13.8V 20A linear power supply

Linear power supplies for communication equipment are among the most commonly built electronic projects. Almost every technically inclined radio amateur has built at least one. But unfortunately most designs, even those published in well respected books, are unnecessarily complicated, or have some specific drawbacks. The design presented here is a little bit unusual in its arrangement, but offers some advantages over the usual designs that I will explain in the following paragraphs.

Basics of linear power supplies

First, let's start from the basics: A linear power supply has a transformer that steps down the line voltage to some voltage that is higher than what will be required at the regulated output. Then a rectifier and a filter capacitor transform the low voltage AC into a moderately filtered DC that still is unregulated and has some ripple. Finally, a regulating circuit "burns off" the excess voltage, leaving only the exact amount desired at the output, typically 13.8V for communication equipment.

One typical mistake made by many amateur designers is using a transformer that has a voltage that's too low for the combination of rectifier, filter and regulator used. The situation is this: You need 13.8V at the output at all times. Your regulator eats up a certain minimum voltage, which depends on its design. Many regulators need at least 2V across them, so you need 15.8V minimum at the worst time across the filter capacitor. This is the voltage at the minimum point of the ripple waveform, but the capacitor needs to be charged to the maximum of this ripple voltage. So, the size of the capacitor defines how much additional voltage you need for this. A 60000uF capacitor, used at 20A, and discharging during almost a half cycle at 50Hz (10ms), will drop the voltage by almost 3.3V. So, you need to charge the capacitor to at least 19.2V under the worst conditions! If you are using a bridge rectifier made from silicon diodes, which loose about 1.2V each at peak current, then you end up having two diodes conducting at the time of charging the capacitor, dropping a total of 2.4V. So, the transformer needs to develop 21.6V peak voltage. This happens under heavy load, as most of the charging of the capacitor happens during a very short time, so there is a lot of voltage drop in the transformer, maybe 10 to 15%, depending on its size. So, you need to consider a transformer that develops about 24 or 25V peak voltage. Finally, you need to consider that the power line from which your design gets its power is not 100% stable! Allowing for 10% worst case sag in the power line, you end up needing a transformer that at nominal line voltage and small load provides about 27V peak! That would be 19V RMS.

If you use a transformer with a lower rating, or a smaller filter capacitor, or a regulator that has a minimum drop of more than 2V, then your power supply will loose regulation under some conditions. Many amateur designers run into this problem.

On the other hand, if you use a regulator with a lower drop, and/or a larger filter capacitor, then you can slightly ease the transformer voltage requirements. This can be very useful to keep the filter capacitor voltage rating requirement at 25V, since otherwise you would be forced to use a 35V capacitor, which is much larger and more expensive. A lower transformer voltage is also an advantage from the efficiency point of view. After all, the complete excess voltage has to be burned off by the regulator, causing a huge power loss and requiring a large heat sink!

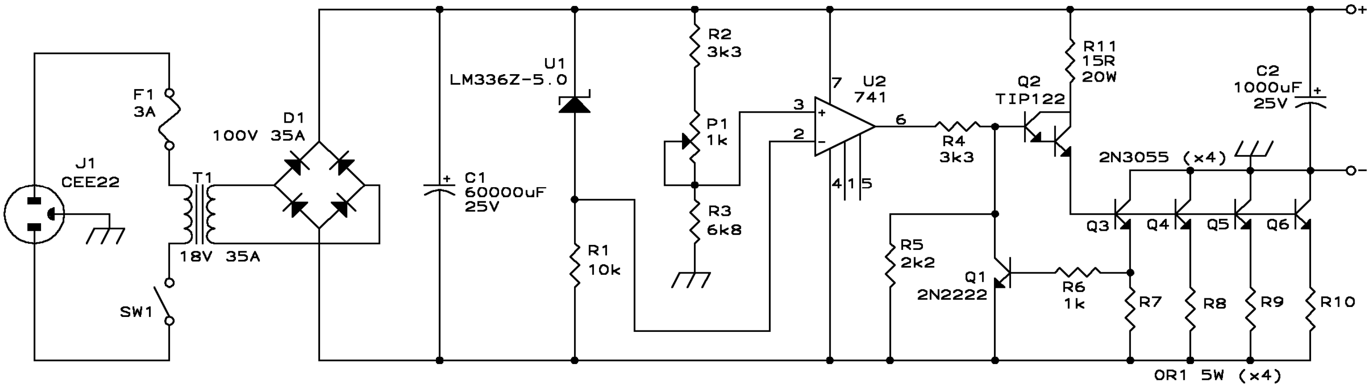
Another issue is what kind of pass elements to use for the regulator. MOSFETs are not a good choice, because they are much more expensive than bipolar transistors for a given minimum voltage drop and power dissipation. So, almost every power supply uses bipolar transistors. NPN transistors are usually preferred over PNP ones, because they are cheaper for a given performance, and there is wider selection. So far, so good. But most designers place their pass transistors on the positive side, in emitter-follower fashion, adding a Darlington driver (or two Darlington stages). This is a very bad choice for several reasons: One, each transistor connected in that way produces a minimum voltage drop of 0.6 to 0.7V. A three-stage arrangement, as is often needed, would have a minimum drop of around 2V, plus the drop caused by any equalizing resistors! Also, the transistor collectors, which are connected to the cases, are at the unregulated positive voltage, and thus require insulation from the heatsink and power supply case. The necessary mica insulators add a huge amount of thermal resistance, making it much harder to cool the transistors properly.

This design

In the power supply presented here, several measures were taken to get rid of the problems mentioned above. The pass transistors are located in the negative rail and connected in common-emitter configuration rather than as emitter-followers. Thanks to this, the regulator's minimum voltage drop is extremely low, only about 0.1V for the transistors plus 0.5V for the equalizing resistors. The other advantage is that the collectors are directly connected to the negative pole of the power supply's output, which in most applications is grounded. That means that no insulation is required between the transistors and the grounded power supply cabinet! This eases the cooling very considerably. Thanks to the low regulator drop, a low cost 25V filter capacitor can be used.

The voltage adjustment potentiometer is arranged in such a way that if the wiper contact fails, the voltage will go down, never up. This is an important safety issue, avoiding damage to connected equipment.

Here is the schematic diagram: Use the full resolution version for printing.



This power supply delivers a highly regulated 13.8V, adjustable over a moderate range, at a continuous current of up to 20A. It is current-limited to approximately 25A, and short circuit protected for as long as the heat sink can keep the transistors cool enough. It is probably the simplest design that can accomplish this.

Some notes about this circuit:

- Use a transformer for the primary voltage you need. The 3A fuse is for 220 or 240V primaries. If you use something in the neighborhood of 110V, use a 6A fuse.

- The rather high transformer rating of 35A accounts for the losses that occur due to the capacitive input filter. If your transformer is rated for capacitive input, then a 25A value is enough.

- Of course you can make up C1 by placing several smaller capacitors in parallel. Likewise, the 0.1 Ohm, 5 Watt resistors can be made up by several in parallel, for example by 5 resistors of 0.5 Ohm, 1 Watt each.

- The LM336Z-5.0 voltage reference IC should not be replaced by a zener diode. Zeners are not nearly as stable. A different voltage reference IC can of course be used, if R2 and R3 are modified for the different voltage.

- D1 and Q2 through Q6 need heatsinking. Only Q2 needs insulation. D1 dissipates up to 60W, Q2 up to 25W, while the pass transistors dissipate up to 30W each in normal use, but may reach a level of 130W during short circuit! Take this into account when choosing the heat sink!

- R5 exists only to make sure that the transistors can actually be driven off. The 741 is not a single-supply operational amplifier, so it cannot drive its output very low. If a true single-supply opamp is used, then R5 becomes unnecessary.

How it works

U1 provides a regulated reference voltage that's always 5V below the positive rail. U2 compares this reference voltage to a sample from the output (ground against positive rail) and drives a Darlington transistor connected as emitter follower, which in turn drives the four pass transistors connected in common emitter configuration. Four resistors equalize the current through the transistors, and one of these resistors does double duty by serving as current sense resistor. If the current through this resistor exceeds about 6A, then Q1 will start conducting, swamping the drive from U2 to the negative rail and thus limiting the output current.

No parts were added to control frequency response, loop damping, etc. All trust was placed on the 741's rather low frequency response and high stability, combined with a 1000µF capacitor across the output. In practice this has proven to work well enough, but purists may want to experiment with the loop response and add some compensation capacitor.

Construction notes

A power supply like this is simple to build, but it uses large and heavy parts, so physical construction should be strong. The 630VA transformer is heavy, and even the heat sink will not be small. So, build or buy a good, solid, sturdy cabinet. Try to use aluminum for the cabinet, since steel will vibrate from the transformer's stray field. The cabinet should be very well ventilated.

The heat sink needs to be large. How large...? Well, it depends. Do you want your power supply to be short circuit protected without a time limit? That will require a really large heat sink!

In normal use at the 20A level there will be about 200W dissipation. The diode bridge can run at 35A when kept cool at 25 degrees Celsius (which is utopic, by the way!). As silicon can withstand 150 degrees before melting down, the 35A bridge running at 20A can survive about 75 degrees case temperature. The pass transistors are rated for 115W at 25 degrees, which means that at 30W each they can run safely at almost 120 degrees. The driver transistor can dissipate 60W at 25 degrees, so at 25W it may heat up to 98 degrees.

The thermal resistance from the bridge to the heat sink is probably better than 0.2 degrees per Watt, so the bridge is happy if the heat sink stays below 65 degrees. The power transistors probably have around 0.5 degrees per Watt of thermal resistance to the heat sink, so they need the heat sink to stay below 105 degrees or so. Easy. The limiting factor in this case is the driver transistor, because it needs to be insulated! That transistor with its mica insulator will have about 1.5 degrees per Watt thermal resistance, thus requiring the heat sink to stay below 60 degrees or so. You may want to replace the TIP122 by a Darlington transistor having a higher power rating, so the bridge would become the limiting factor.

In the above case, you need a heat sink that doesn't warm up to more than 60 degrees Celsius while dissipating 200W. If you consider a highest ambient temperature of 30 degrees, then the heat sink may heat up only another 30 degrees above ambient. That is a thermal resistance of 0.15 degrees per Watt, which means a HUGE heat sink! If you really want to run this power supply at 20A continuous duty, you may be better off with a more moderate (still large) heat sink plus a small fan that blows air through it!

You may use a rather small heat sink, rated for 0.7 degrees per Watt or so, if you will use this power supply for a typical HF transceiver that needs 20 to 23A peak, but at an average of no more than 5A or so. This is what many commercial power supplies do.

If you use a small heat sink, and run the power supply at high average current, you WILL burn it up. Take my word for it. Too many people have blown up their power supplies in this way.

Just for fun, lets see how much the heat sink requirement increases if you want protection against continuous short circuit. The total power dissipation would be around 550W. The bridge and driver transistor would run much like they would at 25A load, while the dissipation in the pass transistors is hugely higher than normal, reaching about 130W! As the 2N3055 is rated for 115W at 25 degrees, it means that the transistor cases would have to be kept below 9 degrees! Considering the 0.5 degrees per Watt of thermal resistance between each transistor and the heat sink, the heat sink would need to stay below -56 degrees Celsius! A giant heat sink running at the south pole maybe could just do the job, otherwise you would need a cryogenic system! Needless to say, it is impractical to implement indefinite short circuit protection in this way! It would become practical if you increased the number of pass transistors, increasing proportionally the equalizing resistors' values, but even then it would require a large heat sink. A foldback current limit would overcome this problem, but it brings along other problems of its own, like the power supply shutting down when charging a capacitor in some equipment. I believe that the best compromise is to build this circuit as shown, using a reasonably oversized heatsink, and shut it off quickly when a short circuit happens, before the transistors can overheat. After all, a 25A short produces a spark that's obvious enough to notice!

A note on R11

I originally did not have R11 in the design. A fair number of readers built the power supply and had good results. But then I got a mail from Carl Ressel, who built it and tried it out feeding a variable voltage onto C1. Very reasonable, only that without R11, Q2 took a very high current while the input voltage was too low to allow the supply to produce normal output! This situation could be fatal for Q2 in the event of a brownout. With the added R11, the problem is solved. This shows how easy it is to overlook a situation that normally does not happen, but sometimes can! A good design must be able to handle *any* situation. Thanks, Carl, for this test!

I did not make a printed circuit board. Anyway, the transformer, fuse, switch, connectors and filter capacitor are mounted to the case, while the 5 power transistors, the 4 large equalizing resistors and the rectifier bridge are mounted on the heat sink. This leaves so few components available to mount on a board, that it doesn't pay to make a PCB. I suggest you mount the remaining components on a piece of perfboard.

The quality of the voltage regulation depends mainly on how you build this project. The single most important factors for good regulation are that the ground connection of R3 must go DIRECTLY to the negative output connector, while the top of R2 and of U1 must go directly to the positive output. Everything else is less important.

I suggest that the case is connected to the negative output ONLY via the pass transistors' cases, in order to avoid any ground loops.

This is a nice beginner's project, as all components are easily available all over the world, the cost isn't extreme, the circuit is very simple, and the resulting power supply will be useful for an entire ham radio career. For more advanced builders, I suggest to try the 40A switching power supply, which is much more elegant, efficient, powerful, smaller and lighter, costs about the same to build, but is much more complex.