LECTURE 9: VOLTAGE REGULATORS

Almost all electronic circuits require a supply of DC voltage for their power. For most circuits it is either desirable or essential that the voltage be constant under varying input (power line) voltage and varying load. The simple power-transformer, diodes, and filter-capacitor based supplies discussed in the lesson on diodes satisfy neither of these criteria, and in addition their outputs will always have significant 120 Hz ripple even with rather large filter capacitors. There are many reasons why it is not a good idea to buy a new Heathkit breadboard for each new circuit you build, though there is that temptation with "temporary" circuits for quick projects.

One source of clean stable power is a commercial power supply, either a stand-alone unit or a line-voltage-powered module that can be built into your circuit. A stand-alone unit is reasonable if, for space considerations, the supply must be located at a distance from the circuit it powers, or if many different boxes are to be powered from the same source. In either case one must take care that the lead resistance between the power supply and the distant circuit does not cause problems. For example, the following circuit can be unstable.

The circuit is a simple three-stage a.c.-coupled amplifier. The instability comes about because of the resistor marked R. If the current drawn by the circuit increases V+ will decrease. A decrease in V+ will cause a decrease in the collector voltage of the first transistor, and thus a decrease at the base of the second transistor. This base decrease is amplified by the second transistor and causes a rise in the second collector and third base. The third base rise is amplified and causes a larger drop in the collector of the third transistor. Why does the collector drop? Because the third transistor is drawing more current. So we see that an increase in the current drawn leads to a further increase in the current drawn; i.e. we have positive feedback and the circuit can oscillate with some period determined by the various Rs and Cs in the circuit.
The main culprit is R which might just be the resistance between the power source and the circuit. Separate power-supply bypass capacitors for each stage (or two stages) is a standard cure for this sort of feedback.

Power supply modules are often a good choice for your circuit. They may look a bit expensive, but they save time and are well engineered. Still, there are times when you should consider the use of three, or four terminal voltage regulators, the subject of this lecture.

A very clear cut case that calls for a regulator chip is when you have one voltage source available in the circuit, and you need a second, lower, voltage. The first voltage can be used as an input to the regulator whose output is the second desired voltage. For example, we have ±12 volts available from the Heathkit board. Some of the chips we use later in the quarter are easier to use with ±6 volt supplies than with ±12 volts and ground, and ±12 volts is too much for the chip ratings. We could use the Heathkit ±12 volts as inputs to regulators that output ±6 volts. We can also utilize "junk box" parts plus a regulator to build a complete inexpensive power supply.

Another common use of voltage regulators is in big systems with one large central power supply. This supply is used as the input power for voltage regulators mounted on each subsystem or circuit board of the system.

The structure of the typical regulator is shown in the following diagram.

The type of control element can be either series, shunt, or switching. The series regulator is, in effect, a variable resistor between the input and output voltages. The shunt regulator is a variable resistor to ground on the output voltage side of a fixed resistor between the input and output.
The switching regulator is a switch between the input and a low-pass LC filter which provides the output. Since the switch is either open or closed at any given time little power is dissipated in the control element, and switching power supplies are the most efficient, though the most complicated. The three types of regulators are sketched below.

\[ V_o = V_i - (R_s)I_L \]

\[ V_o = V_i - R(I_L + I_S) \]

\[ V_o = V_i \frac{t_{on}}{t_{on} + t_{off}} \]

**Series**  
**Shunt**  
**Switching**

**Voltage Regulator Options**

There are many variations on the voltage regulator theme besides the series, shunt, and switching choices. Positive, negative, and dual regulators are available. The negative regulators are a bit more demanding to use than the positive regulators due to details of silicon technology.

There are fixed voltage regulators and adjustable regulators. Some regulators have only three terminals (input, output, and ground), and others have more terminals that are used for such things as current limiting. Protection from excessive current may be in the form of simple limiting of the current to some peak value, or it may be the more desirable "folding back" of the current to a lower value in case the output is shorted. Why is folding back desirable? Suppose we are designing a supply to take an input \( V_i \) and supply an output at \( V_2 \) with a maximum planned for current of \( I \). For this application a regulator must be selected and installed so that it can dissipate a power \( (V_i - V_2)I \). What happens if this supply is short circuited by accident or by a failure in the load? If the regulator is a current limiting regulator it must now dissipate a power \( (V_i - 0)I \). Either the regulator is dissipating too much power or we have expensively overdesigned the circuit. With fold back over-current protection the dissipation is held to safe levels without the need to use overly heavy components. Some regulators protect themselves (if not their loads) by shutting down when they get too hot.
For high power applications (regulator dissipation over a watt) one can either use a high power regulator or use a low power regulator which controls an additional power transistor. When possible I lean toward the high power regulator since it simplifies construction. The data sheets tell how to connect additional power transistors, as well as a variety of optional circuit configurations.

**Important Regulator Circuit Considerations**

**REVERSE BIAS PROTECTION** A dangerous condition can arise if, through some accident, the voltage regulator becomes reverse biased. A reverse bias of greater than about 7 volts of reverse bias may damage the regulator. The protection against this condition is very easy, and is often included even when the chance of problems seems remote. One simply puts a normally reverse biased diode across the regulator as shown below.

![Reverse Bias Protection Diagram]

**STABILIZATION** When using a negative regulator, bypass capacitors are a must on both the input and the output. Recommended values are 2 μF on the input and 1 μF on the output. It is good practice to include a 0.1 μF ceramic capacitor with short leads on the output to improve transient response. This capacitor still "looks like" a capacitor at frequencies which are high enough to make the bigger capacitor "look" inductive.

Positive regulators are inherently more stable than negative regulators, and therefore stabilizing capacitors may not be necessary in all applications. Still, it is good practice to use bypass capacitors at all times. 0.33 μF on the input and 0.1 μF on the output are recommended. The capacitors should be on or as near as possible to the regulator terminals.

Both types of regulators and their associated stabilization capacitors are shown below.

![Positive Regulator Diagram]

![Negative Regulator Diagram]
ERRORS CAUSED BY COMMON CIRCUIT WIRES

Generally one wants to keep all leads short to avoid stray capacitance and line inductance which can lead to stability problems. One must be careful though with the ground lead as ground loop errors can degrade circuit performance if the ground lead does not go to the correct point. The problem is illustrated in the next two drawings. The regulator in these drawings is like our parts kit LM723 in that it has separate "Sense" and "Out" leads.

The voltage which is regulated is that between "G" and "Sense". Between these two terminals are two pieces of current carrying wire with at least some resistance. These resistances are shown in the second drawing as R2' and R3'. We know the current charging C1 is far from constant since the capacitor is charged by large current surges at the peaks of the rectified sine wave. The product (I1)(R2') is sensed by the regulator, and Vout is adjusted to cancel this "error" voltage. Thus Vout (relative to ground) acquires spurious voltage spikes because R2' is in the sensed path. Note that C1 is the filter capacitor not the stabilizing capacitor discussed above. The stabilizing capacitors are not shown in these drawings.
Probably less serious than the R2' error is the fact that the load current flows through R3'. This IR drop subtracted from the regulated value gives the actual value across the load (if we neglect R4'). The following diagram shows how to avoid both the R2' and the R3' errors.

FILTER CAPACITOR CHOICE For each type of voltage regulator there is a certain minimum \( V_{in} - V_{out} \) required for proper operation of the regulator. This value is typically 2 to 3 volts. Some care must be taken if the regulator is being supplied by a simple unregulated DC supply such as that shown in the last figure. The peak \( V_{in} \) will be essentially the peak output voltage of the transformer less two diode voltage drops. As we discussed in the lecture on diodes, the current is supplied by the capacitor between charging intervals which occur every 1/120 of a second (for full wave rectification). It is essential that the voltage across the capacitor not fall below the minimum \( V_{in} \) during this charge/discharge cycle. In other words, the filter capacitor must be large enough to hold the voltage up to the minimum. The minimum capacitor size can be found from:

\[
V_{peak} - 2(0.6) - V_{in \min} = \frac{\Delta Q}{C_{min}} = \frac{I_{supply} \left( \frac{1}{120} \right)}{C_{min}}
\]

A larger capacitor is better, but too large a value for \( C \) will cause trouble for the diodes. Remember that the diodes must pass their current in large pulses. In particular, when the power supply is first turned on the capacitors must be completely charged in one surge. This surge current will be at least:

\[
I_{surge} = \frac{CV_{peak}}{1/120}
\]

and it will be larger if the supply is turned on when the transformer is supplying other than 0 volts. For most circuits this surge current is within the ratings of your power (NOT 1N4148) diodes. In extreme cases bigger diodes must be used, or a small resistor placed in the line feeding the capacitor. The definitive reference on this subject is:

The LM723 Regulator

The LM723 regulator chip is a variable regulator that can provide outputs from 2 volts to 250 volts, depending on the circuit configuration. The minimum drop across the regulator is 3 volts, and the maximum is 38 volts. The unit can supply up to 150 mA of output current, but note that the maximum power dissipation at an ambient temperature of 25 °C is just 660 mW. Now 38 volts times 150 mA is 5700 mW! What this means, of course, is that you can not have maximum voltage drop and maximum current at the same time. If you want 150 mA your voltage drop must be between 3 and 4.4 volts.

The LM723 offers either simple current limiting or foldback current limiting. The following drawing shows the mechanics of the simple current limiting. T2 is the series pass transistor, the $R_s$ of the series regulator. T1 is the transistor that controls current limiting. R is an external resistor connected between the current limit, CL, and the current sense, CS, terminals. When the product of R and I rises to 0.6 volts T1 is turned ON and tries to pull the base of T2 down toward the voltage at CS. Lowering the base of T2, and thus $V_{bc}$, tends to turn T2 OFF, and thus reduce the current through R. The net result is that enough current flows to turn T1 on just enough to let T2 pass that amount of current. For currents less than I=0.6/R the T1 transistor is OFF and plays no role. Note that on page 40 of the data sheets in the Current Limiting equation $V_{sense}$ is our 0.6 volts. If the device is run hot this value may fall to 0.5 volts.

Simple Current Limiting

Foldback Current Limiting

The configuration for foldback is shown in the next drawing. In this case the base of T1 is fed from a voltage divider. Clearly T1 is not turned ON at IR = 0.6. Unfortunately there are two further errors on the data sheets which hamper understanding and application of foldback limiting. We will correct these as we go along.
First let us calculate the current that results when the output is shorted to ground. In this case the emitter of T1 is at ground; the \( V_{\text{out}} \) terminal is at \( IR \), and the base of T1 is at \( \frac{IR^*R1}{R1+R2} \). Note that with this voltage divider, and the other voltage divider equations on the data sheet, it is assumed that the voltage divider is not appreciably loaded. In other words, the current through the divider is large compared to the load current. If we set this voltage divider result equal to 0.6 we obtain \( I_{\text{short}} = 0.6(R1 + R2)/R^*R1 \). This result agrees with the equation on page 40 of the data sheets with the labeling changes \( R \rightarrow R_{\text{SC}} \), \( R1 \rightarrow R4 \), and \( R2 \rightarrow R3 \). These new labels correspond to figure 6 on page 41 of the data sheets. If you plug in the values given in that figure you find \( I_{\text{short}} = 30 \, \text{mA} \), rather than the 20 mA given in the Typical Performance list under the figure. Note that 20 mA would be appropriate for a simple \( 0.6 = IR \).

Having established the fallibility of the data sheets (once again), we go on to calculate the current limit at full regulated output voltage. As usual, we set 0.6 equal to the \( V_{\text{be}} \) of T1.

\[
0.6 = V_{\text{be}} = V_b - V_e = \frac{V_{\text{out}} R_1}{R_1 + R_2} - (V_{\text{out}} - IR) = \frac{V_{\text{out}} R_2}{R_1 + R_2} + IR
\]

so:

\[
I = \frac{0.6 R}{R} - \frac{V_{\text{out}} R_2}{R(R_1 + R_2)}
\]

We note that this expression does not agree with that of page 40 of the data sheets. It is left as a problem to show that the data sheet expression is correct if we put \( V_{\text{reg. output}} \) in place of \( V_{\text{out}} \). Of course, \( V_{\text{reg. output}} \) is a more reasonable value to use.

Returning to the figure 6 example, and putting the circuit values into the corrected page 40 expression we find the limiting current to be 110 mA.

The basic action of the voltage divider is that when the output is not shorted there is a larger current flow through the divider, and thus there is a larger voltage drop across \( R2 \). In this case it takes a larger voltage drop across \( R \) to turn ON T1.

The output voltage of the supply is controlled such that the voltages at the inverting and non-inverting inputs are equal (good old virtual equality). A voltage related to the output voltage is connected to the inverting input, and a voltage related to the reference voltage is connected to the noninverting input. A voltage divider is used to set the desired relationship. If \( V_{\text{ref}} \) (nominally 7.15 volts) is larger than the desired output, the divider is connected between the \( V_{\text{ref}} \) and the non-inverting input and the regulated output is connected directly to the inverting input. If the desired output voltage is greater than \( V_{\text{ref}} \), the divider is put on the other input.
The data sheets have other applications of the LM723, and Horowitz and Hill have a length discussion of this chip and others.