1.6- to 3.6-volt BTL speaker driver reference design

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Introduction

As supply voltages decrease, there is a need for low-voltage analog solutions to real-world design problems. Consider a system that operates directly from the voltage provided by two single-cell alkaline batteries. When the batteries are fresh, the voltage may be as high as 1.8 V per cell. After depletion, the voltage across a cell may be as low as 0.8 V. While there are many solutions that work above the 2.5-V supply threshold, few amplifiers operate as low as 1.6 V to fully utilize the potential of the battery. The TPA610xA2 family of headphone audio power amplifiers, however, provides adequate output power levels at these low voltages. By bridging the outputs from the two linear amplifiers within the TPA610xA2 device across the speaker load, it is possible to get an increase in output power without increasing the supply voltage. This configuration (shown in Figure 1) is called a bridge-tied load (BTL).

While the schematic in Figure 1 is typical of the output architecture for a dedicated BTL amplifier like the TPA7x1 family of audio power amplifiers, the output structure is not the same in the TPA610xA2 family of devices. Figure 1 shows a non-inverting amplifier driving the high side of the load and an inverting amplifier driving the low side. In contrast, Figure 2 shows the internal circuitry of the TPA6101A2 with two inverting amplifiers driving the differential output.

For the remainder of this article, two different BTL configurations that can be implemented with the TPA610xA2 family will be presented. The first configuration works with a differential-input signal applied to the inputs of the amplifier, while the second configuration is suited for a single-ended input signal applied to one input of the amplifier. Also, thermal considerations need to be addressed with the increase in output power that the BTL configuration provides. Finally, the effect of offset voltages in this configuration will be discussed.

Figure 1. BTL driver

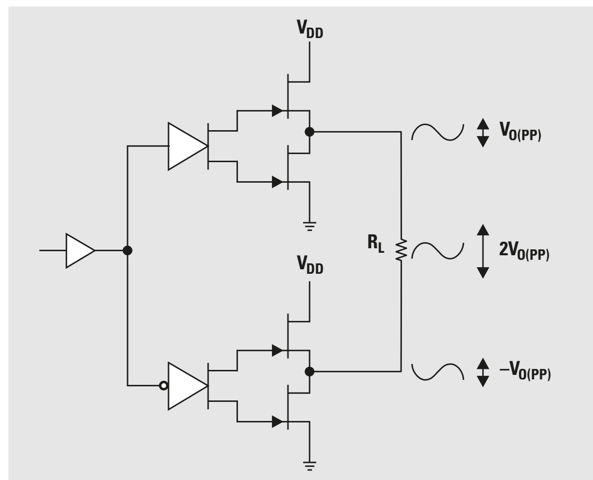
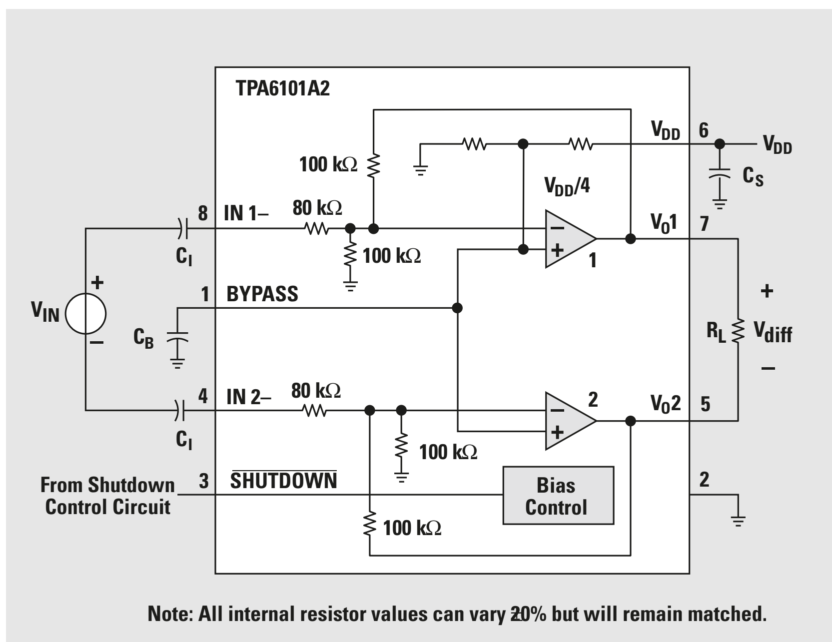


Figure 2. TPA6101A2 configured as a differential-input BTL Driver



BTL configuration for a differential input

The circuit shown in Figure 2 utilizes the TPA6101A2, which has internal gain-setting resistors for an inverting gain of 2 dB. Since the input signal is connected differentially across the inputs, the outputs are 180° out of phase with respect to each other. With the load connected across the outputs, the differential drive across the load means that one output is moving in the positive direction while the other output is moving in the negative direction. This effectively produces a voltage swing across the BTL that is two times the voltage swing seen across a

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ground-referenced load. Inserting $2V_{O(PP)}$ into Equation 1 and substituting V_{rms} into Equation 2 shows that the power to the load (P_L) increases to four times the power seen across a ground-referenced load. Theoretically, this is four times the power to the load from the same supply voltage and load impedance. In actuality, current limiting and thermal considerations will limit the actual power realizable in this configuration.

$$V_{rms} = \frac{V_{O(PP)}}{2\sqrt{2}} \quad \textbf{(1)}$$

$$P_L = \frac{(V_{rms})^2}{R_L} \quad \textbf{(2)}$$

BTL configuration for single-ended (SE) input

If the inverted output signal of amplifier 1 is connected to the inverting input terminal of amplifier 2, the TPA6100A2 can take an SE audio input and provide an inverted signal to the top side of the resistive load and a non-inverted signal to the low side of the bridge-tied load.

Figure 3 shows an SE input that is capacitively coupled through C1 and connected to the inverting terminal of amplifier 1 through R_I1. Since the positive terminal of amplifier 1 is internally connected to a bias voltage of $V_{DD}/4$, the following transfer function for amplifier 1 is obtained based on an inverting gain of the ac-coupled input signal and a non-inverting gain of the internal bias voltage.

$$V_O1 = V_{IN}\left(\frac{-R_f1}{R_I1}\right) + \left(\frac{V_{DD}}{4}\right)\left(1 + \frac{R_f1}{R1}\right) \quad \textbf{(3)}$$

Therefore, if $R_f1 = R_I1 = R1$, the result is an inverted representation of the input signal biased at $V_{DD}/2$. The gain can be increased to a value greater than 1 by adjusting the ratio of R_f1 and R_I1. However, R1 must be set equal to R_f1 in order to bias the output at mid-rail, maximizing output swing. Notice the connecting wire between the output of amplifier 1 and the input of amplifier 2. Once again, this input is capacitively coupled through C2 to remove the $V_{DD}/2$ bias and is connected to the inverting input of amplifier 2 through R_I2. The feedback network must be set with $R_f2 = R_I2 = R2$ so that amplifier 2 provides an inverting gain of 1 and the output of amplifier 2 is a non-inverted representation of the input multiplied by any gain established by amplifier 1, G_1.

$$G_1 = \frac{R_f1}{R_I1} \quad \textbf{(4)}$$

$$V_O1 = -V_{IN}G_1 + \frac{V_{DD}}{2} \quad \textbf{(5)}$$

$$V_O2 = V_{IN}G_1 + \frac{V_{DD}}{2} \quad \textbf{(6)}$$

$$V_{diff} = V_O1 - V_O2 = -2G_1V_{IN} \quad \textbf{(7)}$$

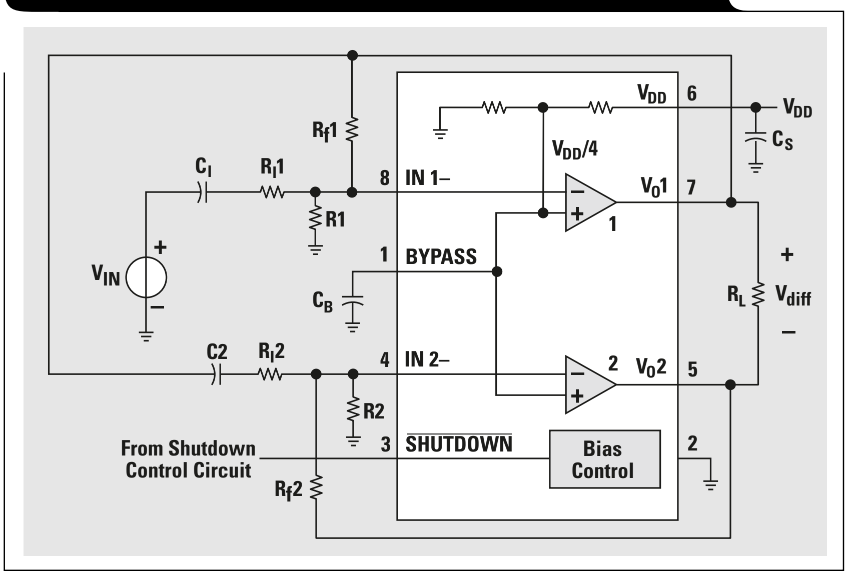
Note that only the TPA6100A2 can be used in this configuration because the gain of the internal amplifiers can be externally set. The remaining members of the device family, the TPA6101A2 and the TPA6102A2, have a fixed gain of 2 dB and 5 dB, respectively. Since the gain is greater than 1, a gain mismatch will exist between the non-inverted and inverted output signals. In the case of the TPA6102A2 with 5 dB of gain, this configuration could cause some large voltage swings across the load with an additional gain of 5 dB in amplifier 2. The differential input configuration (shown in Figure 2) can be constructed with all members of the TPA610xA2 family. The TPA6100A2 device will simply require the use of external resistors, while the other devices will not.

Thermal considerations

Although the bridged amplifier pair will provide four times the power to the load, the power dissipated in the amplifier package will be greater than the normal power dissipated when operated with a ground-referenced load. More power dissipated by the amplifier pair results in more heat that can lead to reliability problems over time. Using maximum allowable junction temperature values for a given power to the load, we can solve for the maximum recommended ambient temperature. Table 1 lists the maximum $I_{DD(rms)}$ for a given junction temperature based on the TPA610xA2 architecture. It also lists the maximum power output for an 8-ohm load where $P_L = I_{DD(rms)}{}^2 \times R_L$.

By choosing a P_L value from Table 1 that is close to the power desired in the system, we can use Equation 8 to calculate the power dissipated in the amplifier, given a supply voltage (V_{DD}) and load (R_L). For example, if V_{DD} = 3 V, R_L = 8 ohms, and a desired power of 0.146 W is chosen, we can calculate P_{dis} = 0.219 W. By inserting this value into Equation 9 and using the θ_{jA} value for the two available packages, we find that the maximum ambient temperature

Figure 3. TPA6100A2 configured as a SE-input BTL driver



for reliable operation is 58.1°C for the MSOP package and 76.5°C for the SOIC.

$$P_{dis} = \frac{4V_{DD}\sqrt{(2P_L R_L)}}{2\pi R_L} - P_L, \text{ and} \tag{8}$$

$$T_{a(max)} = T_j - \theta_{jA} P_{dis}, \tag{9}$$

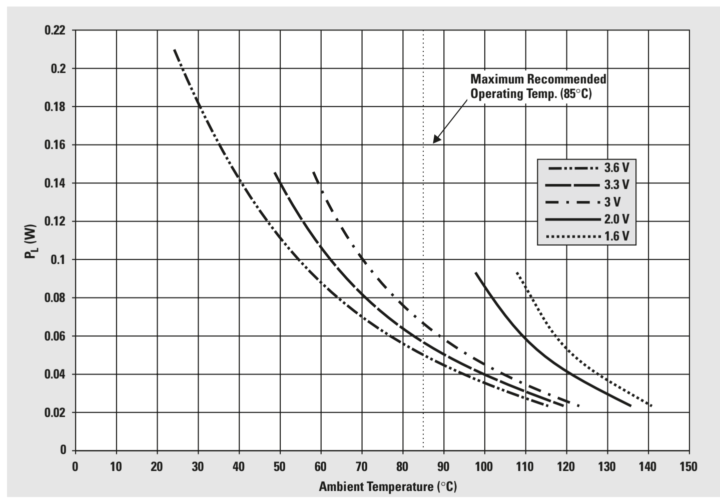
where θ_{jA} = 260°C/W (MSOP) and
θ_{jA} = 176°C/W (SOIC).

Figure 4 is a plot of the maximum ambient temperature vs. power in an 8-ohm load for given supply voltages. The curves are limited to show only the power output possible with the TPA610xA2 configured as a BTL driver. These curves can be used to determine safe operating points for the long- term reliability of the device. Ambient temperatures to the left of the curve represent the "safe zone," while temperatures to the right of the curve are not recommended. The dotted line labeled "maximum recommended operating temperature" indicates that, for proper device functionality, the ambient temperature must not exceed 85°C for the TPA610xA2 family. Using Equations 8 and 9, the circuit designer can generate curves for different loads and a different package.

Table 1. Junction temperature as it relates to P_L

JUNCTION TEMP. MAXIMUM (°C)	$I_{DD(rms)}$ MAXIMUM (mA)	P_L MAX. (8-ohm LOAD) (W)
89	270	0.583
102	189	0.286
106	162	0.210
115	135	0.146
124	108	0.093
137	81	0.052
150	54	0.023

Figure 4. Power vs. maximum ambient temperature for an 8-ohm load (MSOP package)

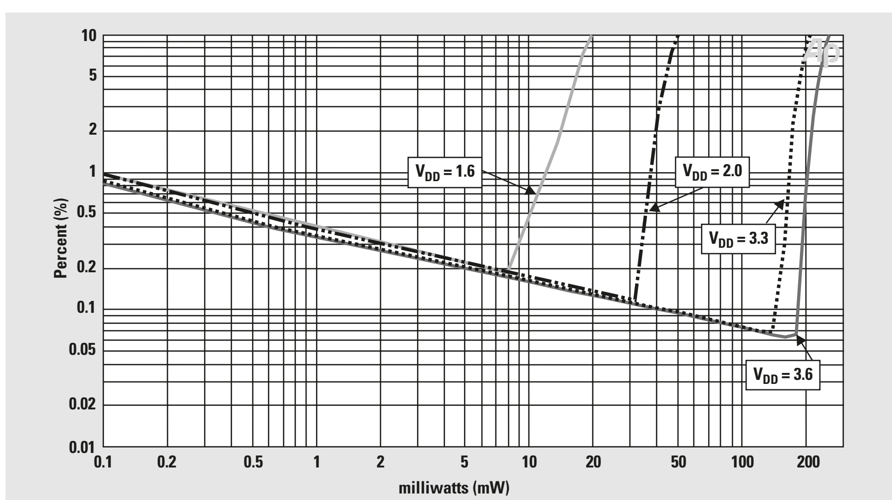


DC offsets in the BTL

Each amplifier in the TPA610xA2 will have an inherent offset voltage associated with it. If the offsets are of equal magnitude and sign, they will cancel across the BTL just like the V_{DD}/2 bias. However, the worst-case scenario for the differential input configuration is an offset of equal and opposite sign. In this case, the dc offsets will add across the load. The offset of the TPA610xA2 is typically 2 mV. With the worst-case scenario, that would result in 4 mV across the load. The worst-case in the single-ended case is also an offset of equal magnitude and opposite sign in each amplifier. Since the output of channel 1 is connected to the input of channel 2 through a series capacitor, the worst-case offset is again equal to 4 mV.

The offset for this particular device is not of great concern. If the offset was larger, it could cause overheating in the speaker voice coil due to the constant power dissipated in the coil. A large offset will also cause displacement of the speaker cone from the normal rest position, which could cause distortion and damage the speaker in the long term.

Figure 5. THD+N vs. power for an 8-Ω load at V_{DD} = 1.6, 2.0, 3.3, and 3.6 V



Results

The differential circuit shown in Figure 2 and the single-ended circuit shown in Figure 3 were examined in the lab with an Audio Precision™ (AP) instrument to measure total harmonic distortion plus noise (THD+N) vs. power across the load. Both circuits produced nearly identical results, so only the single-ended input circuit plots are shown. The plots in Figures 5-7 show data taken with an 8-, 16-, and 32-ohm load, respectively. There are four traces within each plot that represent 1.6-, 2-, 3.3-, and

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3.6-V supply voltages. As shown in Figure 7, the maximum power achieved with 0.1% distortion into a 32-ohm load is approximately 110 mW at 3.3 V and 16 mW at 1.6 V. It is expected that as the load decreases, the power should increase based on Ohm's law. However, the curves in Figure 5 show a decrease of about 8 mW going from 32 ohms to 8 ohms for a 1.6-V supply.

This can be explained by understanding the maximum voltage swing possible at the different supply voltage rails and the current necessary to drive the BTL configuration. Since each amplifier in the BTL configuration is effectively driving half of the load resistance, each amplifier must source 2x the current sourced when the load was referenced to ground. Each amplifier is capable of driving within a few hundred millivolts of each rail for a 10-kΩ load. As this load decreases, the amplifier can no longer source the current necessary to drive the signal to the rail, and clipping will occur at some voltage from the rail. The voltage drop from the rail will continue to increase as the load decreases. Reducing the supply voltage to 1.6 V further complicates the problem because, as V_{DD} decreases, the available voltage to enhance the MOSFET output drivers also decreases. This results in higher $r_{DS(on)}$ values and larger voltage drops from the rail. With all of this in mind, it is a good idea to set the gain of the amplifier to a level that will limit clipping at the lowest expected supply voltage.

Figure 6. THD+N vs. power for a 16-Ω load at V_{DD} = 1.6, 2.0, 3.3, and 3.6 V

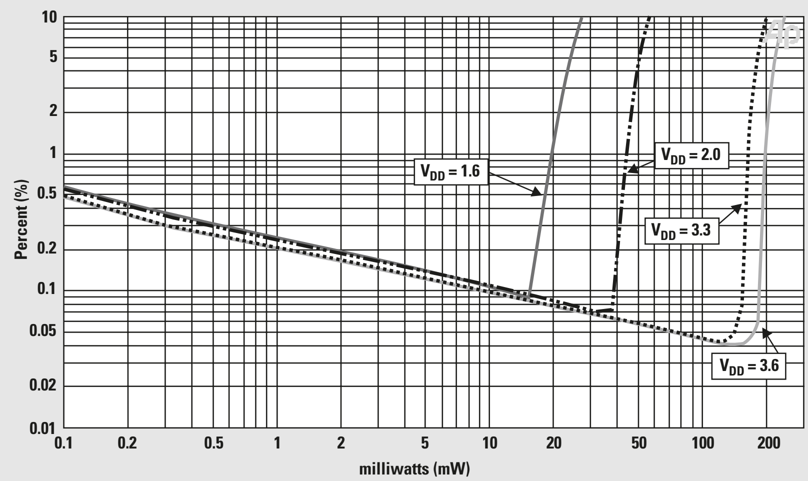
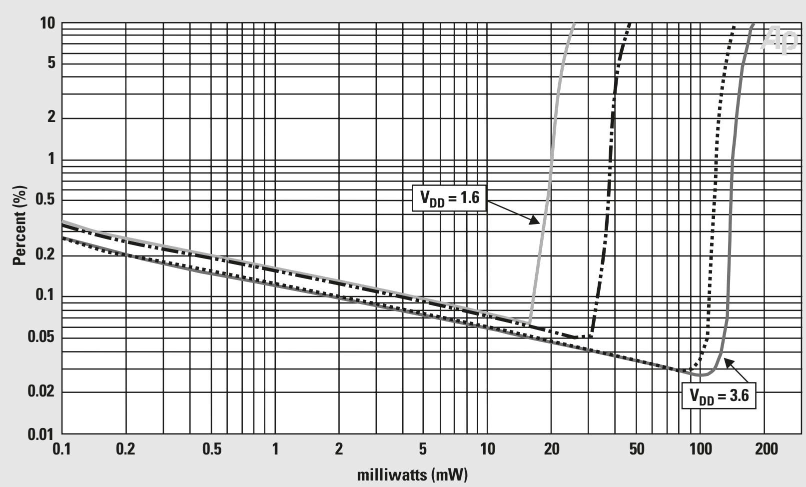


Figure 7. THD+N vs. power for a 32-Ω load at V_{DD} = 1.6, 2.0, 3.3, and 3.6 V



Conclusion

While the TPA610xA2 family was not originally designed as a BTL driver, it can be configured as such for both single-ended and differential inputs and used over the full range of two single-cell alkaline batteries. Careful consideration should be given to the thermal limitations of the package chosen and the power desired across the load. For supply voltages that are held above 2.5 V, the TPA7x1 family of audio power amplifiers or the TPA0211 is recommended to provide better drive capability at 2.5 V and up to 5.5 V. These devices are also available in the PowerPAD™ package to alleviate some of the thermal stresses on the device at these power levels.

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