Fundamentals of Class D Amplifiers

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APPLICATION NOTE 3977

Abstract: A Class D amplifier's high efficiency makes it ideal for portable and compact high-power applications. Traditional Class D amplifiers require an external lowpass filter to extract the audio signal from the pulse-width-modulated (PWM) output waveform. Many modern Class D amplifiers, however, utilize advanced modulation techniques that, in various applications, both eliminate the need for external filtering and reduce electromagnetic interference (EMI). Eliminating external filters not only reduces board-space requirements, but can also significantly reduce the cost of many portable/compact systems.

Introduction

Most audio system design engineers are well aware of the power-efficiency advantages of Class D amplifiers over linear audio-amplifier classes such as Class A, B, and AB. In linear amplifiers such as Class AB, significant amounts of power are lost due to biasing elements and the linear operation of the output transistors. Because the transistors of a Class D amplifier are simply used as switches to steer current through the load, minimal power is lost due to the output stage. Any power losses associated with a Class D amplifier are primarily attributed to output transistor on-resistances, switching losses, and quiescent current overhead. Most power lost in an amplifier is dissipated as heat. Because heatsink requirements can be greatly reduced or eliminated in Class D amplifiers, they are ideal for compact high-power applications.

In the past, the power-efficiency advantage of classical PWM-based Class D amplifiers has been overshadowed by external filter component cost, EMI/EMC compliance, and poor THD+N performance when compared to linear amplifiers. However, most current-generation Class D amplifiers utilize advanced modulation and feedback techniques to mitigate these issues.

The Basics of Class D Amplifiers

While there are a variety of modulator topologies used in modern Class D amplifiers, the most basic topology utilizes pulse-width modulation (PWM) with a triangle-wave (or sawtooth) oscillator. **Figure 1** shows a simplified block diagram of a PWM-based, half-bridge Class D amplifier. It consists of a pulse-width modulator, two output MOSFETs, and an external lowpass filter (L_F and C_F) to recover the amplified audio signal. As shown in the figure, the p-channel and n-channel MOSFETs operate as current-steering switches by alternately connecting the output node to V_{DD} and ground. Because the output transistors switch the output to either V_{DD} or ground, the resulting output of a Class D amplifier is a high-frequency square wave. The switching frequency (f_{SW}) for most Class D amplifiers is typically between 250kHz to 1.5MHz. The output square wave is pulse-width modulated by the input audio signal. PWM is accomplished by comparing the input audio signal to an internally generated triangle-wave (or sawtooth) oscillator. This type of modulation is also often referred to as "natural sampling" where the triangle-wave oscillator acts as the sampling clock. The resulting duty cycle of the square wave is proportional to the level of the input signal. When no input signal is present, the duty cycle of the output waveform is equal to 50%. **Figure 2** illustrates the resulting PWM output waveform due to the varying input-signal level.

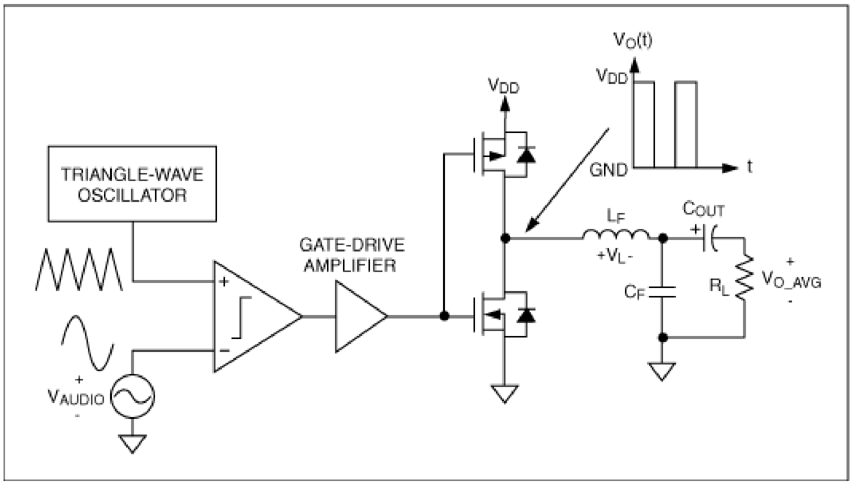

Figure 1. This simplified functional block diagram illustrates a basic half-bridge Class D amplifier.

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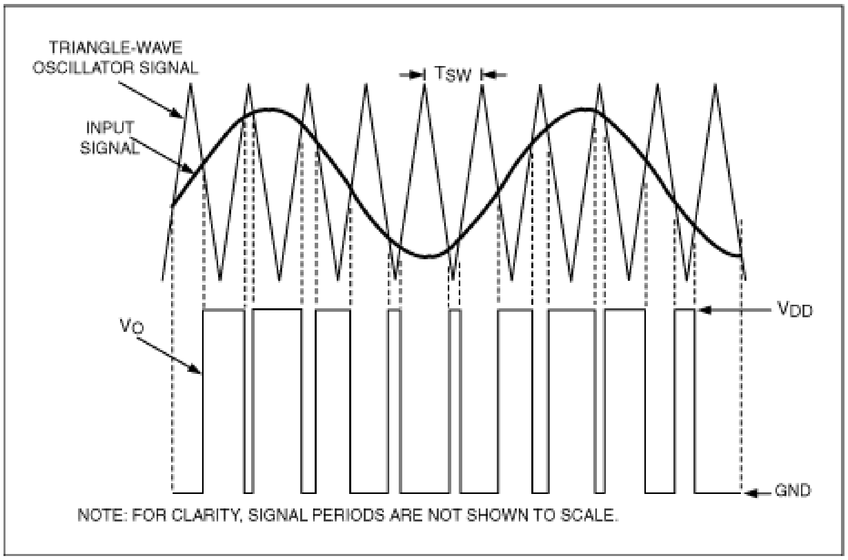

Figure 2. The output-signal pulse widths vary proportionally with the input-signal magnitude.

In order to extract the amplified audio signal from this PWM waveform, the output of the Class D amplifier is fed to a lowpass filter. The LC lowpass filter shown in Figure 1 acts as a passive integrator (assuming the cutoff frequency of the filter is at least an order of magnitude lower than the switching frequency of the output stage) whose output is equal to the average value of the square wave. Additionally, the lowpass filter prevents high-frequency switching energy from being dissipated in the resistive load. Assume that the filtered output voltage (V_{O_AVG}) and current (I_{AVG}) remain constant during a single switching period. This assumption is fairly accurate because f_{SW} is much greater than the highest input audio frequency. Therefore, the relationship between the duty cycle and resulting filtered output voltage can be derived using a simple time-domain analysis of the inductor voltage and current.

The instantaneous current flowing through the inductor is:

where $V_L(t)$ is the instantaneous voltage across the inductor using the sign convention shown in Figure 1.

$$I_L(t) = \frac{1}{L}\int V_L(t)dt \qquad \text{(Eq 1)}$$

Because the average current (I_{AVG}) flowing into the load is assumed constant over one switching period, the inductor current at the beginning of the switching period (T_{SW}) must be equal to the inductor current at the end of the switching period, as shown in **Figure 3**.

In mathematical terms, this means that:

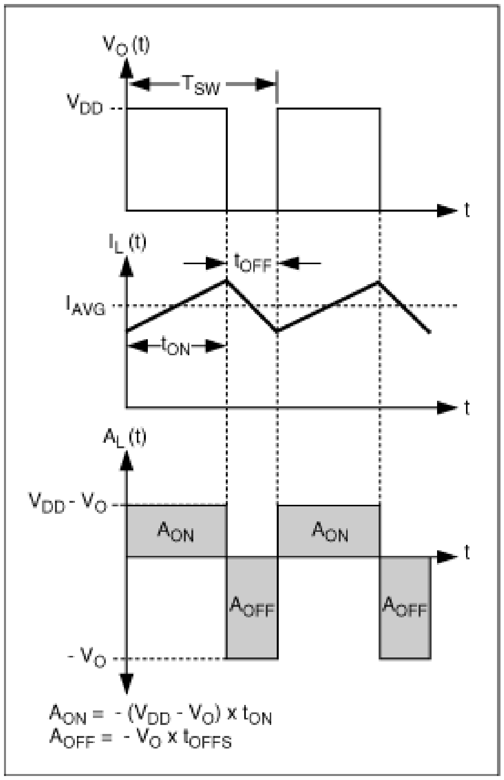

Figure 3. Filter inductor current and voltage waveforms are shown for a basic half-bridge Class D amplifier.

$$\frac{1}{L}\int_0^{T_{SW}} V_L(t)dt = I_L(T_{SW}) - I_L(0) = 0 \qquad \text{(Eq 2)}$$

Equation 2 shows that the integral of the inductor voltage over one switching period must be equal to 0. Using equation 2 and examining the $V_L(t)$ waveform shown in Figure 3, it is clear that the absolute values of the areas (A_{ON} and A_{OFF}) must be equal to each other in order for equation 2 to be true. With this information, we can now derive an expression for the filtered output voltage in terms of the duty ratio of the switching waveform:

$$A_{ON} = |A_{OFF}| \qquad \text{(Eq 3)}$$

$$A_{ON} = (V_{DD} - V_O) \times t_{ON} \qquad \text{(Eq 4)}$$

$$A_{OFF} = V_O \times t_{OFF} \qquad \text{(Eq 5)}$$

Substituting equations 4 and 5 into equation 3 gives the new equation:

$$(V_{DD} - V_O) \times t_{ON} = V_O \times t_{OFF} \qquad \text{(Eq 6)}$$

Finally, solving for V_O gives:

$$V_O = V_{DD} \times \frac{t_{ON}}{t_{ON} + t_{OFF}} = V_{DD} \times D \qquad \text{(Eq 7)}$$

where D is the duty ratio of the output-switching waveform.

Using Feedback to Improve Performance

Many Class D amplifiers utilize negative feedback from the PWM output back to the input of the device. A closed-loop approach not only improves the linearity of the device, but also allows the device to have power-supply rejection. This contrasts with an open-loop amplifier, which inherently has minimal (if any) supply rejection. Because the output waveform is sensed and fed back to the input of the amplifier in a closed-loop topology, deviations in the supply rail are detected at the output and corrected by the control loop. The advantages of a closed-loop design come at the price of possible stability issues, as is the case with all systems utilizing feedback. Therefore, the control loop must be carefully designed and compensated to ensure stability under all operating conditions.

Typical Class D amplifiers operate with a noise-shaping type of feedback loop, which greatly reduces in-band noise due to the nonlinearities of the pulse-width modulator, output stage, and supply-voltage deviations. This topology is similar to the noise shaping used in sigma-delta modulators. To illustrate this noise-shaping function, **Figure 4** shows a simplified block diagram of a 1st-order noise shaper. The feedback network typically consists of a resistive-divider network but, for simplicity, the example shown in Figure 4 uses a feedback ratio of 1. Also, the transfer function for the integrator has been simplified to equal 1/s because the gain of an ideal integrator is inversely proportional to frequency. It is also assumed that the PWM block has a unity-gain and zero-phase-shift contribution to the control loop. Using basic control-block analysis, the following expression can be derived for the output:

$$V_O(s) = \frac{1}{1+s} \times V_{IN}(s) + \frac{s}{1+s} \times E_n(s) \qquad \text{(Eq 8)}$$

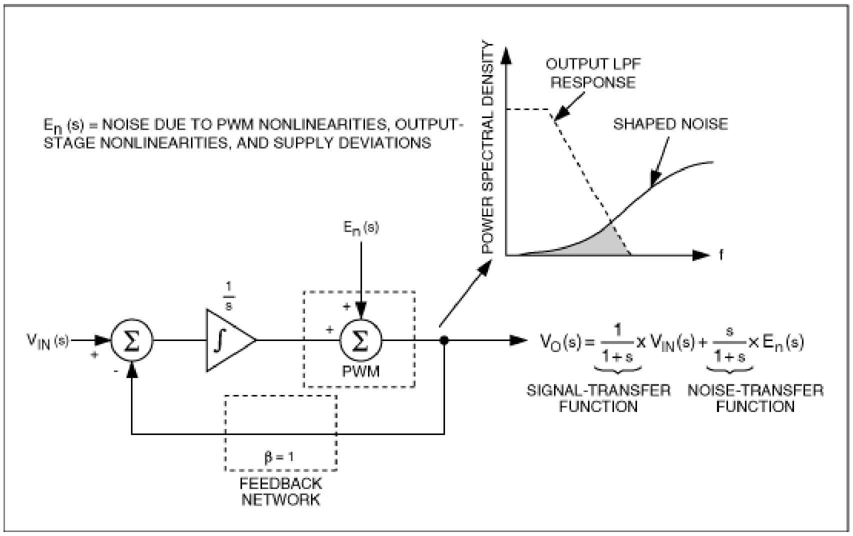

Figure 4. A control loop with 1st-order noise shaping for a Class D amplifier pushes most noise out of band.

Equation 8 shows that the noise term, $E_n(s)$, is multiplied by a highpass filter function (noise-transfer function) while the input term, $V_{IN}(s)$, is multiplied by a lowpass filter function (signal-transfer function). The noise-transfer function's highpass filter response shapes the noise of the Class D amplifier. If the cutoff

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