Power Supply Considerations for DDX® Amplifiers

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Table of Contents

Abstract

The best performance of any audio amplifier is achieved when it is powered by a regulated power supply. Many audio amplifiers incorporate regulated power supplies to minimize distortion and audio compression effects. A serious problem with linear regulated power supplies is that they will waste between 30 to 50% of their total input power as heat inside the amplifier. When we then add the linear amplifier's power losses, the total can be as high as 75%, with only 25% of the input power actually going to the speaker.

With high efficiency amplifiers, like the all-digital **DDX**® amplifier series, the power supply regulator should be a high efficiency switching type to keep down the overall power losses. Unfortunately, switching power supplies typically cost more than unregulated "brute force" power supplies. This paper offers a high efficiency regulation solution that offers some of the benefits of a switching power supply's efficiency while still being very cost-effective like an unregulated power supply.

Introduction

When an unregulated power supply is not delivering power to the load the voltage is high, but when maximum power is delivered to the load the voltage can drop by 25% or more. Power supply ripple will increase when fully loaded and, due to the power supply rejection ratio (PSRR), appears directly in the output of traditional audio amplifiers as a noise signal. It is usually a direct function of the amplifier's PSRR and appears at a fairly constant level relative to the maximum power output. A conventional amplifier's maximum signal swing has to be set lower than the minimum voltage of an unregulated power supply so that clipping does not occur.

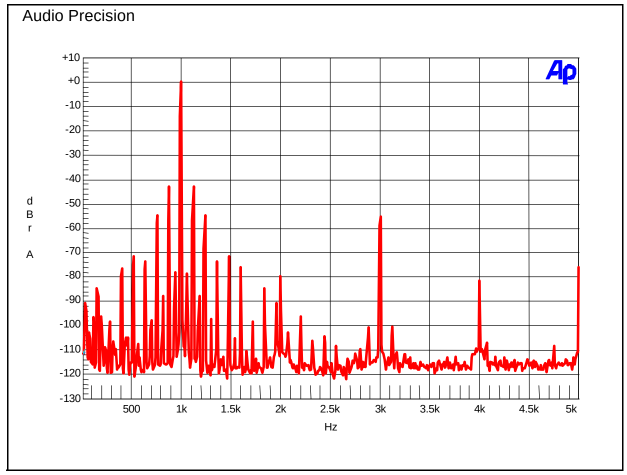


Figure 1. FFT of a DDX® Amplifier, one channel driven -3 dBFS @ 1 kHz, with an unregulated supply, showing AM sidebands due to 120 Hz power supply ripple.

When **DDX®** all-digital amplifiers are used with unregulated power supplies, AM sidebands appear due to the power supply ripple. These sidebands vary directly with the ratio of the AC ripple voltage to the DC voltage. Note that these sidebands disappear completely when the output is in the no-signal or damped state. With the power supply used in this paper, the sidebands measured 40 to 45 dB below the actual output level with one or two channels operating. As **Figure 1** shows, the output has acceptable power supply ripple rejection because the energy content consists of just amplitude modulation (AM) sideband noise around the 1 kHz carrier. There is almost negligible (-85 dBFS) 120 Hz fundamental content. The sidebands do not appear as harmonic distortion because they are not harmonically related to the carrier frequency. Instead they appear as noise or non-harmonic distortion in the THD+N plot. Due to psycho-acoustic frequency masking, these sidebands become virtually undetectable in a real listening environment.

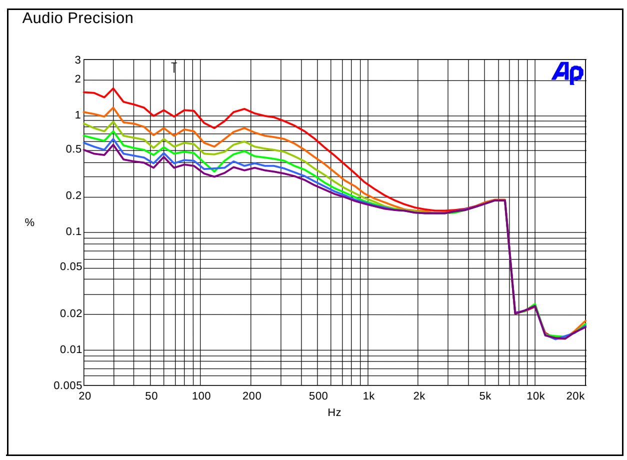


Figure 2. Measured THD+N vs Frequency. Unregulated supply powering two DDX® channels @ -3dBFS (10.74 W /channel, 21.4 Vdc, 0.13 Vrms, 0.42 Vp-p). Upper trace is for a capacitance of 9400 uF. Each successive trace adds one more 4700 uF capacitor for a total of 32,900 uF.

As a first approach, one might try to just add more capacitance to reduce the power supply ripple but, as **Figure 2** shows, this method requires enormous capacitance with diminishing benefit as each capacitor is added.

When using a **DDX®** amplifier with an unregulated supply it is possible to reasonably simulate some of the more desirable audio performance characteristics of a regulated power supply by floating a Low Drop-Out (LDO) regulator circuit in series with the supply's output. Connecting the Low Drop-Out regulator's reference pin to a capacitor-smoothed voltage divider across the **DC input**, rather than to the regulator's own output voltage, will "float" the output voltage as a percentage of the DC input voltage. Two different ripple attenuator designs are reviewed: one that uses a commercial Low-Drop-Out (LDO) adjustable regulator, and one that uses a high beta quasi-NPN series pass transistor as a regulation element. They both effectively remove 40 dB or more of ripple while preserving excellent overall efficiency. The following design examples were designed and tested to work with up to four 8-ohm, or two 4-ohm DDX® amplifier channels simultaneously.

Design Example 1: Using a 3-Terminal Low-Drop-Out (LDO) Regulator

We'll first design a ripple attenuator for use with an inexpensive, brute force, unregulated 24 V supply. We start with the following values that are typical for a fully loaded supply:

V_{high} = 24.0 V (Supply not loaded.)
V_{low} = 18.0 V (Supply loaded at 2 A.)
V_{pp} = 1.5 V (Ripple will be close to zero when supply is not loaded.)
V_{LDO} = 0.3 V (This is the LDO regulator's drop-out voltage.)
V_{reg} = 2.5 V (The regulated output voltage of the LDO.)
I_{GND} = 125 uA (Quiescent current through the LDO's GND pin.)

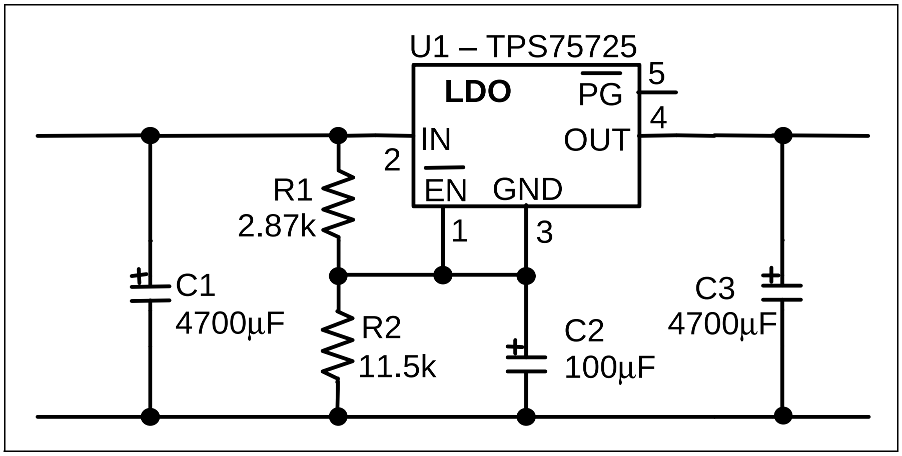


Figure 3. LDO Ripple Attenuator Schematic

The chosen LDO regulator sources 125 uA to the resistive divider through its GND pin. Since we want this current to have a negligible effect on the voltage divider resistors, we choose R_1 such that its no load current is ~1.25 mA (10 times the GND pin's current). That leads us to the following:

$$R_1 = \frac{\left(\frac{V_{pp}}{2} + V_{LDO} + V_{reg}\right)}{1.25mA} \cong 2870\Omega \qquad \textit{Eq. 1-1}$$

It then follows that:

$$R_2 = \frac{\left(V_{low} - \left(\frac{V_{pp}}{2} + V_{LDO} + V_{reg}\right)\right)}{1.25mA} \cong 11.5k\Omega \qquad \textit{Eq. 1-2}$$

Using these resistance values will assure that the input to the LDO will be above its minimum input voltage of 2.8V as long as V_{low} doesn't go below 14.8 volts. In order to attenuate the A-C ripple across C_2 by 40 dB we need to set the corner frequency to less than 1/100th of the AC ripple frequency (120 Hz), or 1.2 Hz. We can now calculate:

$$C_2 = \frac{1}{2pf\left(R_1 // R_2\right)} = 58mF \qquad \text{(100 µF was used in the test circuit.)} \qquad \textit{Eq. 1-3}$$

Calculating the voltage across C_2:

$$V_{C2} = \frac{R_2 * V_{low}}{R_1 + R_2} = 14.4V \qquad \textit{Eq. 1-4}$$

Adding the regulator's voltage, we now find that the output voltage is:

$$V_{out} = V_{C2} + V_{reg} = 16.9V \qquad \textit{Eq. 1-5}$$

Audio compression will be directly proportional to the change in V_{out}:

$$\text{Compression Ratio} = \frac{\left(\dfrac{V_{Low} * R_2}{R_1 + R_2} + V_{reg}\right)}{\left(\dfrac{V_{High} * R_2}{R_1 + R_2} + V_{reg}\right)} = .779:1 \text{ or } -2.17\ \text{dB} \qquad \textit{Eq. 1-6}$$

In this example, for a 1.1 volt power supply reduction we have effectively removed the ripple. The primary sidebands in the output are now reduced by an additional 40 dB to -85 dB and secondary sidebands are lost in the noise floor. See **Figures 7a and 7b.**

Since the leakage current through the regulator and bleeder are negligible, the output efficiency will be:

$$h \cong \frac{Vout}{Vin} = \frac{16.9}{18} = 0.94 \qquad \textit{Eq. 1-7}$$

If we now factor in the **DDX**® amplifier's 88% efficiency, the overall efficiency is 82.6%. Since the best-case average efficiency of most analog audio amplifiers is less than 50% this means that, using the same transformer, rectifiers and capacitors, **a DDX® amplifier with an LDO version ripple attenuator delivers 65% more power to the load than an analog audio amplifier.**

Design Example 2: Using a Series Pass Transistor.

We'll now design a transistor-based ripple attenuator for use with the unregulated 24 V supply. We'll use the following values that are typical for a fully loaded supply:

V_{high} = 24.0 V (supply not loaded)
V_{low} = 18.0 V (supply loaded at 2A)
V_{pp} = 1.5 V (Ripple will be close to zero when supply is not loaded.)
V_{Dsat} = 1.0 V (The quasi-darlington's saturation voltage = V_{be1} + $Q2_{sat}$)
V_{be2} = 0.65 V (The maximum base-emitter voltage for Q2.)
H_{fe1} = 40 (@ 3A)
H_{fe2} = 100 (typ.)

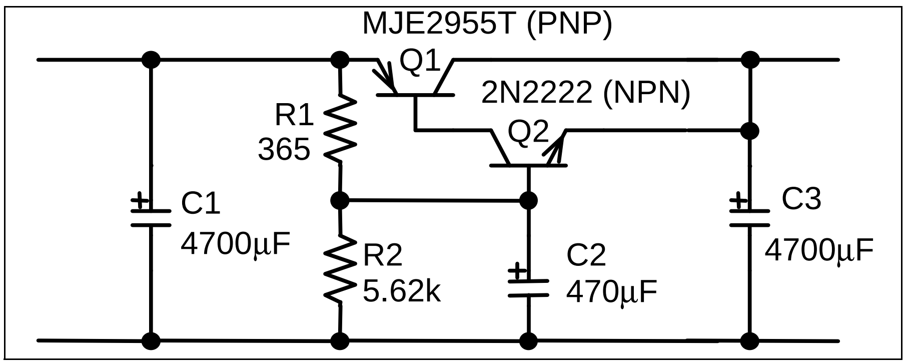


Figure 4. Transistor Ripple Attenuator Schematic.

In this design, since the effective H_{fe} of the Q1-Q2 pair is 4000, the current drawn into the base of Q2 is:

$$I_{b2} = 2A/4000 = 0.5mA$$

We would normally use 10 times Q2's possible base current but we want to economize in the losses and use minimally sized resistors. As we shall see, 6 times the base current is a fair compromise and works out OK. We will use 3 mA for the bleeder current in the resistor divider:

$$I_{bleeder} = 3.0mA$$

The current in R_1 is now 3 mA at no load and 3.5 mA at full load. It then follows that:

$$R_1 = \frac{\left(\frac{V_{pp}}{2} + V_{Dsat} - V_{be2}\right)}{I_{bleeder}} \cong 365\Omega \qquad \textit{Eq. 2-1}$$

Calculating at low voltage, but without considering Q2's base current:

$$R_2 = \frac{V_{low} - \left(\frac{V_{pp}}{2} + V_{Dsat} - V_{be2}\right)}{I_{bleeder}} \cong 5.62k\Omega \qquad \textit{Eq. 2-2}$$

Notice the sign reversal for V_{be2} as opposed to V_{reg} in Example 1. In this design, the voltage drop across R_1 increases with the load current because the current drawn into the base of Q_2 increases the voltage drop across R_1. While this gives us added ripple margin protection at peak currents it also adds just slightly to the compression effect.

For a 1.2 Hz corner frequency (with R1 in parallel with R2), C_2 must now be:

$$C_2 \approx \frac{1}{2pf\,(R_1 // R_2)} = 387 mF \qquad \text{(470 μF was used in the test circuit.)} \qquad \textit{Eq. 2-3}$$

Calculating the voltage across C_2 at full load (2 A):

$$V_{C2} = V_{low} - R_1 * (I_{bleeder} + I_{b2}) = 16.72V \qquad \textit{Eq. 2-4}$$

We now find that:

$$V_{out} = V_{C2} - V_{be2} = 16.07V \qquad \textit{Eq. 2-5}$$

Audio compression will still be directly proportional to the change in V_{out}. Note that the compression equation fully accounts for the voltage drop caused by Q2's base current:

$$\text{Compression} = \frac{\left(V_{Low} - R_1 * (I_{bleeder} + I_{b2}) - V_{be2}\right)}{\left(\frac{V_{High} * R_2}{R_1 + R_2} - V_{be2}\right)} = 0.734 : 1 \text{ or } -2.69\text{dB} \qquad \textit{Eq. 2-6}$$

Since almost all the current for the pass elements goes to the output, the efficiency will be:

$$h \cong \frac{Vout}{Vin} = \frac{16.07}{18} = 0.89 \qquad \textit{Eq. 2-7}$$

Factoring in the **DDX**® amplifier's 88% efficiency, the overall efficiency becomes 79%. Since the best-case efficiency of an analog audio amplifier is less than 50% this means that, using the same transformer, rectifiers and capacitors, <u>**a DDX® amplifier with a transistor version of the ripple attenuator delivers 58% more power to the load than an analog audio amplifier.**</u>

We have again removed the ripple and improved the sound. The AM sidebands in the output are again reduced by 40 dB to -85 dB as in Design Example 1. See **Figures 7a and 7b.**

A Word About Compression

When audio amplifiers run with unregulated power supplies and the output load increases, the voltage sag can translate directly to a reduction in audio output. This effect is called 'compression'. The gain of most linear amplifiers is set such that the amplifier operates as if the minimum voltage at full load is all that is available. By not using all the voltage that is available at all times the output transistors act as linear voltage regulators and dissipate this excess power as heat for medium level passages. This results in lower power output and poorer efficiency.

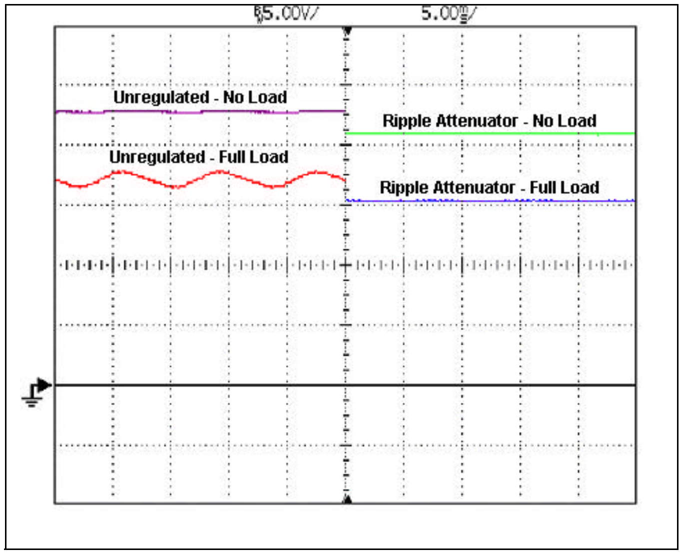


Figure 5. Voltage waveforms of the ripple attenuator vs. an Unregulated Supply, both delivering 50 Watts.

For the unregulated supply that we have been discussing, the ratio of no-load to full-load voltage is 0.750:1. That means that it is responsible for about 2.50 dB of compression. Table 1 shows the ratio of full-load to no-load supply voltage for the three cases:

The LDO method yields less compression and the transistor method slightly more compression than the unregulated supply, but they each differ by LESS THAN ±0.4 dB from the unregulated supply. This difference in compression between the three methods is audibly unnoticeable. Up to this point we have been discussing steady state or RMS power. Most audio content has a fairly small average power but periodically has short bursts of full power. The power supply's stored energy can deliver high power for repeated short bursts without voltage sag. This effect is called "**dynamic headroom**" and effectively reduces the impact of compression to just the sustained loud passages.

Type	**Ratio**	**DB Ratio**
LDO Regulator	0.779:1	2.17 dB
Unregulated	0.750:1	2.50 dB
Transistor Reg.	0.734:1	2.69 dB

Table 1. Ripple Attenuator Ratios.

Conclusions

Voltage regulation with either version of the ripple attenuator approximately tracks the unregulated supply itself, but AM sidebands in the amplifier's output are decreased by about 40 dB by reducing the 120 Hz power supply ripple. Unlike a linear amplifier, the 120 Hz ripple fundamental 'disappears' (-85 dBFS) in the output of a **DDX**® amplifier.

The top trace of **Figure 6** shows THD+N for a single **DDX**® amplifier channel powered by an unregulated supply. The test equipment doesn't see the AM modulation as distortion but instead adds it in as noise in the curve. In the lower trace, with the ripple attenuator enabled, THD+N is greatly reduced. Remember these are unwanted sidebands, not harmonic distortion that are being removed.

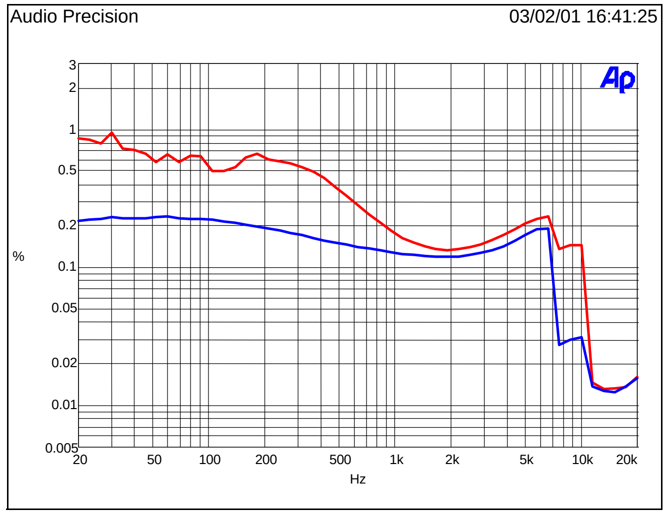
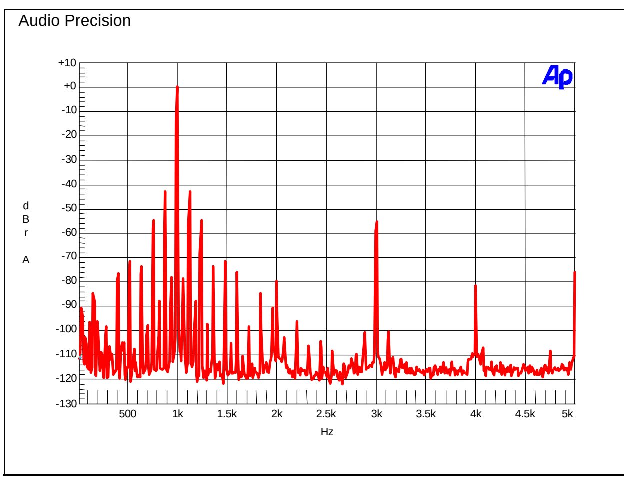


Figure 6. Measured THD+N vs. Frequency.
One Channel driven, 8 Ohm load, Vol. = -3 dBFS.
Top: No **Ripple Attenuator**
Bottom: With **Ripple Attenuator**



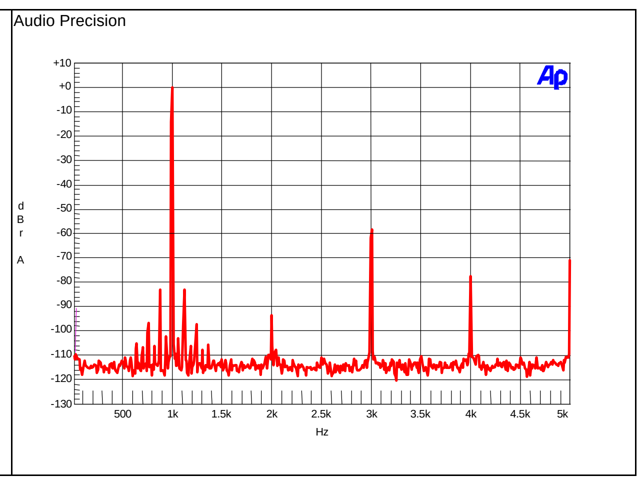


Figure 7a. Normalized FFT of an Unregulated Supply With One Channel Driven to -3 dBFS

Figure 8b. Normalized FFT for the Transistor Ripple Attenuator With One Channel Driven to -3 dBFS.

A comparison of the waveforms in **Figure 7** above shows this clearly. **Figure 7a** shows the sidebands in the output for one channel of a stereo amp running with an unregulated supply. **Figure 7b** shows the greatly reduced sidebands in the output for one channel of a stereo amp running with a transistor version of the ripple attenuator.

The **DDX**® **amplifier** and ripple attenuator combination is still 58-65% more efficient than an analog audio amplifier. Rather than using the additional available output power, one can translate these increased efficiencies backward to the original raw DC power supply configuration and realize additional savings by reducing the size of the power transformer, rectifiers and capacitors as well.

References

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