Shunt Regulator:
The Almost Forgotten Circuit

This author reveals a little-known, but useful, power supply design.

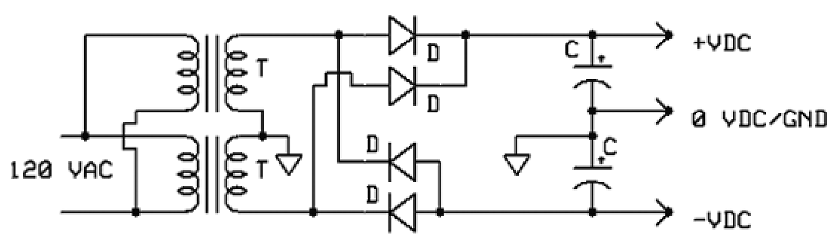

FIGURE 1: Conventional power supply.

Most of you power your sound systems from the AC power lines. This requires a power supply to convert the 120V AC to the needed DC voltage. The most common form of power supply is a voltage stepdown transformer to a bridge rectifier, followed by filter capacitors **(Fig. 1)**.

AC TO DC

When AC voltage was young, one of the early problems was to equate the power delivered by an AC system with that of the better known DC values. The AC voltage sine wave had a peak voltage above that of the DC voltage, but the average value was, of course, *zero* **(Fig. 2)**!

That is why you use the RMS value, which is a great choice if you are using AC to light lamps or drive motors. When you turn AC to DC, you quickly learn that the peak value of a sine wave is 1.414 times the equivalent DC value.

If diodes act as perfect one-way valves when you use a full-wave bridge to rectify the AC, you get a waveform that is double the frequency and all positive- or negative going. There are, of course, limitations to real diodes such as an internal voltage drop, noise generation, and leakage current. I have actually measured giant noise spikes induced by rectifier diodes when they were going from conduction into the blockage mode. These diodes were, of course, defective. Some folks place small capacitors across special diodes to minimize noise.

The general rule of thumb is that the diodes actually drop .7V when the voltage passes through them, and they block the reverse voltage completely when the voltage is reversed. Of course, if the reverse voltage goes too high, the diode breaks down and begins to conduct above its peak inverse voltage (PIV). See **Figs. 3** and **4.**

When you add capacitors to the basic rectifier circuit, they store the voltage between the peaks of voltage. When the rectified AC is first supplied, the capacitor will charge to a value equal to the peak voltage applied. Some of the current either drawn by the load or leaking through the capacitor will cause this voltage to drift down while the rectified AC is below the voltage stored on the capacitor. This voltage will be recharged when the rectified AC waveform again is greater than the charge on the capacitor.

Keep in mind the voltage across the diode will be twice the peak DC voltage. One half of this will be the charge on the capacitor and the other half will be from the transformer on its negative-going peak.

Notice that positive current only flows through the diode when the capacitor is charging **(Fig. 5)**. Current only passes from the phase angle of 164-180°. As a result, the peak current to charge the capacitor is much greater than the average current delivered to the load. (180° of 60Hz AC is equal to 8.333 milliseconds.)

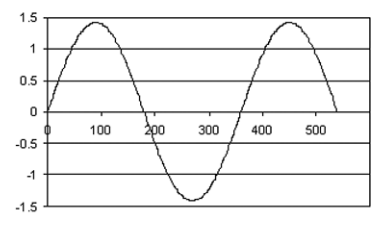

FIGURE 2: AC voltage sine wave.

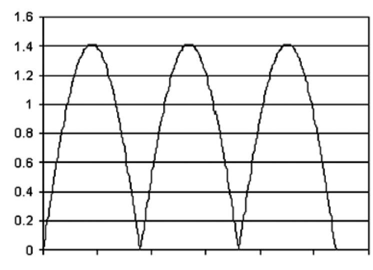

FIGURE 3: Typical diode measurement.

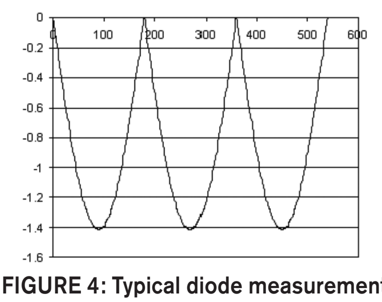

FIGURE 4: Typical diode measurement.

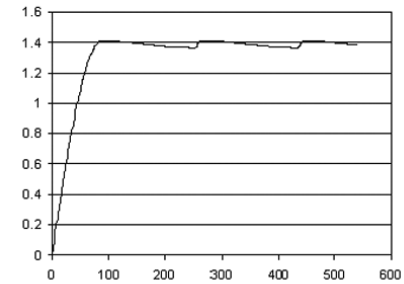

FIGURE 5: Current measurement.

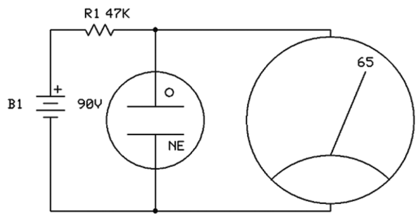

FIGURE 6: Neon shunt regulator.

CAPACITOR CALCULATIONS

You can calculate the voltage ripple across the capacitor from the first derivative of the equation that defines capacitance.

C*V=Q

C*dV/dT + V*dC/dT = dQ/dT = I

For power supplies you may reasonably assume that the capacitance is constant so the equation becomes

C*dV/dT = I

For your normal 60Hz AC line and a diode bridge that doubles the frequency, you get the ripple voltage (dV)

dV = .00833 * I/C (I is in amps, C is in farads!)

The peak voltage is determined by the RMS value of the transformer. For a 25V center tapped transformer, you would have a nominal peak voltage of:

25 * 1.414 * ½ -.7 = 16.975V

For practical reasons you also calculate the minimum and maximum voltages expected for a low line voltage of 108V and a high line voltage of 132V:

108/120 = .9 .9 * 16.975 = 15.2775V minimum

132/120 = 1.1 1.1 * 16.975 = 18.6725V maximum

(Yes, I ignore that the diode drop really doesn't change, but 1-2% accuracy is a reasonable goal considering all the variables and component tolerances.)

You should be able to see why you would use a 25V rated capacitor for this filter.

If you wanted to draw a current of ¼A from this nominal 15V supply, using 2200 *micro* farad capacitors would give a ripple voltage of

.00833 * (¼)/2200 * 10e-6 = .00833 * 1/.0022 = .9466V of ripple peak-to-peak.

As a result, the minimum voltage would now be

15.2775 – .9466 = 14.3309V

You could increase the capacitor to 6800µF to try to keep your ripple down and the minimum voltage above 15V. In practice, it might not work because when you triple the capacitance you also triple the charging current, and the internal resistance of the transformer and diodes may not let you get all that current.

It should be clear by now why a regulator is a good idea. Under the worst-case conditions the nominal 15V supply does not reach 15V, and in the worst case some parts might be damaged if you go to 18V or more.

A BRIGHT IDEA

The very first regulators were shunt regulators, which went across the DC supply and kept it from going above a desired voltage. A neon lamp is the classic example. If you apply the right voltage and current the lamp will glow. This lighting in a bottle relies on the ionization breakdown of the neon gas when a voltage is applied. The voltage required is not thousands of volts, but under 100, due to the close spacing of the electrodes and the low gas pressure. It takes a higher voltage to start the breakdown process than to maintain it.

The neon bulb has an extremely large resistance until the breakdown voltage is reached. After breakdown the resistance drops dramatically and the voltage across the tube should also drop. As the current is increased more gas ionizes, the resistance drops, and more current flows. This is how the voltage is stabilized; too much current will damage the bulb.

If the current drops too low, the breakdown stops and the resistance rises. If a limited current is supplied, then you can obtain a reasonably well-regulated

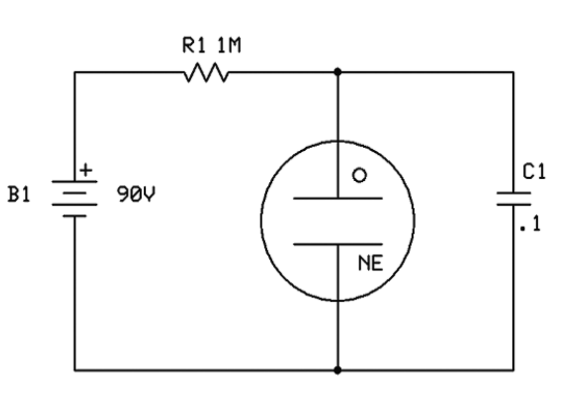

FIGURE 7: Neon relaxation oscillator.

voltage. The usual current-limiting device is a single resistor **(Fig. 6)**.

A capacitor across the tube will reduce the noise caused by the regulation mechanism. If the resistor limiting the current is too large, you will end up with an oscillator **(Fig. 7)**. As the battery and resistor charge the capacitor to the breakdown voltage, the lamp will turn on and pull current from the capacitor until the voltage drops to the extinguishing voltage. Then the lamp will go out. The voltage will then climb again as the capacitor charges until the cycle repeats.

You can use this to make a nice display if you can find some 100MΩ resistors and a few very low leakage .01 to 1µF capacitors. You can get the bulb to flash once every few seconds. An array of ten or more of these circuits gives you a very nice mad scientist display panel.

Using the same ionization discharge principle resulted in the series of gas regulator tubes. Some of them came with octal sockets such as the 0A3 – 75V, 0B3 – 90V, 0C3 – 105V, 0D3 – 150V. Their handy feature of having two pins connected to one side of the tube allowed you to wire one pin as input and the other as output, so when you removed the tube the high voltage that became unregulated did not go to the rest of the circuit. These tubes could handle as much as 40mA of current.

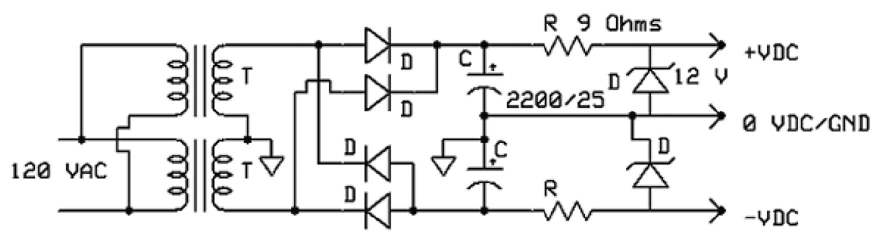

FIGURE 8: Power supply circuit with diodes and resistors.

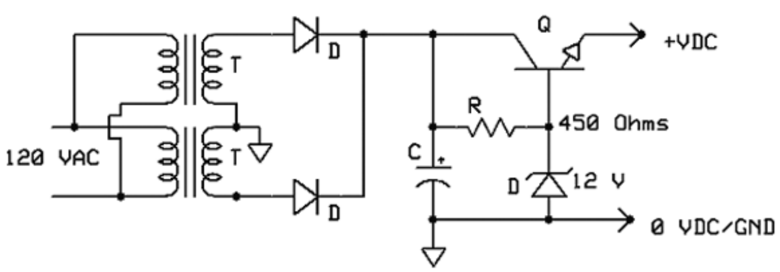

FIGURE 9: Transistor added to power supply circuit.

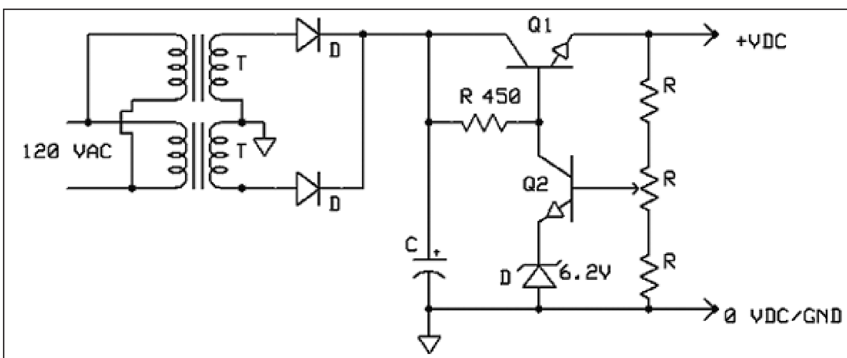

FIGURE 10: Power supply with feedback.

POWER REQUIREMENTS

The zener diode has largely replaced the gas discharge tube as a shunt regulator. The diodes are available in dozens of voltages and wattages. Two different mechanisms inside the diode provide a constant voltage drop across the diode when you hook it up backwards. If you hook it up as a normal diode, then you get the .7V drop. So be sure to wire these in backwards on purpose!

In the power supply circuit you can add resistors and diodes to get a regulated output **(Fig. 8)**. To analyze how this works you need to apply Ohm's law: Current in amps × resistance in ohms = voltage in volts (I * R = E). When your line voltage is low, you have available a minimum of 14.3V. If you draw a current of ¼A, then the drop across the resistors is

.25A * 9Ω = 2.25A * ohms = 2.25V (units count also!)

Without the zener diode the output voltage would be

14.3V – 2.25V = 12.05V.

But your diode will clamp this to 12V. The current through the resistor must be (14.3-12) volts/9Ω = .2555V/ohm = .2555A.

If your load is drawing ¼A, then the remainder must go through the diode or .0055A.

The equation for power is: Current in amps × voltage in volts = power in watts. The power dissipated in the diode would be

.0055A * 12V = .066A * volts = .066W.

At the maximum voltage of 18.7V the current through the resistor would be (18.7-12) volts/9Ω = .744A.

With the same ¼A delivered to the

load the diode would dissipate

(.744-.25) amps * 12V = 5.88W.

If there were no load the worst-case dissipation in the diode would be 8.93W. A 10W zener diode would work for this supply.

In the worst case, the 9Ω resistor would need to be rated at

(18.7-12)/9 * (18.7-12) = 4.99W.

A nice 5W square white ceramic wirewound power resistor would work almost perfectly here, except that at full power these resistors become hot. They are allowed to reach a temperature of more than 425° F at this power and still be in spec! A 10W resistor is a much cooler choice.

The target power dissipation at 120V line voltage for each resistor would be 2.25W, and 3W for each zener diode. This results in a total loss in the regulator of 5.25W and a delivered power of 3W to one side of the load.

The regulation of a zener diode is not perfect. Normally, the diode is modeled as a perfect zener diode in series with an internal resistance. For a 12V 10W zener diode such as the 1N2976, this would be 3Ω at the currents you are using. As a result, you would see 12.75V out of the circuit under normal operating conditions.

POWER TRANSISTOR

In order to achieve better regulation from the power supply circuit, you can add a transistor, which will be used as a series regulator combined with the zener shunt regulator. The classic circuit for this is shown in **Fig. 9**. The transistor in this circuit is provided current through the resistor. At the worst-case low voltage, there is a current to the base of

(14.3-12) volts/450Ω = .027A.

If the current gain of the transistor is a typical 50 or more, then you could get a maximum current of 1.37A out of the supply. Of course, because the filter capacitor was sized for only .25A, the ripple would go up and you really wouldn't quite get this.

The worst-case dissipation for the transistor with a high line voltage and your design current draw of ¼A allowing for a base drop of .7V would be (18.7-(12-.7)) volts * .25A = 1.85W. This is much better than the zener only design. The zener diode could be much smaller, because the maximum current through the resistor is now

(18.7-12) volts/450Ω = .0149A.

Thus the maximum zener power would be .0149A * 12V = .18W.

The maximum current through the resistor is not the previously calculated .0149A! That is only the current if you are not being careless. If you short the output of the supply, the current would be

(18.7-.7) volts/450Ω = .04A.

This would give you a maximum power of .72W. You could use a ½W resistor, but I would use a 1W resistor in my own supply.

This circuit has less power wasted in the regulator and is more accurate than just a simple diode circuit because the zener sees a more constant current. It also costs less because a power transistor is cheaper than a big zener diode and power resistor. The downside of this circuit is that there is still a variation in voltage with load as the base-to-emitter drop varies with current draw, as does the gain of the transistor.

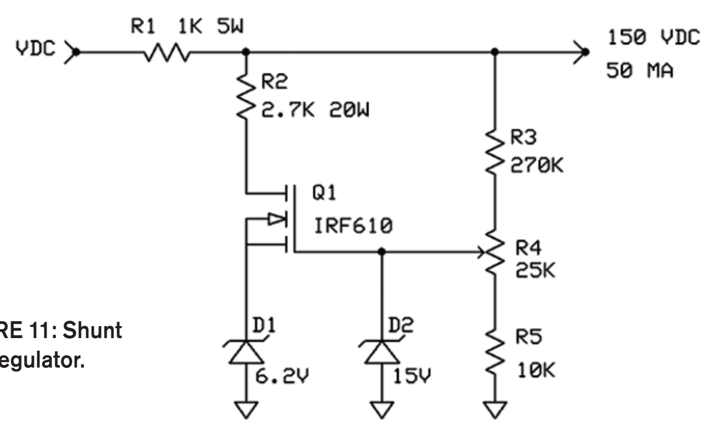

FIGURE 11: Shunt only regulator.

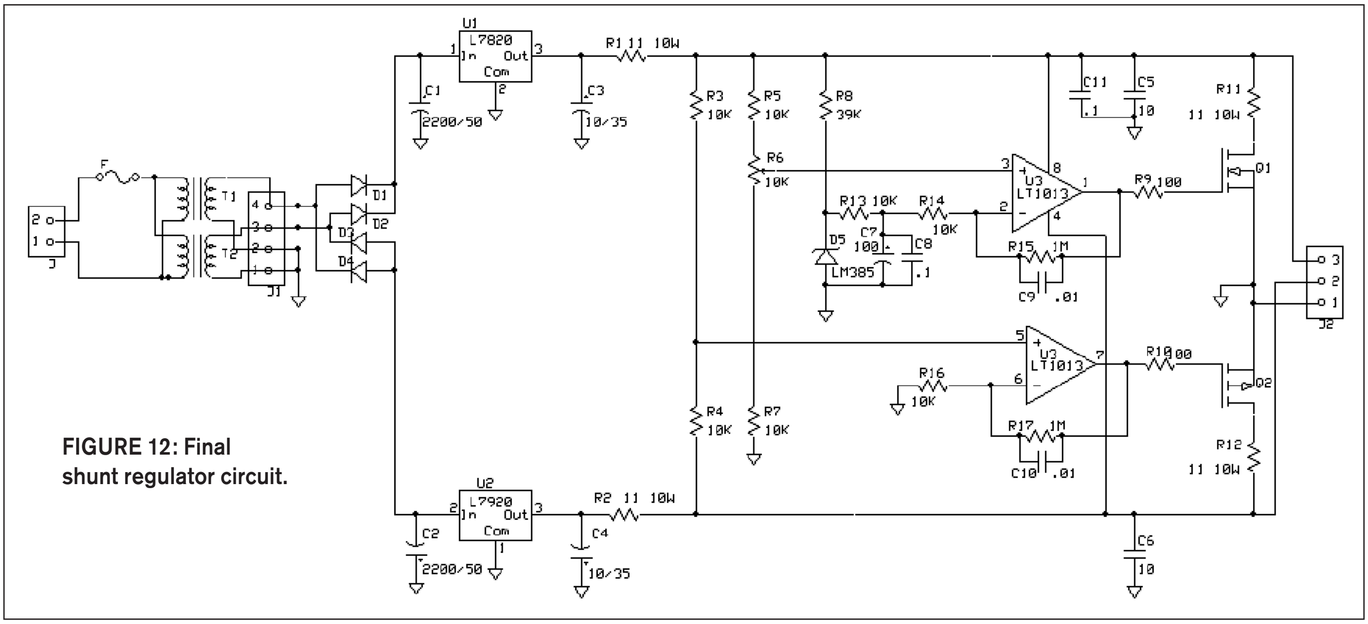

FIGURE 12: Final shunt regulator circuit.

FEEDBACK VERSION

It is possible to improve the regulation of a regulator circuit by adding feedback. If you look at the output voltage and compare it to the zener reference voltage, you can use the difference signal to give a more accurate supply **(Fig. 10)**.

In this version of the power supply Q2 sees the output voltage through a voltage divider. If the voltage at the base of Q2 goes above about 6.9V, it pulls down the voltage available to Q1. The zener diode acts as reference to be compared to the voltage from the output. A 6.2V zener diode is used because that value typically has the lowest voltage variation with current and temperature.

You can expand this basic circuit with more gain, using an op amp for the feedback loop and, of course, many different voltages. With the right transistors it can regulate several hundred volts.

The feedback series pass design has been expanded to some quite nice versions. The LM78xx series of regulator ICs are similar to this discrete circuit but offer more such as short circuit protection.

SHUNT-SERIES CIRCUIT

In **Fig. 11** you'll note a shunt only regulator that uses a MOSFET to great advantage. D1 and the gate turn-on voltage of the MOSFET are compared to the output voltage. With a voltage to current gain of 1.5 siemens and a voltage reduction in the divider chain of 25 to 1, this circuit should keep the output within a volt or two of where you want it. You can use an even higher voltage version with power amps to keep the peak voltage as high as you would like without risking frying your output tubes before they warm up!

The disadvantage of all of the series regulators is that they provide current to the load and require it to be used up. That is a reasonable assumption if the load involves resistors or capacitors. Of course, when you put a charge into a capacitor with a resistive load, the discharge curve is an exponential curve, rather than linear!

As soon as you have inductance in your load circuit, it is possible to store energy in the inductor and have it try to dump this back onto the supply rails at the wrong time. Although the distortion on the supply rails will be reduced by at least 30dB in a well-designed audio circuit, it is better to start with less. That is why I prefer a shunt regulator on the supply rails for audio circuits.

To increase the efficiency first use a series regulator. This passes a voltage higher than the final output voltage—but not too high to damage much if things go wrong—to a resistor that limits the current to the shunt regulator. An op amp looks at the output and compares it to a zener reference. The gain of the op amp is limited to 100, which reduces the amount of op-amp noise that is introduced to the supply rails and also reduces the issues with phase margin and oscillation.

A MOSFET is used to pull the rails down to the desired voltage. To make the MOSFET happier, place a resistor in series to eat up some of the excess power. This resistor also helps the gain phase margin. A nice secondary effect is that the dominant correction curve is more linear, being primarily controlled by two resistors, so that less odd harmonic distortion is impressed onto the supply rails by the power supply.

FINAL CIRCUIT

In the **Fig. 12** circuit a straightforward stepdown transformer feeds a diode bridge that is then filtered by 2200µF 50V capacitors providing a raw or unfiltered DC supply of just under 30V. There is about 1V of ripple on this supply, which feeds L7820 (or L7920) regulators to produce a reasonably clean 20V source R1 (or R2) to provide a current limit to the output rails.

The rails are loaded by Q1 (Q2) through R11(R12) and are monitored by R5, R6, and R7, which provide a voltage divider to the input of U3; this is compared to the reference voltage provided by D5. If the voltage is higher, then the error signal is used to drive Q1 harder. The negative side is referenced to the positive rails and will track the voltage on them. Some folks do not like tracking regulators for audio, so they can just reuse the reference voltage and add another resistive divider chain and make two adjustments.

This shunt regulator provides a rail that is almost 20dB quieter than just the regulator alone. C5 (C6) is used to remove noise from the rails. I used a polypropylene capacitor here. If you try to set the gain of the op amp too high, you might get the system to oscillate. That is why I just aim for 20dB of improvement.

U1, U2, Q1, and Q2 each dissipate about 5W. I used a small piece of aluminum about 3in^2 for their heatsinks. R1, R2, R11, and R12 each dissipate about 2.5W. I used 5W resistors—you may choose to use 10W resistors so they run cooler. It is just a matter of taste.

This power supply can put out 400mA at 15V. It is just fine for most preamps, CD players, and so on. You can use the same basic design up to several hundred volts if you skip the pre-regulators and use dropping resistors and zener diodes to protect the op amp. You can even use just the shunt part on an existing power supply to clean it up.

Now that you know the shunt regulator better, you probably already have an idea of where to use one. *aX*

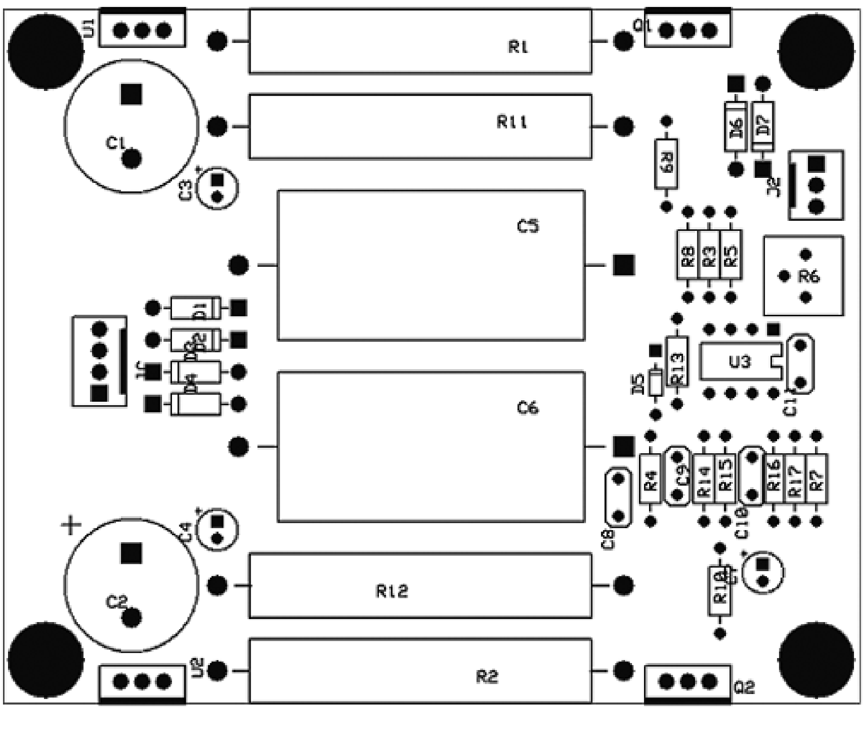

FIGURE 13: Component placement on board.