Cross-over Distortion Reduction on 3 Level PWM for Audio Amplifiers

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Abstract - A new control/modulation method for digital audio power amplifiers is proposed. With this approach the cross-over harmonic distortion is reduced. The use of three-level PWM output voltage instead of two-level is another characteristic of this approach. From the use of the three-level two main advantages can be obtained: more resolution and increased efficiency. However, there is an important disadvantage: higher cross-over distortion and worst THD+N for signals with small amplitude, than the obtained with two level PWM output voltage. Therefore, to overcome this disadvantage the proposed control/modulation method uses three-level PWM output voltage for signals with large amplitude and two-level for signals with small amplitude. This allows the construction of a completely digital audio power amplifier with better efficiency than those using two-level PWM output, with comparable THD+N.

I. INTRODUCTION

With the continuing rapid development of switched high power electronic devices, the interest on digital audio power amplifiers has been growing. Improved efficiency over traditional audio power amplifiers is the most important factor for the recent interest in digital audio power amplifier. Class D output of the digital audio power amplifier allows efficiencies clearly better than 85%. This fact associated with an almost completely digital path for the signal allows an integration and size reduction that was completely impossible few ears ago. For applications like home cinema, where seven or more amplifiers are necessary, or for battery-operated systems, efficiency is an important issue.

The main solutions for digital audio power amplifiers are the use of interpolation, Noise-Shaping techniques and low-resolution PWM output, typically PWM at 352.8 kHz with 8bits of resolution [1]. However, these techniques introduce a distortion in the modulation of uniform sampled PCM signals into PWM signals. This distortion introduced by the non-linear modulation is well known, and several methods have been presented to reduce this problem [2,3,4]. Some of those methods use n-grade polynomial interpolation to calculate the duty-cycle obtained if natural sampled PWM (NPWM) had been used. This modulation is usually called Pseudo Natural PWM (PNPWM). This method can achieve excellent results, but requires high computational power. Alternative methods employ a linear approximation to produce a Linear PWM (LPWM). LPWM generates more distortion than PNPWM but this algorithm requires much less computational power. Other techniques rely on feedback of analogue variables [5,6,7], but those cannot be classified as all digital audio power amplifiers. The “state of the art” digital audio power amplifier is represented in Figure 1.

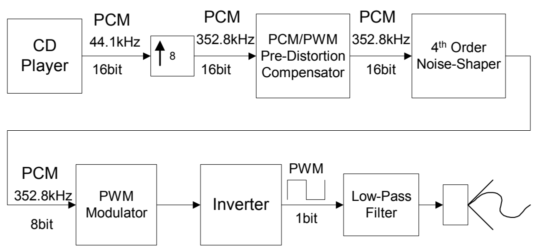

Fig. 1. Digital audio amplifier

II. DISTORTION ADDED BY OUTPUT SWITCHES

From the investigation of the PCM to PWM modulation linearization, it is fair to say that good solutions are already available, from the scientific point of view, but they are too expensive to be commonly available to consumers. On the other hand, there is a special concern with the distortion added by PCM to PWM modulation methods, if the distortion added by power output switches is many times bigger than that of conventional analog amplifiers.

To produce a two-level PWM modulation from the PCM input signal, which represents a pure sinusoid sampled at constant frequency, Fc, two different types of modulation can be used: 1) Single Edge PWM modulation, with only one of the PWM edges is modulated or 2) Double-edge modulation, where double edge of the PWM are modulated. If the first option is selected then, one of the PWM edges is coincident with the beginning or the end of the PCM sample and other edge position determines the duty-cycle of the PWM sample. If the second option is selected, then the position of double edge determine the PWM duty-cycle and their distance to the centre of the PWM sample is identical.

Using a double Fourier series expansion [8], it is possible to calculate the spectral components of both types of PWM modulation. If single edge PWM modulation is used, then the signal is given by (1). If double edge of the PWM are modulated then the signal can be represented by (2), where ω_v is the angular frequency of the input signal, ω_c is the angular frequency of the PWM carrier and M is the modulation index.

$$
\begin{aligned}
S_S(t) = & -\sum_{n=1}^{\infty} \frac{\mathrm{J_n}(\frac{n\pi M\omega_v}{\omega_c})}{n\pi}\frac{\omega_c}{\omega_v}\sin(n\omega_v t - n\pi\frac{\omega_v}{\omega_c} - n\frac{\pi}{2}) \\
& + \sum_{m=1}^{\infty}\frac{1-\mathrm{J_0}(m\pi M)}{m\pi}\cos(m\omega_c t) \\
& - \sum_{m=1}^{\infty}\sum_{n=\pm 1}^{\infty}\frac{\mathrm{J_n}\left[\frac{(m\omega_c + n\omega_v)\pi M}{\omega_c}\right]}{(m\omega_c + n\omega_v)\pi}\omega_c \sin(m\omega_c t + n\omega_v t - n\frac{\pi}{2})
\end{aligned}
\quad (1)
$$

$$
\begin{aligned}
S_D(t) = & \sum_{n=1}^{\infty} \frac{\mathrm{J_n}(\frac{n\pi M\omega_v}{2\omega_c})}{n\pi}\frac{\omega_c}{\omega_v}\sin\left[n\frac{\pi}{2}(1+\frac{\omega_v}{\omega_c})\right]\cos(n\omega_v) \\
& + \sum_{m=1}^{\infty}\frac{\mathrm{J_0}(m\pi\frac{M}{2})}{m\pi}\sin(m\frac{\pi}{2})\cos(m\omega_c t) \\
& - \sum_{m=1}^{\infty}\sum_{n=\pm 1}^{\infty}\frac{\mathrm{J_n}\left[\frac{(m\omega_c + n\omega_v)\pi M}{2\omega_c}\right]}{(m\omega_c + n\omega_v)\pi}\omega_c \sin\left[(m+n(1-\frac{\omega_v}{\omega_c}))\frac{\pi}{2}\right]\cos(m\omega_c t + n\omega_v t)
\end{aligned}
\quad (2)
$$

Table I summarizes the spectral components of the harmonic distortion for both PWM modulations: single edge and double edge modulation.

TABLE I

HARMONIC DISTORTION COMPONENTES

PWM Modulation	Signal Harmonics
Single edge	$\frac{\mathrm{J_n}(\frac{n\pi M\omega_v}{\omega_c})}{n\pi}\frac{\omega_c}{\omega_v}$
Double edge	$\frac{\mathrm{J_n}(\frac{n\pi M\omega_v}{2\omega_c})}{n\pi}\frac{\omega_c}{\omega_v}\sin\left[n\frac{\pi}{2}(1+\frac{\omega_v}{\omega_c})\right]$

Fig. 2 shows the amplitude of the 2nd and 3rd harmonic versus the frequency of the PWM carrier, considering an audio band of 22 kHz, an input signal of 7 kHz and a modulation index M=1. The 7 kHz input frequency was used because it is the higher frequency that still shows a 3rd harmonic on the audio band. For carriers with frequency greater than 300 kHz, if double edge modulation is utilized, both harmonics are well under 60dB witch means that the Total Harmonic Distortion (THD) is better than 0.1%. This value is perfectly acceptable for an audio amplifier for general purpose, and is not an easy task to build an output power system better than that. Knowing that, it makes more sense to spend money on techniques that can relieve the task of the output power switches, or can improve the efficiency of the audio power amplifier, than on techniques to improve the linearity of the PCM to PWM modulation.

Therefore, Figure 3 compares ideal pulses to pulses generated using power MOSFET switches presenting 10 ns rise time and 20 ns fall time (turn-on and turn-off delays and non-linear shapes of rise and fall times are not considered). The resulting pulse will have an area exceeding by 50% the ideal pulse area. Figure 4 represents an ideal 90ns pulse and a the one obtained with MOSFETs with the above rise and fall times. The non-ideal pulse area will only be 5.6% larger than the ideal pulse area. In spite of the simplicity of this analysis (turn-on and turn-off delays and non-linear rise and fall times will worsen these figures), it is shown that rise and fall times differences will introduce distortion. Furthermore, it is clear that pulses with smaller widths will led to increased distortion compared to larger ones.

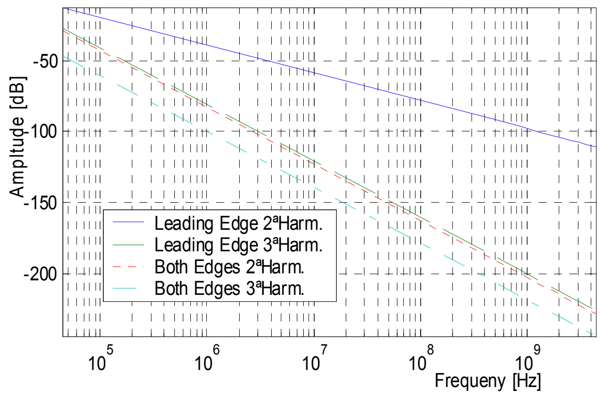

Fig. 2. 2nd and 3rd harmonic components for PCM/PWM modulation.

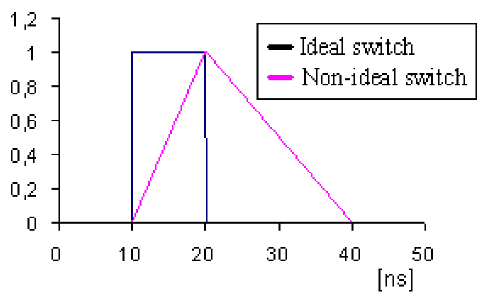

Fig. 3. Ideal pulse of 10 ns width and correspondent non-ideal output pulse.

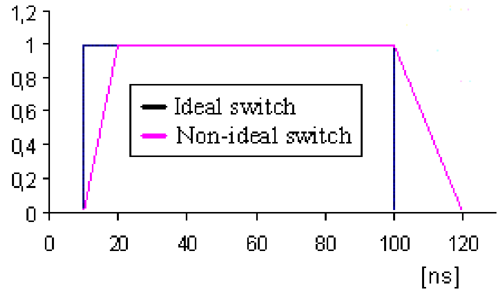

Fig. 4. Ideal pulse of 90 ns width and correspondent non-ideal output pulse

To deal with the non-linearity's of the output stage some authors have been proposing the correction of those non-linearity's by means of an analog system that, using feedback, retimes the position of the edges of the PWM output signal. In [9] an analogue sigma-delta modulador is used to make the output power PWM signal equal, in average, to the reference PWM signal created by digital processing unit. A simplified diagram is shown on fig.5. This technique reduces the distortion added by output power switches and grants some degree of rejection of the power supply interferences, but being an analogue system makes it sensible electromagnetic noise a to errors and non-idealities that are always present at analogue systems. This technique, as it is presented, has two limitations: it uses a half-bridge at the output, meaning that two symmetric power sources are necessary and the modulation index is limited to [0.3, 0.7].

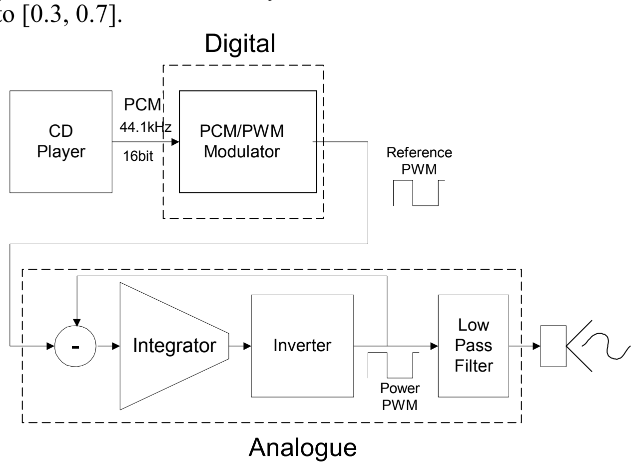

Fig. 5. Power PWM correction.

In [10,11] it is described the technique named Pulse Edge Delay Error Correction (PEDEC). The PEDEC technique, represented is fig. 6, assumes that all errors introduced by the output stage may be corrected if a small change in the position of the PWM edges is correctly made. The output of the digital processing unit is used as reference for an analogue system that by means of feedback corrects the position of the PWM signal with the goal of making the output power PWM signal identical, in average, to the reference PWM signal. This technique also shows limitation dealing with small duty-cycle PWM signals.
Therefore, one may say that even with the research efforts being made to reduce the distortion added by the digital audio power amplifier output stage, the linearity of this stage remains a problem, especially if small duration pulses are present.

III PROPOSED METHODOLOGY

The efficiency of the audio power amplifier represented in figure 1 can be improved, if three-level output is used, as the mean commutation frequency of the output switches will be reduced to approximately 180kHz, half of the frequency when two-level is used. This solution has not being widely used because it introduces more distortion and it is noisier. The distortion increases as the signal becomes smaller, where unfortunately, the human hear is more sensitive to distortion. This is comparable to cross over distortion on class B audio power amplifiers.
The main reason for the increasing distortion for smaller signals, when three-level are used, is the fact that the duty-cycle γ of PWM tends to zero as the samples of the input signal, S_N, tend to zero. In fact, the duty-cycle, for three-level PWM modulation can be calculated from (3).

$$\begin{cases} \gamma_N = S_N + 1 \Leftarrow S_N < 0 \\ \gamma_N = S_N \Leftarrow S_N > 0 \end{cases} \tag{3}$$

This means that the PWM will generate narrower pulses as S_N approaches zero, as shown on (4).

$$\begin{cases} \lim_{S_N \to 0} \gamma_N = 1 \Leftarrow S_N < 0 \\ \lim_{S_N \to 0} \gamma_N = 0 \Leftarrow S_N > 0 \end{cases} \tag{4}$$

For two-level PWM, the duty-cycle can be calculated from (5) so, as S_N approaches to zero, the PWM pulse get wider approaching 0.5.

$$\gamma_N = \frac{S_N + 1}{2} \Rightarrow \lim_{S_N \to 0} \gamma_N = 0.5 \tag{5}$$

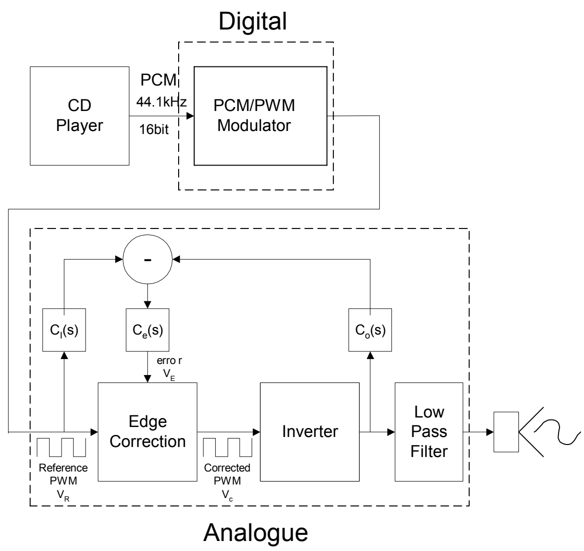

Fig. 6. PEDED system.

Fig. 7 compares the output of a two-level PMW modulation when the output is ideal and when MOS switches are considered for an input tone with 1% of the maximum amplitude. For the same input, figure 8 compares the ideal output for three-level PWM modulation with the output of an inverter build with MOS switches. PWM pulses are especially narrow if 3-level PWM modulation is considered. It is clear that narrow pulses are more distorted than wider pulses, so more distortion will by present at the output of the 3-level PWM modulator for small amplitude inputs.

To eliminate the high distortion introduced by three-level modulation on small signals while maintaining its efficiency, a new modulation that combines two-level modulation with three-level modulation is proposed. A threshold is compared with the input signal amplitude, M_{min}, and if it falls below that threshold then two-level PWM modulation is used, otherwise three-level PWM modulation is used.

The proposed modulation may be represented by (6), where γ_N represents the duty-cycle, S_N represents the actual input signal sample and M_{min} is the minimum signal input absolute value acceptable for tree-level modulation.

$$\begin{cases} \gamma_N = S_N + 1 \Leftarrow S_N < -M_{\min} \\ \gamma_N = S_N \Leftarrow S_N > M_{\min} \\ \gamma_N = \dfrac{S_N + 1}{2} \Leftarrow -M_{\min} < S_N < M_{\min} \end{cases} \quad (6)$$

The output of a signal modulated as defined in (6) is present in fig.9.

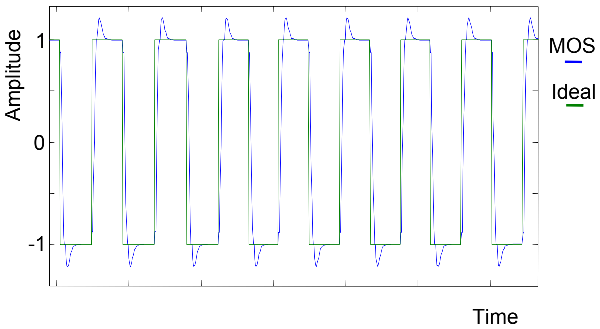

Fig. 7. Two-level PMW modulation.

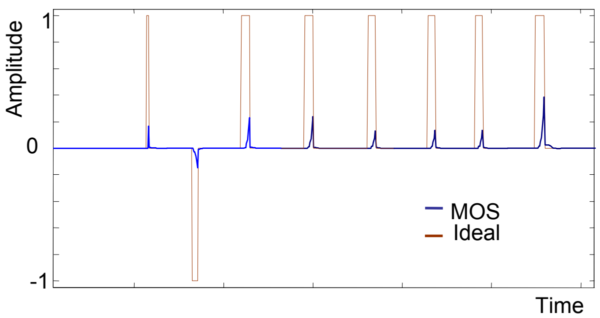

Fig 8. Three-level PWM modulation

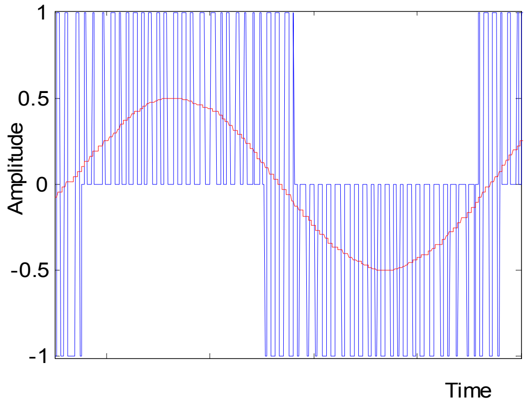

Fig. 9. Results for the three considered modulation

IV. RESULTS

The amplifier employed to test the proposed modulation is presented on figure 10. It uses one full-bridge as output, a double-edge PWM modulator, a 2nd order noise-shaping, one over-sampler filter and 2nd order output filter. The use of double-edge PWM has two advantages: 1) The PCM sample rate is two times faster than PWM frequency (better SNR), and 2) heavily reduces even harmonic distortion components.

The output THD+N versus input amplitude, when the input is a 7kHz sinus wave was obtained by simulation of the proposed amplifier. The results for the three considered modulation are compared in figure 11.

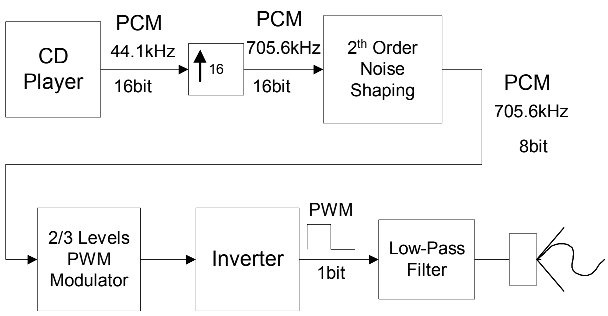

Fig. 10. Proposed amplifier

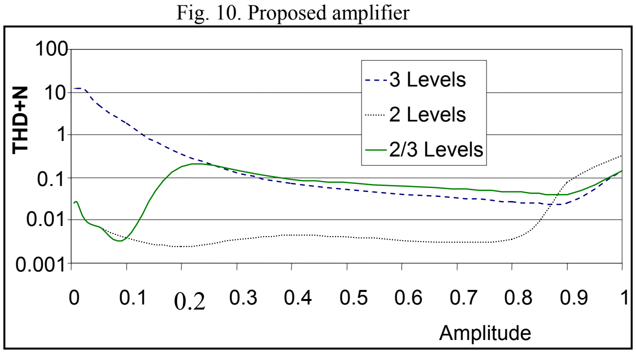

Fig. 11. Results for the three considered modulation

CONCLUSION

A new control/modulation method for digital audio power amplifiers was proposed. With this new method it is possible to obtain a three-level PWM modulation width a low THD+N allowing the use of this type of modulation for audio power amplification. From the use of the three-level modulation, a reduction of the switching frequency and so the improvement of the efficiency can be obtained. From the analysis of the duty cycle, two or three-level PWM modulation is implemented. Therefore, an improvement for small amplitude input signals can be obtained. In the worst situation the THD+N is 0.2%, which is acceptable for most audio applications.

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