PWM AMPLIFIER INTRODUCTION

The recent availability of high-voltage and high-current PWM amplifiers in hybrid packages has attracted the interest of many designers who traditionally use linear amplifiers. The advantage of PWM amplifiers is obvious: efficiency of 70 to 97%. High efficiency translates to lower internal power loss, smaller heat sinks, and reduced overall physical size.

To make it easier to design with these amplifiers, a simple and versatile generic PWM Spice model lets you check out PWM waveforms without the fear of blowing up the amplifiers or getting shocked by high voltages. The methodology behind generating such a model applies not only to hybrid PWM amplifiers, but also to monolithic and discrete PWM amplifiers. The inputs to the model come from the PWM amplifier’s data sheet, and you can run the model on any commercial Spice program.

Even though a PWM amplifier offers analog signals in and analog signals out, its circuit functionality is entirely different from a linear amplifier’s. A PWM amplifier modulates a pulse train in the time domain and uses LC filtering to extract the analog-signal output. You can use PWM amplifiers to emulate linear constant-voltage amplifiers or linear constant-current amplifiers, both at much higher levels of efficiency.

If you’re unfamiliar with how a PWM amplifier works, you’re not alone. Just like op amps, PWM amplifiers come in many sizes and flavors, some with fancy bells and whistles. Fortunately, the amplifiers all operate under the same principle.

A PWM amplifier converts an analog signal into a pulse train of variable duty cycle. The analog input controls the duty cycle of the output pulse train, which switches on and off once during each cycle. When a high output is necessary, the pulse train switches on most of the time and vice versa.

Figure 1a shows a basic PWM amplifier. Vin is the analog input of 1 to 8V dc. AOUT is a pulse train, and BOUT is its inverse. The PWM oscillator determines the frequency of the pulse train, and some PWM amplifiers allow you to put in your own PWM oscillator. As Vin changes from its minimum to its maximum value, the duty cycle of AOUT changes from 0 to 100%, and the duty cycle of BOUT changes from 100 to 0%. The difference voltage of AOUT–BOUT has the same pulse train as AOUT but with double the amplitude of 2xVs p-p (Figure 1b).

If you connect a dc brush-type motor across AOUT and BOUT, you can control the motor speed with Vin. When you set Vin in the middle of its range, for 50% duty cycle at AOUT and BOUT, the motor stands still. With Vin at its maximum, the motor turns at maximum rpm; with Vin at its minimum, the motor reverses direction of rotation and turns at maximum rpm again. You can directly connect AOUT and BOUT to a motor because the winding inductance of the motor turns the pulsed voltage into a rippled dc current whose magnitude controls the motor speed and whose polarity controls the clockwise or counterclockwise direction of the motor. As Figure 1a indicates, most other applications need LC filters to filter out the PWM pulse train to ensure that an analog signal appears at the load.

USE A GENERIC SPICE MODEL

Figure 2 shows the generic Spice subcircuit model of a PWM amplifier. V1 is a ramp of fixed frequency. E1 serves as a comparator that converts the PWM ramp as it crosses Vin into a variable-duty cycle pulse train (Figure 3). S5, V5, S6, and V6 limit the amplitude of the pulse train to ±5V. S1/R1, S2/R2, S3/R3, and S4/R4 represent the four MOSFET drivers for which
R1, R2, R3, and R4 are the respective on-resistances. The four MOSFETs always turn on and off in diagonal sets, that is, when S1 and S4 are on, S2 and S3 are off and vice versa. The inverter X1 provides the diagonal switching control. ISENSE A and ISENSE B are current-sensing terminals, usually available at two output pins for current-feedback control circuitry. For open-loop operation or for voltage-feedback control, just connect ISENSE A and ISENSE B to ground.

When an external load connects between AOUT and BOUT, current flows from Vs to ground through one of two routes: Vs to S1/R1, to an externally connected load between such as motor-torque control and battery chargers. You can use the model and the specifications of a commercial PWM amplifier—in this case, the Apex Microtechnology SA50—to design a constant-current amplifier (also called a voltage-to-current converter). You start out with the following specifications from the SA50 data sheet:

**Analog input voltage/output duty cycles:**
- Vin=4V; AOUT=0% and BOUT=100%
- Vin=6V; AOUT=50% and BOUT=50%

**Design Example: Constant–Current Amplifier**

You commonly use constant-current amplifiers for applications such as motor-torque control and battery chargers. You can use the model and the specifications of a commercial PWM amplifier—in this case, the Apex Microtechnology SA50—to design a constant-current amplifier (also called a voltage-to-current converter). You start out with the following specifications from the SA50 data sheet:

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**Notes:**
- Vin: –10 to +10V.
- I(Load)/Ein = –0.5 A/V.

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- Vin: –10 to +10V.
- I(Load)/Ein = –0.5 A/V.
Analog input voltage range of 4 to 8V dc and the switching frequency of 45 kHz determine the waveform of the PWM ramp (Figure 4), which V1 in Figure 2 produces. You can describe this waveform as a constant-voltage source in any commercial Spice program, such as Intusoft's Model ICAP/4Rx V8.8.1. You enter V1's parameters as manual-driven inputs, and this Spice program automatically generates the following statement for V1:

Vin=8V; AOUT=100% and BOUT=0%

switching frequency: 45 kHz.
MOSFET on-resistance: 0.5Ω total or 0.25Ω each

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\[ V1: V1 \text{ to } 0 \text{ PULSE } 4 \text{ to } 8 \text{ with offset at Vin produces a } 120 \text{V pp sine wave across the load (Figure 7).} \]

\[ L = \text{Load} \times R_{load}^2. \]

To complete the design of a constant-current amplifier, you must have some means of sensing the load current and provide feedback control in case of a load change. Ra and Rb are the two current-sensing resistors. Op amp X4 and its associated components serve two purposes: first, as a difference amplifier with a gain of 20 that converts the current difference between Ra and Rb into a voltage output of –0.5A/V and, second, as a lowpass filter comprising C1, C2, C6, and C7 that filters the ripple currents in Ra and Rb with a corner frequency of 4.5 kHz. The design equations are as follows:

\[ \text{To minimize power losses, you should choose Ra and Rb values of 0.01 to 0.1Ω. In this example, } Fc=4.5 \text{ kHz, } R8=R9=10 \text{kΩ. To minimize loading effects, these resistors must be much greater than } R13=R15=100Ω. \]

Substituting these values into

\[ \text{GAIN} = -\frac{R9}{R10 \times Ra} \text{A/V}, \]  

\[ C6 = C7 = \frac{1}{2\pi \times R13 \times Fc}, \]

\[ C1 = C2 = \frac{1}{2\pi \times R10 \times Fc}. \]
Equation 7 and Equation 8, \( C6 = C7 = 0.35 \, \mu F \), and \( C1 = C2 = 180 \, \mu F \). Choosing \( R10 = 200 \, k\Omega \), Equation 6 yields a gain of \(-0.5 \, A/V\).

\( X3 \) is an integrator that compares the output voltage from \( X4 \) with the input voltage \( E1 \) and provides the correct input voltage for the \( SA50 \) amplifier to close the feedback loop. The design equations for the integrator are as follows:

You can complete the design by choosing \( R12 = R14 = 10 \, k\Omega \) and \( C3 = 71 \, nF \) (Figure 6).

You can now run the Spice program. The load current waveforms (Figure 8) are as expected. Note that there is a small error between the Spice output and the expected value.

\[
R12 = R14, \quad C3 = \frac{1}{2\pi \times (0.05\, \mu F) \times R12}. \tag{10}
\]

For example, with \( E1n = 10V \), the expected output current should be \(-5A \), but Figure 8 shows \(-4.8A \). This difference is because of the loss resulting from the 0.25\( \Omega \) MOSFET's on-resistance. If you set the on-resistance to zero, you get exactly waveforms (Figure 8) are as expected. Note that there is a small error between the Spice output and the expected value.

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LISTING 1—SA50 CONSTANT-CURRENT-AMPLIFIER SPICE CIRCUIT

```
#save V(12) V25 @R4[p] @R4[p] V(3) @R1[p] @R1[p] V(5)
#save V(29) @R3[p] @R3[p] V(7) @R2[p] @R2[p] V(9)
#save @Vs[p] @Vs[p] V(10) @S4[p] @S4[p] V(11) @S2[p] @S2[p]
#save @S3[p] @S3[p] @S1[p] @S1[p] V(12) @V[p] @V[p] V(13)
#save V(18) @E1[p] @E1[p] V(19) @Vs[p] @Vs[p] V(8) @S6[p] @S6[p]
#save @V6[p] @V6[p] V(17) @Road[d] @Road[d] @Load[d] @Rb[d] @Rb[d]
#save @R[d] @R[d] V(16) @V[d] @V[d] V(20) @R[d] @R[d]
#save @R[p] @R[p] @R[p] @R[p] V(18) @R[p] @R[p] V(3) @V[p] @V[p]
#save @V[p] @V[p] @V[p] @V[p] V(21) @V[p] @V[p] V(21)
#save @V[2] @V[2] @V[2] @V[2] V(28) @Ro[d] @Ro[d] @Ro[d]
#save @V2[p] @V2[p] @V2[p] @V2[p] V(23) @V2[p] @V2[p] @V2[p]
#VIEW TRAN Y1
#alias Y1 @Road[d]
.TRAN 22.2E-9 4000E-6 0 22.2E-8 UIC
.PRINT TRAN Y1
R4 1 2 0.25
R1 3 230.25
R3 5 290.25
R2 7 190.25
Vs 9 0 DC=80
S4 29 1 100 _S4_mod
.MODEL _S4_mod SW VT=2.5 RON=1E-9 ROFF=1E9
S2 23 7 10 _S2_mod
.MODEL _S2_mod SW VT=2.5 RON=1E-9 ROFF=1E9
S3 9 5 11 _S3_mod
.MODEL _S3_mod SW VT=2.5 RON=1E-9 ROFF=1E9
S1 3 9 10 _S1_mod
.MODEL _S1_mod SW VT=2.5 RON=1E-9 ROFF=1E9
X1 11 10 INV() 
.SUBCKT INV 1 2
* In out
B1 3 0 V= -V(1)
RD 3 2 1
CD 2 0 .87NF
.ENDS
V1 12 0 PULSE 4 8 0.11E-6 11.1E-6 11E-6 1E-6 12 22.2E-6
E1 13 0 12 18 1E9
#save @E[10] @E[10]
L1 23 4 400u
V5 15 0 DC=5
S6 11 8 0 13 _S6_mod
.MODEL _S6_mod SW VT=2.5 RON=1E-9 ROFF=1E9
V6 0 8 DC=5
Rload 17 6 16
V2 0 22 DC=12
Lload 4 17 1m
Rb 25 0 1
Ra 19 0 1
X4 16 14 20 21 22 PA21 ()
.SUBCKT PA21 1 2 3 4 5
* PINOUT ORDER +IN -IN OUT +V -V
```

The LC filter design is similar to that of the constant-current amplifier except the LC filter requires no matching network because of the 8Ω resistive load (Figure 9a). The SA02 amplifier’s PWM frequency is 250 kHz, so the design sets the LC filter’s corner frequency to 25 kHz. The design of the difference amplifier (X4) is somewhat different, however. This constant-voltage amplifier configuration senses the output voltage, not the output current. The voltage at AOUT and BOUT is much higher than the voltage across the current-sensing resistors in the previous example. Instead of boosting the gain, resistor dividers lower the sense voltage to levels that a small signal amplifier can handle. The integrator’s (X3) time constant is faster to provide the frequency response necessary for audio applications. The SA02 audio-speaker driver has a –10V/V voltage gain and a 10-kHz power bandwidth. Figure 9b shows the circuit’s input and output waveforms. Note that it takes about 50 µsec for the output’s sine wave to stabilize.

FIGURE 9 (B). A similar model using specifications from the SA02 amplifier is part of a constant-voltage feedback amplifier (a). The output sine wave takes about 50 µsec to stabilize (b).
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