Tri-Way Low Voltage Supply, Pt. 2

To show the versatility of this supply, the author puts the Tri-Way board through its paces.

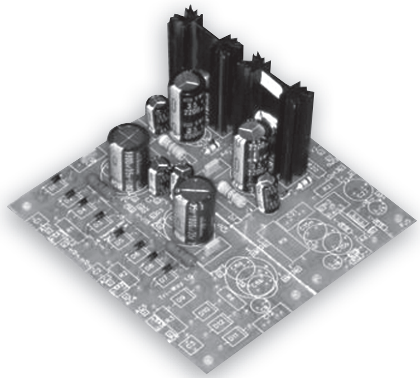

PHOTO 1: The Tri-Way board, with most of the parts installed for use in a compressor.

I'm going to go through three very different designs using the Tri-Way. I'll do the first one the long way, showing all the math; I'll whiz past the other two, stopping only to point out how they differ from the first. To keep the equations straight, I've numbered them.

Before I start, I must remind readers that a good power supply design should not only work under normal conditions, but also should be built to keep working under worst-case conditions. These might include low or high line voltages, components at the limits of their specified tolerances, and high operating temperatures. (Ever work a festival in 100° heat with the mixer in the sun? I have.) I design for multiple worst-case scenarios, and my supplies very seldom fail or misbehave.

EXAMPLE 1: THE COMPRESSOR

This was the *ur*-circuit, the one for which the board was conceived. It's pretty standard stuff: a dual-channel compressor which requires a maximum of 0.25A from ±15V supplies. (Seem like a lot? The compressor itself pulls only 65mA; the rest is to light the metering LEDs.) I'll refer to part numbers for the + supply; the - supply will use the same values.

The first step is to specify a few givens. I'm using two separate transformer windings, so I'll use D1-D8 to produce two bridge rectifiers. R4 will be 1Ω; C4 will tentatively be 1000µF, and C13 will be 3300µF. (If one cap is bigger, I like to put it in the second stage of filtering to minimize turn-on current draw.)

An LM317 drops a nominal reference voltage of 1.25V between its output and adjust terminals. If R16 = 200Ω, then it will draw a total nominal reference current of:

1. Iref = (Vref/R16) + Iadj = (1.25/200) + 0.00005 = 0.0063A (6.3mA)
   (What's Iadj? That's current coming out of the adjust terminal, as specified in the datasheet.)
   For an output voltage of 15V, the adjust terminal should be at:
2. Vadj = Vout - Vref = 15 - 1.25 = 13.75V
   That voltage comes from dropping the reference current through R13, which should be:
3. R13 = Vadj/Iref = 13.75/.0063 = 2183Ω
   The nearest E96 value is 2.21k. If the current is 6.3mA, the power dissipated in R13 will be:
4. P = $(\text{Iref})^2$ * R13 = $(.0063)^2$ * 2210 = .088W

A quarter-watt metal film resistor should be able to handle that without problems. So far, so good.

NOT QUITE NOMINAL

In the real world, though, not everything runs at nominal ratings. Resistors have tolerances, and so do regulators' reference supplies. I've specified 1% resistors; if R16 is 1% low, then its real resistance will be 198Ω. If the regulator, meanwhile, is running at the high ends of its Vref and adjust-terminal current tolerances, then Vref will be 1.3V, and the reference current will be:

5. Iref-hi = (Vref-hi/R16-lo) + Iadj = (1.3/198) + 0.0001 = 0.00667A (6.67mA)
   If, meanwhile, R13 is 1% high, its real resistance will be 2232Ω. Pass the above current through it and you get:
6. Vreg-hi = Vref-hi + (Iref-hi * R16-hi) = 1.3 + (.00667 * 2232) = 16.2V
   And R13 will dissipate, in the worst case:
7. P = $(\text{Iref-hi})^2$ * R13hi = .0992W
   Still pretty reasonable for a quarter-watt resistor.

So under the worst combined conditions, the regulator will be putting out a bit over 16V. This won't hurt the audio circuits any, but it'll affect the design process.

What happens when everything goes in the opposite direction—Vref is at its low limit of 1.2V, R16 is at its high limit of 202Ω, and R16 is at its low limit of 2188Ω? (There's no minimum spec for adjust-terminal current, so I'll use the "typical" figure.) Then (sparing the math):

8. Iref-lo = 5.99mA
9. Vreg-lo = 14.3V
   I'll use those numbers later.
   OK, I've presented the worst case for regulator current draw; it'll be 6.67mA. Since the specified load current is 250mA, total current drawn from the supply will be 256.67mA. Those are more significant figures than necessary; let's call it 257mA, or 0.257A.
   Next you need to figure how much voltage the regulator needs across it to keep regulating properly, known as the "dropout voltage." That comes from a chart in the spec sheet, and, interpolating a little, at this current draw it wants at least 1.8V at a chilly temperature of 10° C. (I've worked gigs like that, too.)
   If the dropout voltage is 1.8V, then you'll need at least:
10. Vunreg = Vreg-hi + Vdropout = 16.2 + 1.8 = 18.0V to maintain regulation under worst-case conditions. I normally add a fudge factor of 0.25V to allow for supply ripple, so I really want:

11. Vunreg = 18.25V

That's the bottom-line number: the raw supply must feed the regulator at least 18.25V.

COLD AND RAW

For the raw supply design, I'll start with the transformer, choosing one with 18V AC. (That's the voltage of each winding; remember that I'm using separate windings for the two halves of the supply.) Nominally 18V AC, that is.

Unfortunately, this is another spot where things don't stay nominal. In the US, fluctuations of ±10% in the volts coming out of the wall are pretty typical, and in most of the country summertime voltages are near the lower end of that tolerance.

This means that I must design the power supply for a transformer that's really putting out, not 18V AC, but 16.2V AC. This runs through the full-wave diode bridge and into a filter capacitor. I make the (deliberately pessimistic) assumption that I'll drop 2.5V in the diodes, and, of course, I'll drop some voltage, Vdrop1, in R4:

12. Vdrop1 = R4 * Itotal = 0.257V

The peak voltage produced by a sine wave is Vac * sqrt(2), so taking the losses (and low line voltage) into account,

13. Vpk-lo = (Vac-lo * sqrt(2)) - 2.5 - Vdrop1 = (16.2 * 1.414) - 2.5 - 0.257 = 20.15V

We've specified that C4 = 1000µF, and C7 is 100µF, so the total input-section capacitance is 1100µF, give or take a bit. How much ripple will there be? This will depend on several factors, but a good rule-of-thumb calculation, when C is expressed in µF and I in amperes, is:

14. Vripple1 = 2400 * Itotal/C = 0.561V AC

A respectably low number. How to compute the DC voltage? Another rule of thumb calculation, again with capacitance in µF and current in amps:

15. V DC = Vpk * (1 - ((4170 * Itotal)/(Vpk * C)))

For this design, at -10% wall voltage, that works out to:

16. V DC-lo = 20.15 * (1 - ((4170 * 0.257)/(20.15 * 1100))) = 19.18V DC

I said earlier that the minimum voltage the regulator wanted to see, Vunreg, was 18.25V DC. So:

17. Vdrop2 = V DC-lo - Vunreg = 19.18 - 18.25 = 0.93V

18. R7 = Vdrop2/Itotal = 0.93/0.257 = 3.602Ω

The first choice would seem to be a 3.6Ω resistor, but what about its tolerance? If it's 5% high, that's 3.78Ω; the voltage drop will be 0.971V. That would make Vunreg = 18.21V. Hmm. . . the difference is only 0.05V under worst-case conditions. I think it's safe to specify a 3.6Ω 5% resistor; the power through that resistor will be:

19. P = $(\text{Itotal})^2$ * R7 = $(0.257)^2$ * 3.6 = 0.238W

A 1W resistor will work, and so will a 2W. Being cautious, I'll go for 2W.

What about the ripple? R7 and the capacitors which follow it (3400µF, more or less) form a low-pass filter; its cutoff frequency Fc is:

20. Fc = 1/(2 * π * R7 * C13||C16) = 13.0Hz

The ripple will be mainly 120Hz (on a 60Hz electrical grid, anyway), and will be reduced by approximately:

21. Fc/Fripple = 13.0/120 = 0.108x

Since the ripple at the first capacitors was 0.561V AC, the ripple on the second capacitors will be:

22. Vripple2 = 0.561 * 0.108 = 0.061V AC

That's plenty low enough to ignore.

DISSIPATION IS RUINATION

The last thing to calculate is the power the regulator will dissipate, worst-case. This happens when the regulated voltage is at its lowest possible value, Vreg-lo, while the wall voltage is at its hottest. We already know Vreg-lo = 14.3V and Vdrop1 = 0.257V DC for this circuit; if the wall voltage is 10% high, the transformer's secondary will be putting out V AC-hi = 19.8V AC. So:

23. Vpk-hi = (V AC-hi * sqrt(2)) - 2.5 - Vdrop1 = (19.8 * 1.414) - 2.5 - 0.257 = 25.25Vpk

24. V DC-hi = Vpk-hi * (1 - ((4170 * Itotal)/(Vpk-hi * C))) = 25.25 * (1 - ((4170 * 0.257)/(25.25 * 1100))) = 24.27V DC

25. Vunreg-hi = V DC-hi - (Vdrop2) = 23.34V DC

So the voltage across the regulator will be:

26. Vregdrop = Vunreg-hi - Vreg-lo = 23.34 - 14.3 = 9.04V DC

And the power dissipated by the regulator, worst-case, will be:

27. P = Vregdrop * Itotal = 9.04 * 0.257 = 2.32W

With a Wakefield 637-10ABP heatsink, the thermal rise should be about 37° C;

assuming an ambient temperature of 40° C, the chip temperature should be 77° C. That should be fine; the LM317T is rated to a chip temperature of 125° C.

The compressor will be attached to the regulator all the time; it draws a minimum current of 65mA. This is enough to keep the regulator regulating happily, so no additional load resistor is required; I'll leave out R19.

EXAMPLE 2: THE FILAMENTS

What about using Supply 2 to produce 6.3V DC at 1.2A, which will power four 12AX7s (wired for 6.3V) or two 6SN7s? To avoid tedium, I won't show most of my work this time.

Looking at the regulator, if Ro-a = 200Ω again, then Radj = 800Ω (nearest E24 is 806Ω). The regulator's dropout voltage (from the datasheet) is 2.25V, so under worst-case conditions the unregulated voltage at the regulator's input needs to be (mumble, mumble) 9.23V DC.

Using the same filter capacitors (1100μF at the input, 3400μF in stage 2 of the filter) and a 12V AC wall-wart transformer, Vpk-lo = 11.57V DC, ripple voltage will be 2.63V AC, and the voltage at the first filter capacitor will be 6.99V DC.

TILT! That's not going to work; the voltage at the first cap is less than the voltage regulator needs to see at its input.

What to do? A higher-voltage transformer would work, of course, but I'm already using a 12V AC transformer to get 6.3V DC; higher seems extravagant. Instead, the best approach is to increase the filter capacitance.

What if I make both big caps 4700μF (plus 100μF from the little electrolytics in parallel)? Now the voltage at the first filter cap is 10.52V DC, and the ripple is about 0.6V AC. That's better; doing the arithmetic for the dropping resistor R8, it should theoretically be 1.07Ω; 1.0Ω is the next lowest value.

Putting that much current through a 1.0Ω resistor will dissipate 1.21W, so R8 needs to be a hefty one; that's why I left room on the board for 5W dropping resistors. (Come to think of it, I should probably juice up R5, too; there's *just* enough room on the board for a 3W Panasonic metal oxide resistor.)

With these values the ripple at the regulator's input will now be 0.17V AC, a level I can live with.

What about heat? At high line voltage the worst-case regulator dissipation will be (more mumbles) a bit over 8W. Uh-oh; with the little heatsink I used in Example 1, the temperature rise will be 128° C, and if the ambient temperature is 40° C the chip will be sizzling at 168° C.

This clearly calls for a bigger heatsink. The Wakefield series I specified for this board goes up to 2.5″ high, which provides significantly lower thermal resistance, but with this kind of power I think it's time to punt by putting the regulators off-board. The LM317K and LM337K come in TO3 packages (available from Mouser), and something like a Wakefield 680-125A heatsink mounted on short spacers would dissipate 8W handily. I could mount this heatsink on the outside of the cabinet, provided I used a plastic insulating cover on the regulator itself, since there is voltage on the case.

EXAMPLE 3: THE PHANTOM WALKS!

For the third example, I'm going to use Supply 3 for +48V DC phantom power to run a couple of microphones. Phantom-powered mikes draw varying currents, but the worst case would be dead shorts, which would draw 14mA apiece. (Not that you would care about the regulation if the mike is a dead short.) I'll also want to draw another 15mA to preload the regulator (I'll get to that in a bit), for a total of 43mA.

With a voltage this high, I'll use a TL783 regulator instead of an LM317, and that changes a few things. The TL783 has higher dropout voltages and adjust-terminal currents, and its nominal reference voltage is 1.27V instead of 1.25V. (Oddly, the tolerance limits are still the same, 1.2V and 1.3V.) Texas Instruments recommends that the adjust terminal not be bypassed with a capacitor, so I can leave out C24.

Setting the reference resistor R18 to 1k, the nominal current is:

28. Iref = (Vref/R18) + Iadjust = (1.27/1000) + 0.000083 = 0.00135A (1.35mA)

    To get 48V DC from the output I'll need:

29. Vadj = Vreg - Vref = 48 - 1.27V = 46.73V DC

    And the adjusting resistor will be:

30. R15 = 46.73/.00135 = 35,071Ω

    The nearest E96 value is 34.8k. Maximum current through the adjust string will be 1.42mA, and maximum power dissipation in R15 will be 0.071W, so a quarter-watt resistor will be adequate.

The dropout voltage for a TL783 drawing 43mA is roughly 5V; making the usual allowance for regulator and resistor tolerances (and my 0.25V fudge factor), the voltage at the regulator's input should be at least 57.0V DC.

I'll begin with a 48V AC transformer, C6 = C15 = 470μF and C9 = C18 = 33μF. Doing the usual arithmetic, the DC voltage on the first stage of the filter will be +58.2V DC under low-line conditions. Dropping this to 57.0V DC would require a 28.5Ω resistor; the next-lowest value is 28.0Ω. That'll dissipate 0.055W; a quarter-watt resistor will do. (The nearest E24 value is 27Ω.)

The rest of the design is pretty straightforward; maximum voltage under high line conditions would be 72.1Vpk, and it's prudent to add another 10% fudge factor for a lightly loaded transformer. That means the maximum voltage on the first capacitor could be about +79V DC, so the caps should be rated at 100V working voltage. With the capacitors I specified (the largest 100V units that would fit in the space), ripple voltage at the regulator input will be about 20mV, which is negligible.

What about idle current? Unlike the previous examples, this is a circuit where the current drawn by the load will vary a lot. Some microphones, such as Neumann KM 84s, pull as little as 0.5mA from the phantom supply, while others draw as much as 6mA. Ideally, the regulator should keep regulating under all circumstances, even when there's no microphone connected.

Texas Instruments specifies a minimum current draw of 15mA for the TL783 to perform properly. Under worst-case conditions (Vref = 1.2V DC, R18 = 1010Ω), the adjustment string will draw 1.27mA; to draw 15mA total the load resistor R21 will need to pull an additional 13.7mA. The worst-case low regulated voltage will be 45.0V DC, so a 3278Ω resistor will do the job. The next-lowest E24 value is 3k, which actually draws 15mA under nominal conditions.

How much heat will R21 dissipate? If the regulator is at its highest possible voltage (50.1V DC) and the resistor is at the low limits of its tolerance (2850Ω), then:

31. Pdiss = $((50.1)^2)/2850$ = 0.88W

    A 2W resistor is the minimum for reliable performance, and since there's room on the board for a 3W Panasonic metal-oxide resistor, that's what I'd use.

Finally, the regulator will dissipate 1.14W under worst-case circumstances, which the smallest specified heatsink will handle easily.

BRIEF DIVERSIONS

It might occur to you that the above calculations are the sort of thing that spreadsheets do well. That's correct; I've designed a spreadsheet which does them, but it's not quite ready for prime time yet. Watch this space.

Speaking of spreadsheets, I've produced an Excel file with parts lists for the three examples above; it's posted on the magazine's website, www.audioXpress.com. The lists include the power transformers and all the parts on the boards except mechanical bits (insulating washers, standoffs, pins, and so on).

WINDING UP

The Tri-Way board can be useful for a variety of projects; I've left open as many options as possible, in the hope that readers will find new ways to make it sit up and do tricks.

As I said when I wrote up the Gamp supply, I no longer fabricate my own circuit boards; the chemicals are more toxic and messy than I want to deal with, and I can at least hope that commercial manufacturers have better facilities to handle and dispose of the stuff safely. You may not agree, so I've made a board layout that's posted on the *audioXpress* website; it's as close to the fabricated layout as my graphics programs will allow.

Or, of course, you could buy your board(s) from me; like the Gamp boards, the price will be US $24 per unit (there'll be a small discount for quantities >2), plus shipping/handling. You can e-mail me at pstamler@pobox.com, and no, I don't expect to get rich from this project either.

Many thanks to Cory King of the Webster University Audio Construction Club. I hope you have as much fun using this board as I had designing it! **aX**