modulation, so a typical class-D amplifier contains a modulator.

The modulator converts an audio signal (analog or digital) into a stream of pulses. The pulse widths depend on the amplitude of the audio signal, while the spectrum contains an audio signal and unwanted high-frequency components. This modulated signal drives the output stage, often a half- or full-bridge power switch. Switching output stage transistors (MOSFETs) are always fully on or fully off because they are amplifying a two-level signal. In that way, the operation of the MOSFETs in the triode region (where power efficiencies drop) is avoided. When a transistor is on, the voltage across it is ideally zero, while when the transistor is off the current through it is considered to be zero. In any case, the power dissipation of the output level will be equal to zero, which means that the ideal power efficiency of the switch is equal to 100% and can reach greater than 95% power efficiency in practice with appropriate design [6].

After amplification of the modulated signal, the switch output signal contains audio signal and high-frequency components. The output signal must be filtered before it can be sent to a speaker. The last stage is the filter stage , or demodulation stage, which consists of a low-pass filter (LPF). The signals in the audible range (up to 20 kHz) pass through LPF, while the high-frequency signals (above 20 kHz) are significantly attenuated. Filtered analog output signal is an amplified replica of audio analog input signal.

The feedback network from the power stage output to a modulator input (which can be active or passive), suppresses total harmonic distortion produced by power stage non-linearities and non-idealities. The negative feedback control loop also reduces the pulse-height errors [3].

Figure 1 shows block diagram of class-D amplifier (a) and typical architecture of this amplifier (b) [7].

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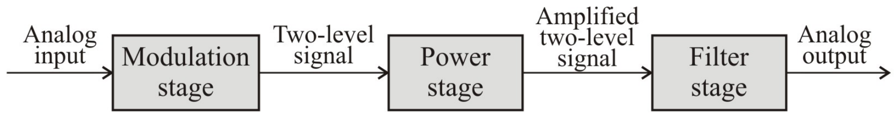
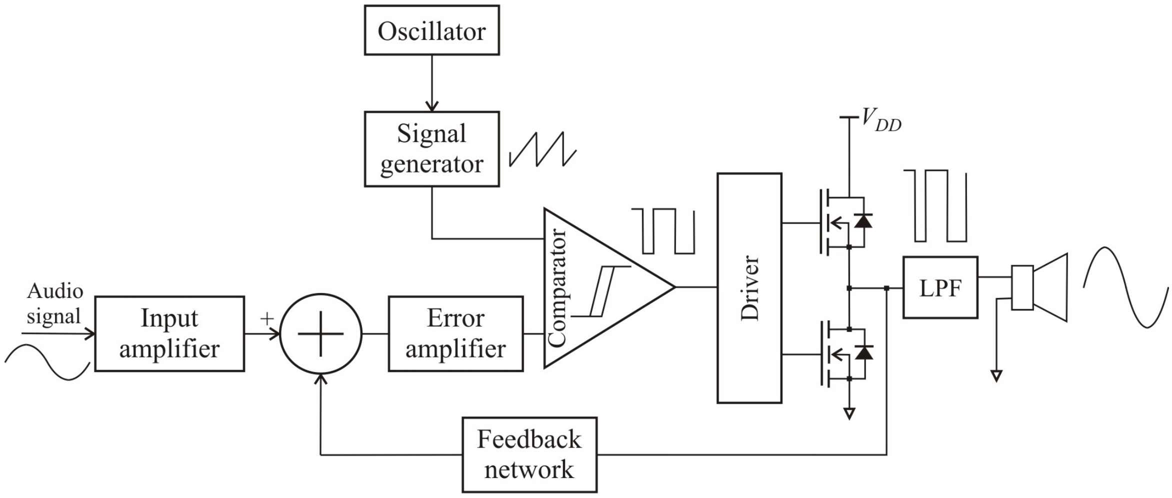



(a)




(b)

Fig. 1. Block diagram of class-D amplifier (a) and typical architecture of class-D amplifier (b)

## III. Modulation Stage

The great significance of the amplifier has a modulation stage. The loss of information in the modulation causes distortion of the audio signal and significant decreases sound quality.

There are many techniques of modulation that can be used in class-D audio amplifier. The choice of modulation techniques is often determined by the requirements that relate to simplicity and effectiveness. A simplified design means a use of smaller number of components and a lighter and more portable device. Effectiveness is important characteristics because modulation is essential to sound quality and the amplifier must achieve less than 1% distortion and greater than 90 dB Signal to Noise Ratio (SNR) [8].

The most commonly used modulation techniques are pulse width modulation (PWM) and pulse density modulation (PDM).

### A. Pulse width modulation

The pulse width of PWM modulator output is varying with the amplitude of the input signal. A fundamental system to create pulse-width modulated signals is shown in Fig. 2 [7].

In PWM technique, the input audio signal $v_m$ is compared with the carrier signal $v_c$. If the input signal is higher than the carrier signal, the output signal $v_{PWM}$ will be set to a higher value ($v_H$). Otherwise, the output signal will have a lower value ($v_L$): If the input signal is higher than the reference, the pulse is switched to the high level, otherwise to the low level:

$$v_{PWM}(t) = \begin{cases} v_H & \text{for} \quad v_m(t) > v_c(t), \\ v_L & \text{for} \quad v_m(t) < v_c(t). \end{cases} \quad (1)$$

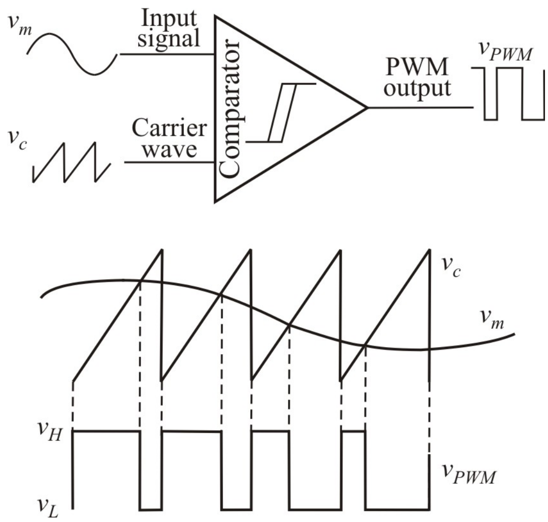



Fig. 2. Fundamental PWM principle

The period of the carrier signal defines the cycle-time of the PWM pulses.

Two important parameters of the PWM modulation can be defined:

- The ratio $F$ of the carrier frequency $f_c$ and the input signal frequency $f_m$, which defines the spectrum of the PWM output signal. In practical modulators this ratio is higher than the 10.
- The modulation index $M$, which is the ratio between the input signal amplitude $V_m$ and the amplitude of the carrier signal $V_c$. Preferably, the $M < 1$ for the PWM modulation.

The main disadvantages of PWM are the inherent nonlinearity of the PWM process which causes the distortions in audio signal baseband in many applications and extremely small pulse width in the case of full modulation.

### *B. Pulse density modulation*

In many applications, PDM can be used instead of PWM. In pulse density modulation, the number of pulses in a time window is directly proportional to the average value of the input audio signal. In PDM technique, width of individual pulses can not be arbitrary, but is instead quantized to multiples of the modulator clock period.

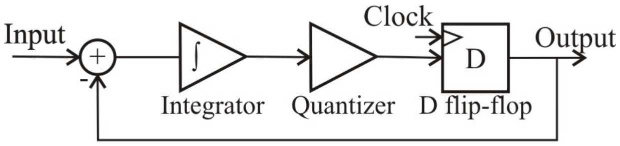



Fig. 3. First-order sigma delta (ΣΔ) modulator

PDM signal conversion can be realized by the analog or digital 1-bit sigma delta modulator (ΣΔ modulator). ΔΣ modulator can be realized using only an integrator and a D latch, as shown in Fig. 3. The audio signal is the input to a integrator circuit. When this signal surpasses a threshold, it resets the integrator and triggers the D-latch. This provides a series of set-width pulses at the output with variable spacing between them, whose time density distribution represents the instantaneous amplitude of the original input signal [7]. To reduce the quantization noise, the switching frequency must be significantly greater than the frequency of the input signal.

Due to the oversampling, the switching frequency can be large, which means higher power dissipation than in case of PWM. On the other side, ΣΔ technique provides better linearity than the PWM technique.

## IV. Results and Discussion

In this paper, influence of switching frequency on harmonic distortion of output signal is examined, for both techniques of modulation. Parameter for estimation of distortion is total harmonic distortion (THD), which is defined as:

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \dots}}{V_1} \cdot 100[\%], \qquad (2)$$

In eq. (2), $V_n$ is RMS (Root Mean Square) voltage of respective harmonic ($V_1$ is RMS of fundamental frequency). Since in practice harmonics higher than fifth do not contribute significantly to THD, we were taken 5 harmonics into consideration.

The PSpice scheme of PWM class-D amplifier with modulation index $M$=0.95 is depicted in Fig. 4.

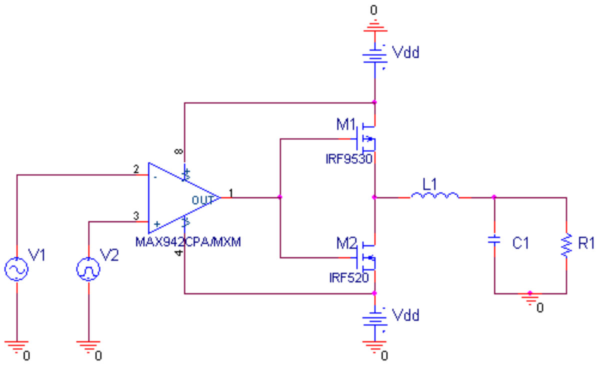



Fig. 4. The PSpice scheme of class-D PWM amplifier

The PSpice scheme of class-D amplifier with one bit sigma-delta modulation is depicted in Fig. 5.

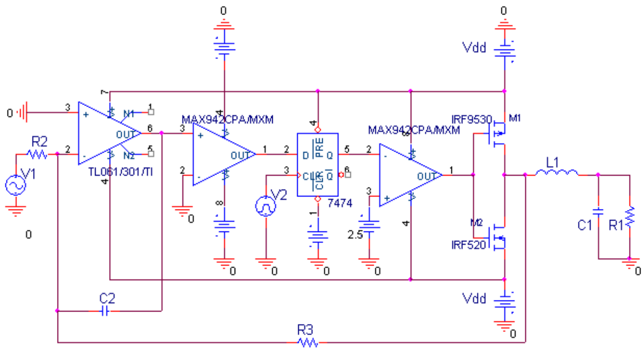



Fig. 5. The PSpice scheme of class-D PDM amplifier

As can be seen from Fig. 5, the PDM amplifier uses one bit sigma delta modulation instead of PWM stage in PWM amplifier. To avoid saturation of integrator stage at the beginning of PDM amplifier, time constant $R_2C_2$ should be greater than period of pulse generator signal $T_s=1/F_s$ [9]. In this paper, time constant $R_2C_2=2T_s$ has been used. The feedback resistor is with resistance $R_3$=100 kΩ.

At the output of both techniques, the low-pass passive Butterworth filter of second order with cut-off frequency 18 kHz ($L_1$=100 µH and $C_1$=0.68 µF) is used.

As well, supply voltage is ±5 V, and load speaker is approximated as a simple resistance of 8 Ω. MOS transistors (IRF 9530 and IRF 520) are with the on-state resistance 0.2 Ω and maximum current 10 A [10,11]. Speed comparator MAX942 [12], with propagation delay 80 ns has been used in both the PWM and PDM modulation techniques. As input signals, we used test tones of amplitudes 1 V and frequencies 1 kHz and 5 kHz. For a test tone of 5 kHz, THD calculation was included only components in audio range (i.e. first three harmonics) [7].

The switching frequency is adjustable from 300 kHz up to 800 kHz, with 100 kHz step. A summary of simulation results is presented in Table I.

TABLE I
THD (IN %) FOR PWM AND PDM MODULATION IN DEPENDENCE OF SWITCHING FREQENCY

| | Frequency of test tone | | | |
|---|---|---|---|---|
| | PWM | | PDM | |
| Frequency [kHz] | 1kHz | 5kHz | 1kHz | 5kHz |
| 300 | 3.06 | 2.64 | 1.83 | 11.53 |
| 400 | 4.76 | 4.21 | 0.92 | 3.46 |
| 500 | 6.42 | 5.68 | 0.52 | 5.79 |
| 600 | 7.46 | 7.16 | 0.65 | 1.07 |
| 700 | 8.77 | 8.41 | 0.35 | 1.01 |
| 800 | 9.94 | 9.03 | 0.32 | 1.49 |

The above simulation results show that the distortion of output signal is highly affected by the switching frequency.

In PWM modulation, increasing switching frequency contribute to higher THD. In these experiments, for PWM modulation the lowest THD is obtained with switching frequency 300 kHz. The time waveform for 5 kHz test tone and corresponding output signal is depicted in Fig. 6.

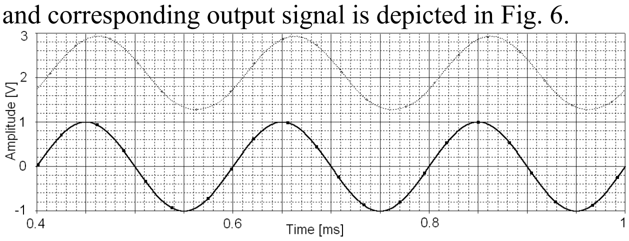



Fig. 6. Time waveform of test tone (solid line) and output signal (dotted line)

In PDM modulation THD is low enough as long as the switching frequency is sufficiently high, where obtained THD is by an order of magnitude lower than for PWM modulation.

It is important to emphasise that the THD value for PDM modulation is highly sensitive to number of quantization bits [13]. Relatively high values of THD is a consequence of conventional, less accurate 1-bit quantization.

## IV. Conclusion

In this paper we analyzed the influence of switching frequency on total harmonic distortion of the class-D audio amplifier output signal. The analysis was done for two modulation techniques, PWM and PDM. Results of circuit simulations obtained by PSpice show that THD for PDM has a lower value for higher switching frequencies.

Since THD only includes distortion for a single test tone, future work will include tests for intermodulation distortion and analysis of efficiency as well.

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