

Look out!

It's the F5 *TURBO* POWER AMP!

Nelson Pass 2/5/12

Intro

Five years ago I launched the F5 power amplifier project which culminated in a production run of 100 amplifiers and a DIY article. It has proven to be a popular design, and as of this writing approaches 2 million views on DIYAudio.com.

The F5 is a nice simple design, sounds good and measures well. There are other such offerings in the world, but this one seems to have struck a chord in the mind of the DIY enthusiast as well as *paying* customers. Of course it has limited output power at 25 watts, so it is not surprising that there have been numerous requests, complaints and even some independent effort for

MORE POWER. You want more? I give you more.

But First, the Original

If you are not already versed in the design and construction of an F5, I refer you to the original article published in AudioXpress magazine and also to be found at www.firstwatt.com (download the F5 manual from the Products page).

In addition to the details of the design, the article contains lots of tutorial information about how gain devices work. If you have any intentions of playing with an F5 Turbo, you will want to read this material, otherwise when you email me a question about the stuff covered there you will receive an *RTMF* sort of reply. I should add that the nearly 12,000 postings in the F5 thread also cover some of this material, but it's pretty tedious reading them all.

A number of modifications to this have been proposed and even executed by DIYers, including the removal of the current limiting protection circuit, paralleling more and different output devices, balanced operation, cascoding and of course bigger power supplies.

The documentation on the performance of these modifications is unfortunately sparse, and I know that many DIYers won't tackle a project without some "official assurance" that it will work. I played with most of these things during the original development work, and I applaud the people who have done variations independently – please don't complain that I have copied someone else's achievement.

The F5 TURBO v1

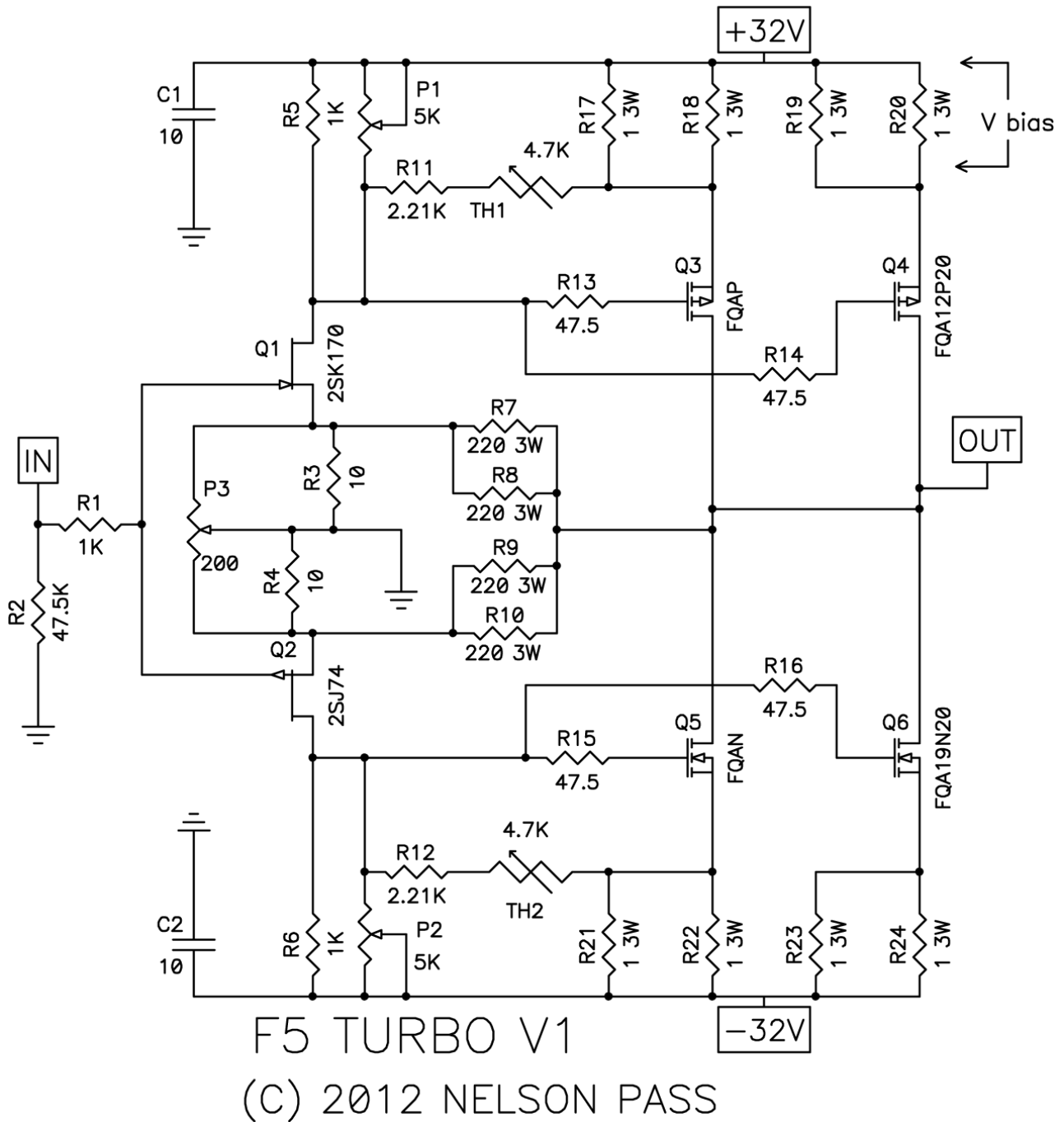
Increasing the power supply voltage is the obvious way to get more power out of an F5. You can simply raise the supply rails to +/-32 Volts and get 50 watts into 8 ohms right away without other modification. 24 V AC secondaries on the power transformer will do it. Don't forget to use higher voltage power supply capacitors. Probably you should also upgrade R9 through R12 to 5 watt resistors. Depending on your heat sinking, you will probably want to adjust the bias so that the power transistors don't run too hot.

As a rule of thumb, the output devices should not be operated at more than about half their maximum rating, and generally the case temperature needs to be under 100 deg C. For most amplifiers this means a heat sink temperature of about 50 to 55 deg C., which is the temperature that you can put your hand on for about 10 seconds.

The devices are biased at about 1.3 amps in the original circuit for a dissipation of about 30 watts per device. We are not in a good position to ask the original heat sinks to dissipate more, so if you increase the supply to 32 volts, you may need to operate at a lower bias point – I used about 1 amp (0.47 volts across R7 and R8). This will still get you a decent distortion spec to 50 watts. If you have difficulty keeping the bias stable, you can increase the values of R7 and R8 to 0.68 ohms without significant penalty.

You can remove the current limiting (Q5, Q6, R15 to R18 of the original) as long as you are cautious about shorting the output. I don't recommend dropping the thermistors – you are going to need them for thermal stability.

Want to drive 4 ohms with this? You can do it, but I recommend that you consider the upgrade to the F5 Turbo V1:



Here you see the F5 without the limiters and with an additional set of output devices. With adequate heat sinking, you can bias them to 1 amp each, for a total of 2 amps, which will operate the circuit Class A well above 100 watts peak into 8 ohms. You probably take the bias to 3 amps with enough sink.

The more technically astute DIYer may note that the input Jfets are now being exposed to greater voltage and dissipation, and this might be a concern. With respect to voltage, the operating point of these devices is around 30 volts, 5 volts over their rating. In actual testing these devices break down around 43 volts, and I depend on Toshiba's famed conservatism to carry the day. If you don't want to trust Toshiba as much as I do, then you can cascode these devices, which is covered here later.

The average dissipation of the Jfets with a 32V supply will be about 28 volts times the operating current. A 2SK170 or 2SJ74 with a 10 mA I_{dss} will operate at about 8 mA in this circuit, which gives a dissipation of about 220 mW. A quick calculation shows that its maximum junction temperature at 220 mW is reached with an ambient temperature of about 70 deg C. A wise DIYer will either select a Jfet with a lesser I_{dss} (say 8 mA) and/or see to it that the Jfets gets some cool air or a little heat sink. Or you can cascode them.

You may also notice that the feedback resistors R7 through R10 have been increased, increasing the amplifier's gain to about 22 dB and decreasing the amount of feedback by about 7 dB. If we are going to put out more power it is appropriate to have some more gain, and it gives us more margin for feedback stability – the amplifier still is flat to about 800 Khz. Of course we have noted that the 100 ohm resistors will start to cook at the higher power levels, so we would be making some changes to them anyway.

Along the same lines you will also notice is that I have doubled up the Source resistors to a parallel pair of 1 ohm values in order to increase the dissipation from 3 watts to 6 watts.

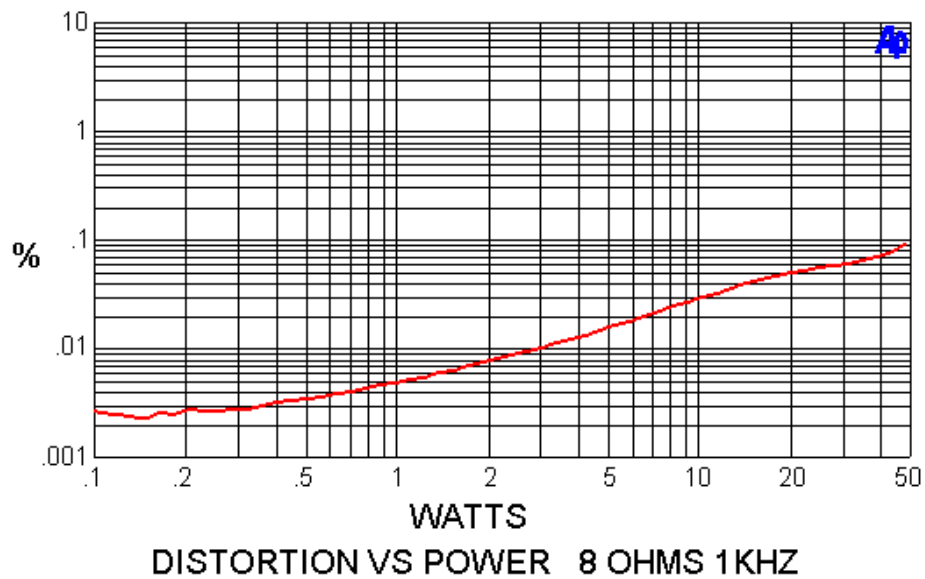
I built a few V1 circuits into a standard First Watt stereo F5 chassis, and you can see it here:



And here is the inside:



No, they are not for sale. These were biased low at 1 amp per channel and gave the following distortion curve into 8 ohms:



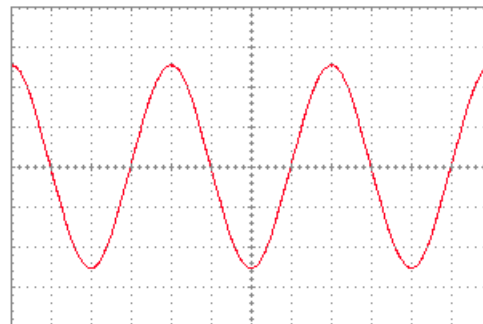
Less feedback and lower bias means a little more distortion, and this does about 0.005% at 1 watt, where the original did about 0.002%.

You can just see the slight hump in the curve at 0.05% and 20 watts where it transitions out of Class A. This is a common artifact – you can go through Stereophile's measurements of amplifiers and see examples where a high bias Class AB amplifier does a similar transition.

Into 4 ohms the hump becomes more pronounced and the amplifier is seen to clip at 100 watts output. If you have a more heat sinking available (a mono version of the F5 chassis would do) you can do better yet with higher bias, in which case the hump goes away.

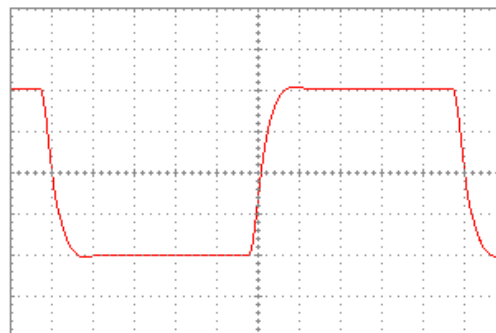
At 1 amp bias, these sinks only run warm, but if you are after the highest performance, you want to run as much bias current as you can.

Here is a photo of V1 doing a clean 1 Khz sine wave into 0.1 ohms showing peaks of +/-23 amps. This amplifier will poop out slightly above 1 ohm.



28 AMP PEAK INTO 0.1 OHM

I mentioned that it pretty much retains the bandwidth of the original in spite of a doubled up output stage. Here is a 100 Khz square wave at 1 V rms.

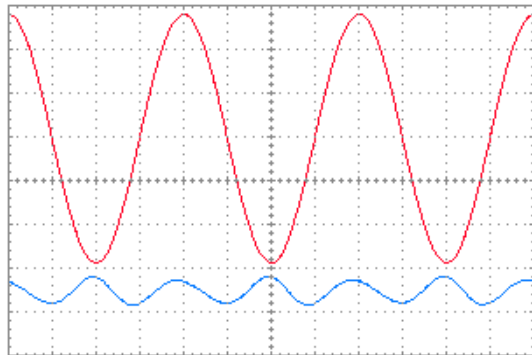


100 KHZ SQUARE WAVE @ 1V

Subjectively this is a little different than the original. The lesser amount of feedback and larger output stage makes it seem a little more authoritative while at the same time a little more relaxed. I say that because the listener (me) experiences more relaxation.

One thing that many will appreciate is the addition of P3, which due to inattention on my part was not public until recently. It allows the adjustment of the distortion character between complete nulling of the second harmonic distortion to an arbitrary ratio of second to third harmonic. It definitely alters the sound, and reaffirms that things going on below 0.1% are audible. In any case, you can adjust it to taste.

Here is what the waveform looks like when the second harmonic is allowed to be about 0.03%:



P3 ADJUSTED FOR 2ND HARMONIC

So where do we go from here?

F5 TURBO v2

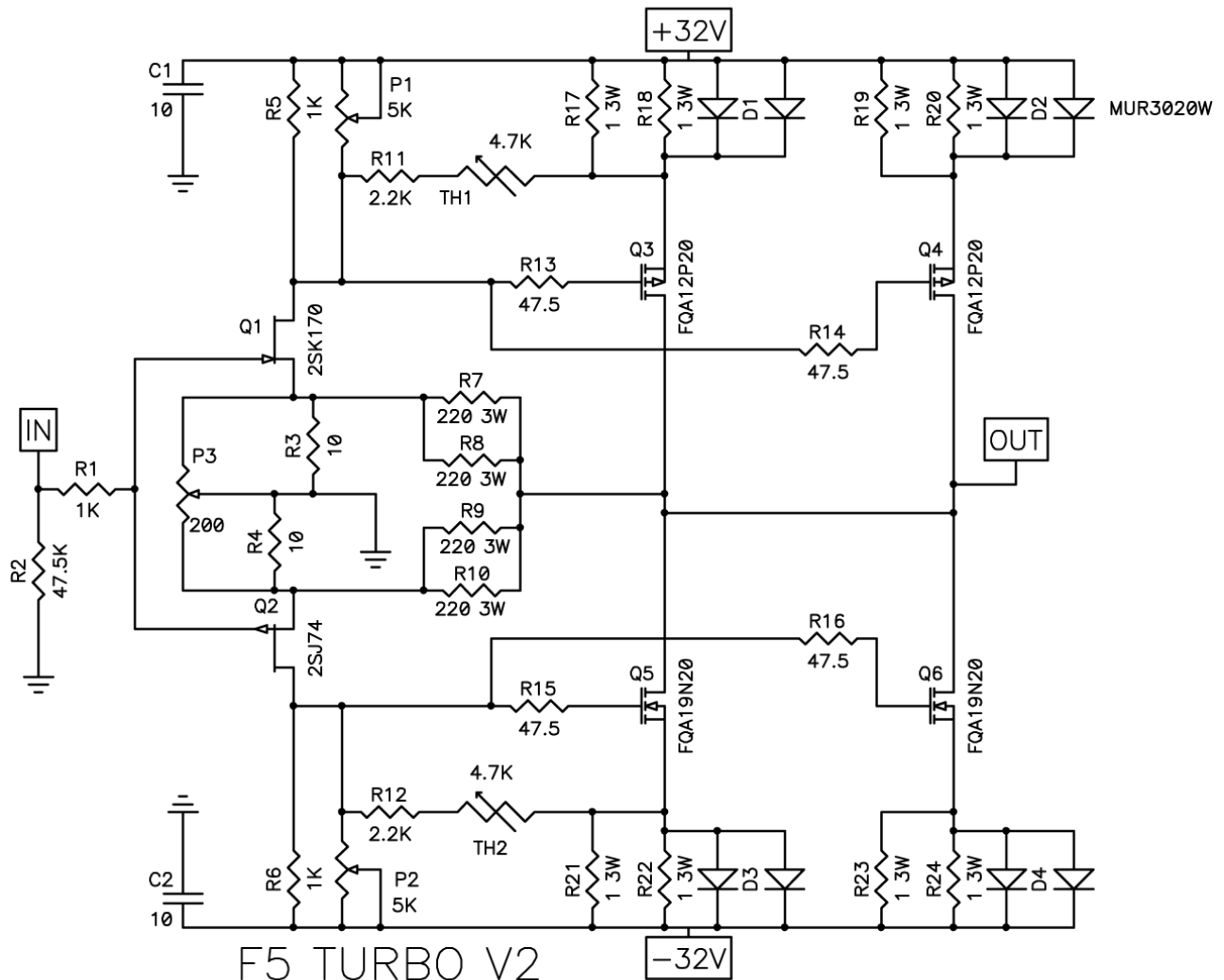
One of the things holding back the amount of current we can deliver is the power supply and the Source resistors we use to ballast the output devices. The output devices themselves are not usually the culprits, having been designed to switch rather high currents. The Fairchild devices originally specified in this design can do 22 amps each. You might therefore expect a pair of them to peak out at 44 amps, but from V1 you see that with 0.5 ohms of Source resistance they only give you about 23 clean amps.

What if you remove the Source resistance altogether?

First off, you get the 44 amps. In addition, with Fets you get an output stage that will deliver more Class A power at a given bias figure due to the square law character of the Fets. Unfortunately you also tend to get a thermally unstable circuit that is prone to bias hogging. This is true of Vertical Mosfets and even more so with Bipolar transistors. There are a couple of examples of high end amplifiers on the market which boast no ballast resistance, but the praise for their sound is accompanied by rumors about reliability.

As an alternative, you can consider carefully matched Lateral Mosfets which have a declining temperature coefficient. Unfortunately they tend to have lower current ratings, and so are not suited to this particular goal.

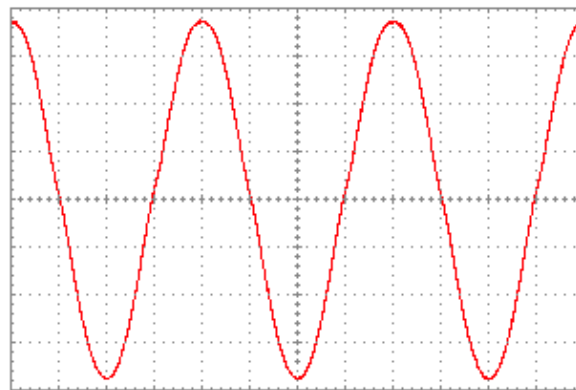
Fearless Amplifier Builders (FAB) might just go ahead and try output stages without Source or Emitter resistors. For the rest of you, here is the V2:



F5 TURBO V2
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It looks just like V1 except that there are some diodes in parallel with the Source resistors of the output devices. These are some of those fancy new-fangled high speed power diodes from Vishay, MUR3020W, rated at 400A peak and having an equivalent resistance of about .03 ohms per parallel pair. Inserting these in parallel with the 0.5 ohm Source resistance gives us an impedance which is very low at high currents but devolves to the 0.5 ohm value at less than an amp.

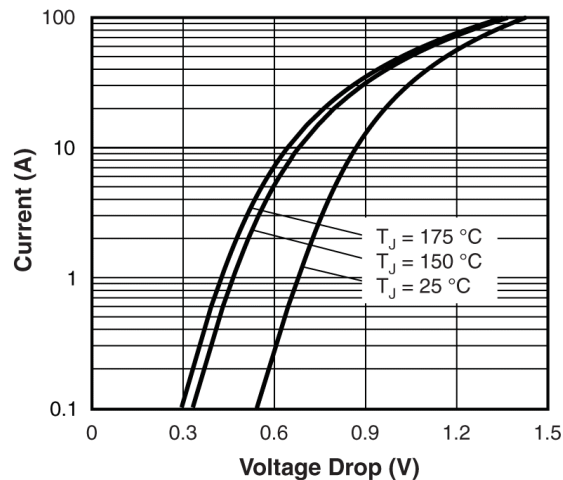
The result is that the amplifier can now deliver 38 amp peaks:



38 AMP PEAKS INTO 0.1 OHM

Well, that was easy. The distortion character at ordinary power levels is pretty much the same, and ditto for bandwidth and such. Actually it's pretty much the same until you get a couple amps going to the load, and then the F5 Turbo starts flexing its newfound muscles.

You do have to watch a couple of things. Here is a curve from Vishay's spec sheet that gives the voltage drop versus current for different temperatures.



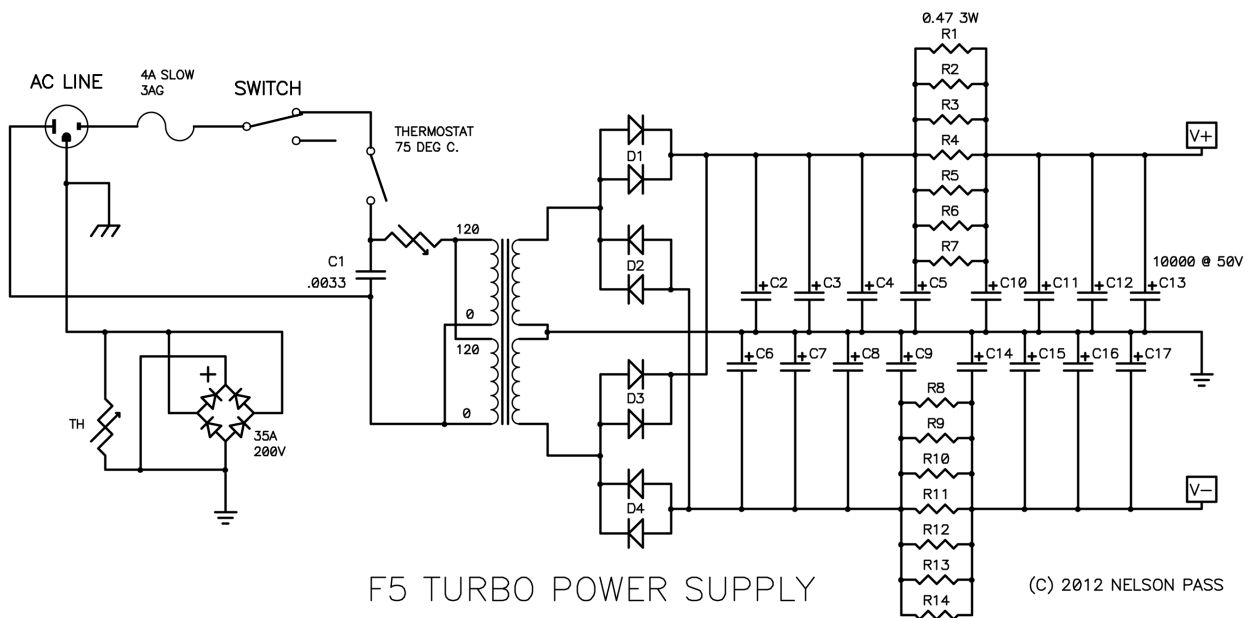
We see that these devices will slowly start conducting at voltages just above the idle voltage across the 0.5 ohm Source resistors. It will be necessary to heat sink these diodes, remembering that their case is electrically connected.

The point at which the diodes conduct is temperature dependent, so you will want to set the bias so that it makes a nice transition above the bias point and doesn't run away when the amplifier gets hot.

If you are competent, fearless and also own a fire extinguisher, you can find this point. Just run the amplifier into a reasonably low impedance until it gets good and hot – as hot as you plan to let it get - ever. Then adjust the bias to a point below where the idle current starts to really take off. You should find that this point is around 0.4 volts across the 1 ohm resistors. If you are a fraidy-cat, then just set it at 0.3 volts, and conservatively fuse the AC line.

A number of DIYers have speculated on or even tried the Toshiba 2SK1530 and 2SJ201 Mosfets. These are really nice (discontinued) audio transistors and are very fine for F5's, but keep in mind that with a 12 amp rating they have a smaller maximum current than the Fairchild parts. This will not prevent them from sounding very good, however, and I do recommend them in general.

Of course you are going to need a beefier power supply to do deliver all this additional power. Here is an example of such a power supply.



Power supplies like this have been described elsewhere, and there is nothing magic about this one – we are just scaling things up. The same Vishay rectifiers are used here, and you see that we are using lots more capacitors. The CRC filtering is still there to keep the supply noise lower, but the resistance has been lowered to 0.067 ohms to ensure low losses. You want CLC? Go for it. The thermistor in series with the primary is familiar, and I recommend the CL30 type. Of course this shows the 120V AC version. For 240V the primary coils are wired in series and the fuse value is halved.

The power transformer needs to be VA rated at least twice the actual dissipation of the amplifier. The secondary AC voltages can be approximated by multiplying the DC rail voltages by 0.75, for example, for 48 volt DC rails, each secondary is going to be about 36 volts. Your actual results will vary a bit with different transformer manufacturers.

As commonly seen in my previous projects, you will also see a thermistor / diode bridge combination used to provide ground loop isolation between the chassis, which is hardwired to the AC outlet ground, and the circuit ground. An ordinary CL60 thermistor and a 35 amp rectifier bridge should suffice.

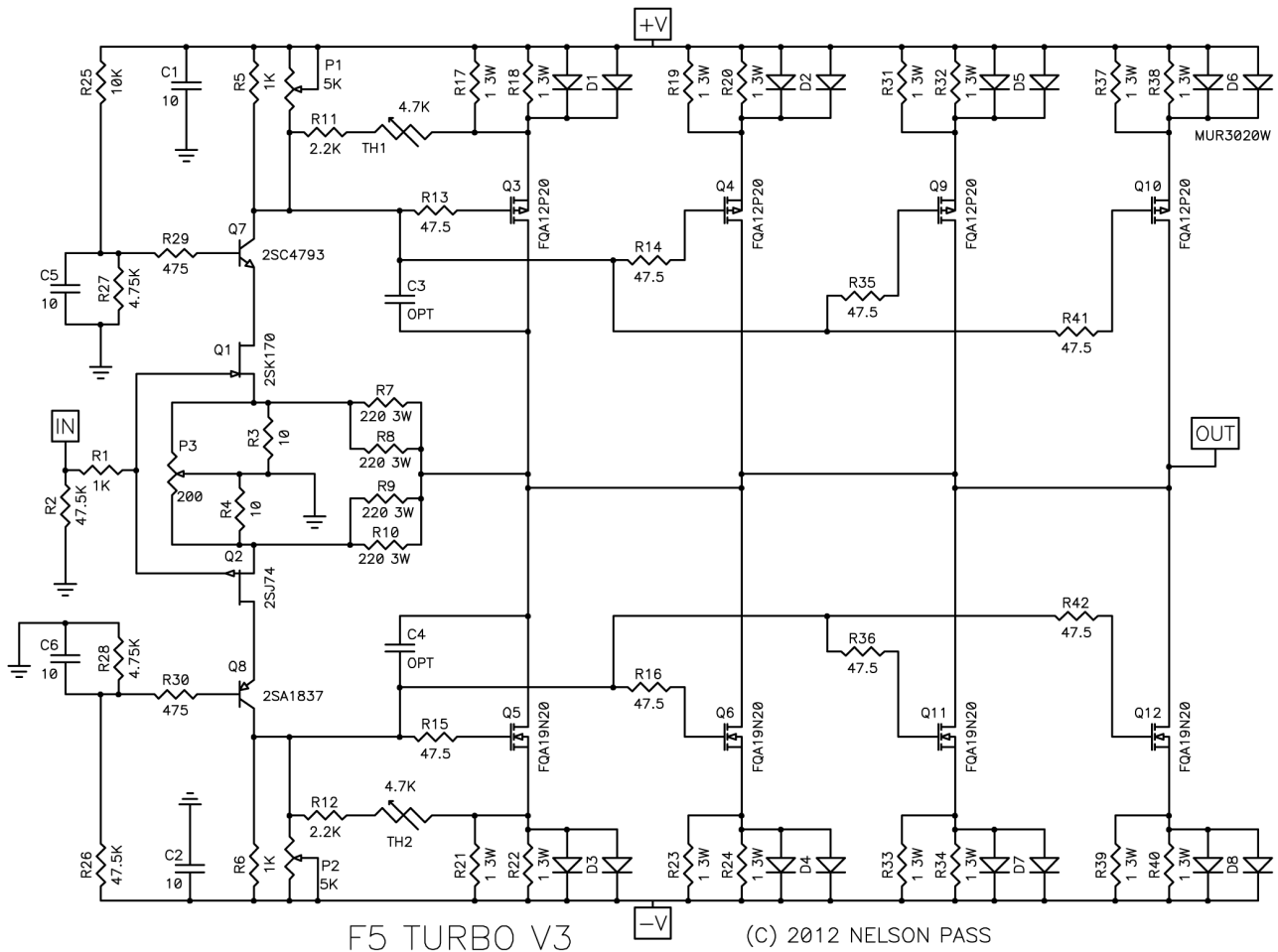
F5 TURBO v3 *and beyond the fringe...*

I am totally aware that 50 watts is still not wild enough for some of you. V3 will take you to 100 watts or more and then we will speculate on how you can go higher on your own.

The first thing we have to deal with is the voltage limitations of the input Jfets, which we have already taken past the normal limit. To raise the supply voltages for more power it will be necessary to either find some higher voltage Fets or to cascode the input circuit. Finding equivalent quality Jfets to the 2SK170 and 2SJ74 with a higher voltage rating is going to be difficult, so we will cascode them.

Cascoding is a very useful technique where the gain transistor (in this case each of the Jfets) is coupled to another transistor operated in Common-Gate or Common-Base mode. This cascode transistor contributes very little of its own characteristic to the amplification, but it acts like a voltage umbrella, shielding the gain transistor from the high DC voltage and noise of the power supply rails.

Here is V3:



The differences are found in the doubling of the number of parallel output devices and their associated parts for 240 watts of dissipation and the addition of Q7 and Q8 and the networks that bias them.

In the example of cascode Q7, a voltage reference is set by resistors R25 and R27 between V+ and Ground so that the Jfets see about 1/3 of the rail voltage. This voltage is also filtered by C5 which removes rail noise. R29 keeps Q7 from parasitic oscillation – an important part missing from most DIY efforts I have seen. This parasitic can be pretty subtle, not showing up on an oscilloscope, but very damaging to the distortion and noise performance of the amplifier.

The choice of Q7 and Q8 is not critical – for the most part they merely need not to break. Here is one of the few places I prefer Bipolars to Fets, as they will be less inclined toward the aforementioned parasitics.

So now we have broken through the voltage limits of the input stage. Power Mosfets are commonly available to 200 volt ratings, which sets the next voltage limitation at +/-100 Volt rails. This could give us 600 watts rms into 8 ohms. Probably best not to try that with this particular circuit.

The V3 schematic shows 4 pairs of output devices. Realistically you can expect to get more than 100 watts rms Class A into 8 ohms and 200 watts Class AB into 4 ohms. You are going to need some serious heat sinking, and I suggest that the power supply of V2 would be appropriate for a single channel. Peak output currents of 70 amps are expected but not guaranteed.

Depending on layout and other little issues, we might ultimately have to consider using capacitors to perform frequency compensation which have been absent (along with coupling capacitors) in previous F5 versions. In actual testing I found that ringing and oscillation issues can be dealt with by optional C3 and C4 in values ranging around 1 nF. An alternate location where compensation can be performed is capacitance of similar value across the feedback resistors R7 and R10. I did not encounter oscillation, but at these bandwidths we are working near the edges, so it's a possibility.

Is it rational to try paralleling devices for more and more power?

Of course! There are many who think audiophiles are already irrational, but I notice that those people all have some irrational streak of their own and are not really in a position to judge. I routinely parallel 18 pairs of devices in production, and I sleep well at night.

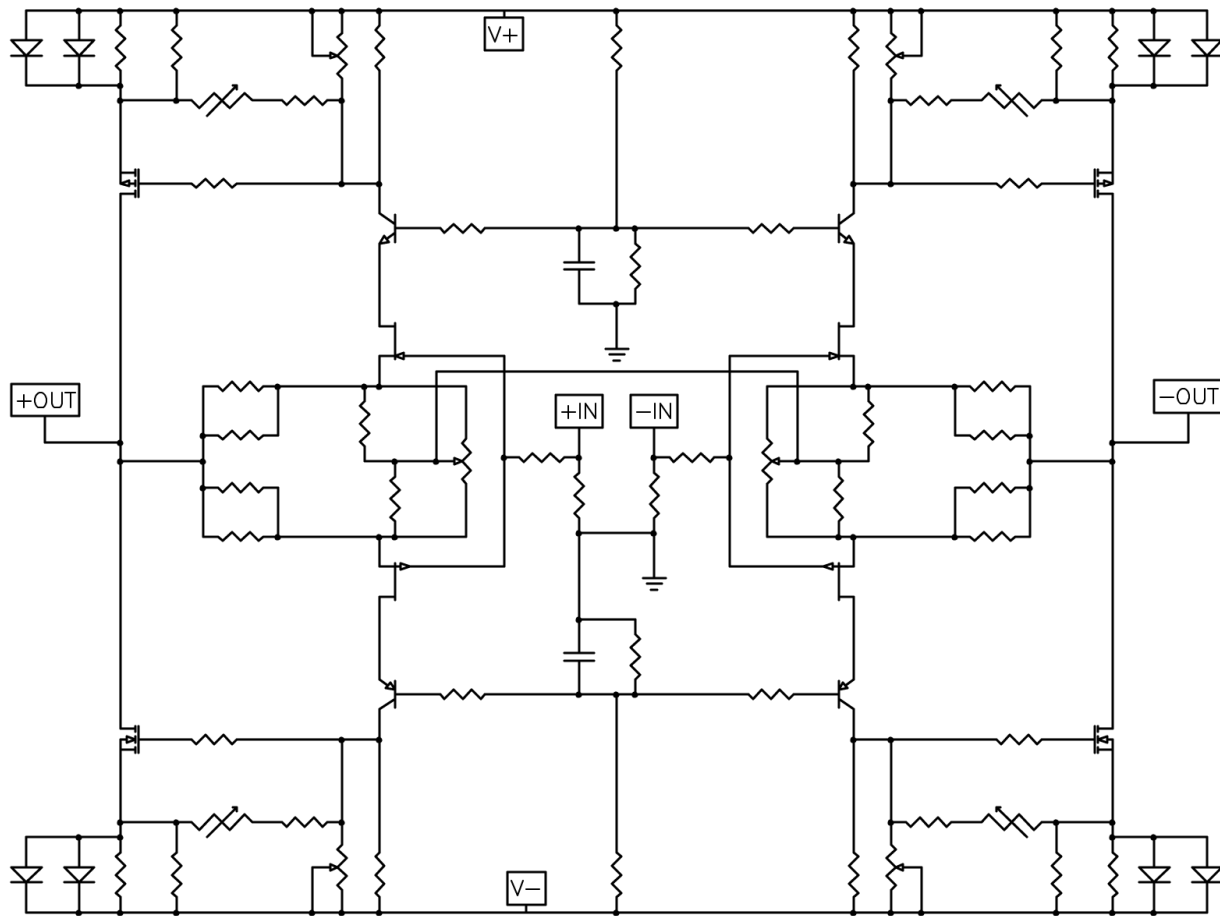
That said, the capacitance of the output stage devices starts to pile up and the bandwidth starts to go down. If I can get 800 Khz bandwidth from this amplifier with 2 pair of devices, then I might expect something on the order of only 80 Khz from 20 pair.

Even this is not much of a barrier – we simply parallel input Jfets to raise the current available for driving these devices and decrease the impedance of the feedback loops. After about 4 sets in parallel you need to give them Gate resistors to avoid parasitic oscillation and you are good to go - probably to 500 watts or so into 8 ohms and more into lower impedances.

There is an alternative approach to scaling these circuits, which would be to also use balanced operation. There is a nice thread on DIYAudio.com called *F5X – The EUVL Approach* where my friend Patrick has developed a balanced version of the F5.

We can use a very similar approach to balance the F5 Turbo. Balanced circuits like this can be used to increase the power bandwidth by doubling the effective slew rate (the slew rates of the two output stages are added) and also increasing the speed of each because fewer heat dissipating devices are needed in each half output stage for a given power level.

Here is a template for a balanced version of the F5 Turbo:



F5 TURBO BALANCED TEMPLATE

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What you see is a simplified V3 which has been mirrored so as to make two identical halves. Only one pair of output devices is shown on each half – you would be making your own decision as to how many you might need in parallel. Of course you can eliminate the diodes and the cascodes to make a simple balanced version, and with some parallel output devices you can still get to 200 watts or so with 32 volt rails. A crucial detail is that the feedback loops which went to ground on V3 and other versions of the F5 now are attached to each other. Another item to note is that the cascode devices share the same reference voltages, although this is not a requirement.

Paralleling input Jfets will allow proportional scaling of the drive for more parallel output devices, so it ultimately comes down to the trade off between dissipation, output power and sound quality.

High power amplifiers with only two actual gain stages are pretty rare. There are products that describe themselves as having only two stages, but with few exceptions you find that they are calling a multi-stage front end the “first stage” and a multistage power circuit the “second stage” When I think of gain stages, I think of active devices which substantially increase the gain. Input differential pairs are a stage. Current mirrors after the input transistors are a stage. Darlington's are two stages. Cascodes and constant current sources don't count, nor do additional parallel or complementary devices.

Actually I can only think of one such 2 stage power amplifier - the Pass Labs X-1000 delivers 1,000 watts into 8 ohms, and has pretty much set the bar for high power with such a simple circuit. You can see its schematic in the patent – a differential pair followed by balanced folded cascodes and banks of complementary followers.

Here is another candidate, the balanced version of the F5 Turbo V3. With 70 volt rails, Jfets in sets of 4 parallel, and 30 pairs of output devices, we should be able to get to that 1,000 watt 8 ohm figure reliably.

Getting high quality from these simple circuits goes back to the trade-off I mentioned earlier. With very simple circuits high quality and high power translate to high bias and high dissipation.

Some people seem to get excited about energy consumption of power amplifiers. This is a reasonable concern, but you want to keep it in perspective. A gallon of gasoline holds about 36 Kilowatt Hours of energy. If I drive to the post office in an Explorer, I will use that much. Or I can choose to run a Class A power amplifier at 500 watts for an hour a day.

Allowing for 50% efficiency of the power company, I'm good if I skip the post office once a month.

Junk mail and bills anyway.

I'm just sayin'.....

Conclusion

This project is dedicated to Ed Dell.

2012 marks forty years that I have been publishing with AudioXpress and during that time I have had the pleasure of working with the publisher Ed Dell although I have never met him in person.

Ed has helped to shape entire DIY audio community, and February 12th is his birthday.

You can send him a birthday card:

Ed Dell
The Scott-Farrar Home
11 Elm Street
Peterborough, NH 03458

Happy Birthday Ed and many thanks from everyone.

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