PDHonline Course E408 (3 PDH)

Low Voltage Power Supplies II - Linear Regulators

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Low Voltage Power Supplies II – Linear Regulators

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1. Introduction

Direct Current (DC) power supplies are a requirement of most electronic devices including appliances, computing equipment, mobile devices, radios, televisions, industrial equipment and a whole host of other products. Unregulated DC sources, such as batteries or those derived from rectified Alternating Current (AC) sources, often do not provide the level of precision and accuracy required by modern electronic circuitry. The problem with these unregulated sources is that the output voltage of the power supplies changes too much for changing conditions of the input and output. Series resistances in these unregulated sources result in a DC output voltage that will increase or decrease with increases and decreases in the current drawn by the load, and with increases and decreases in the input source voltage to the supply.

The magnitude of these changes is too large for many classes of applications. Computing devices, sensors and communications devices often need a more precise DC voltage. Linear Voltage Regulators react to these varying conditions by continuously measuring the output voltage and comparing it to a fixed reference voltage. As the DC voltage changes due to external conditions the change is sensed and an error signal is fedback to a device that increases or decreases the output voltage until the reference and the output are again equal.

In this course, Section 2 describes the basic principles of operation of series linear voltage regulators. Section 3 discusses design considerations associated with linear voltage regulators using discrete devices including transistors, resistors, capacitors and operational amplifiers. Section 4 discusses integrated circuits that perform many of the functions of a linear regulator. Section 5 discusses protection mechanisms commonly found in integrated linear regulators. Section 6 shows how multiple regulators can be used to build a DC power supply capable of driving higher current loads.

2. Principles of Operation

Figure 1 shows the block diagram of a Linear Regulator. This regulator is classified as a series regulator because it uses a series pass transistor to regulate the output voltage. This type of voltage regulator is one of the most common forms of linear regulation. Series linear regulators achieve regulation by comparing the DC Output Voltage (V_{OUT}) or a fraction of it (V_{SENSE}) to a precise reference voltage (V_{REF}) and generating an error signal when they are not equal. That error signal is used to adjust the current to the load (I_{OUT}) until the V_{OUT} = V_{REF}.

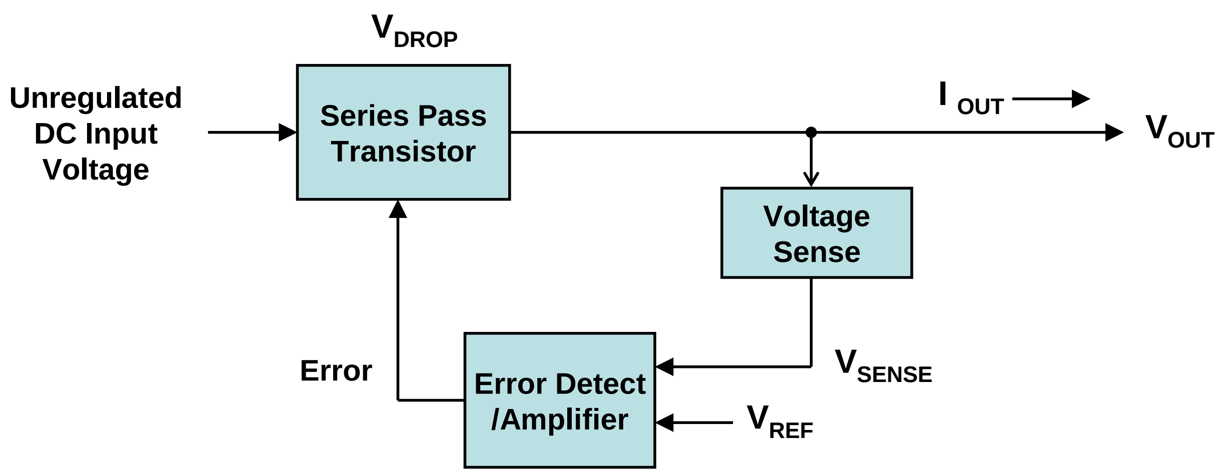

Figure 1 – Series Linear Regulator Block Diagram

The series pass transistor is commonly a bipolar junction transistor (BJT), Metal Oxide Silicon Field Effect Transistor (MOSFET) or Insulated Gate BJT (IGBJT). Darlington Transistor pairs are also used here when large gains are required between the error signal and the output current, I_{OUT}. The series pass transistor is essentially a current source for the load and its main purpose is to provide the "right" amount of current so that V_{OUT} is maintained at the nominal rated output voltage of the supply. When a current controlled series pass transistor is used such as a BJT or Darlington pair, the pass transistor is acting as a current amplifier of the error signal where the error signal is in the form of a current to the base of those devices. When a voltage controlled series pass transistor is used such as a MOSFET or IGBJT, the pass transistor is acting as a transconductance amplifier where the error signal is in the form of a voltage to the gate of those devices.

V_{SENSE} is proportional to V_{OUT} and tracks the output voltage. In the steady state, $V_{SENSE} = V_{REF}$ and the current drawn by the load is I_{OUT}. The series transistor is operating at approximately the same current as I_{OUT} and there is a fixed voltage drop (V_{DROP}) across the series pass transistor. If V_{SENSE} increases due to changes in the load, an Error signal is applied to the series pass transistor causing I_{OUT} to decrease, V_{DROP} to increase, V_{OUT} to decrease and V_{SAMPLE} moves towards the value of V_{REF}. Once the $V_{SENSE} = V_{REF}$, a new steady state V_{DROP} and I_{OUT} are established for the new load conditions.

A decrease in V_{OUT} causes the opposite changes in these voltages and currents again bringing moving towards a new steady state where $V_{SENSE} = V_{OUT}$.

A similar chain reaction takes place for an increase or decrease in the Unregulated DC Input Voltage. The input change causes V_{DROP} to change and in turn V_{OUT} to change. The change in V_{OUT} is sensed and an Error signal adjusts the series pass transistor.

V_{SENSE} is often a simple resistive voltage divider so that the input to a comparator tracks the changes to V_{OUT} without delays. This essentially creates a gain of less than one for this feedback component. The resistive divider has advantages in terms of simplicity and cost.

V_{REF} is usually derived independent of the regulator circuit itself so that it will not be varying due to changes taking place in the feedback loop and regulation process itself. Using a voltage divider for the sense circuit means V_{REF} is less than V_{OUT}. This makes it practical to derive V_{REF} from the unregulated side of the power supply. V_{REF} can be derived from the unregulated DC input voltage or, in the case of an AC-DC power supply, a separate winding from the transformer.

The Error Detect/Amplifier circuit provides two functions. The first is to detect the difference between V_{SENSE} and V_{REF} and can be implemented with discrete transistors, however, operational amplifiers (Op Amp) are commonly used here. The second function is to provide an error signal that is in a useful form to drive the particular Series Pass Transistor being used. For example, a MOSFET or

IGBJT would require a voltage input. A BJT or Darlington pair would require a current proportional to the error.

3. Discrete Linear Regulator Design

This section will look at some of the design considerations in the blocks of the Series Linear Regulator shown in Figure 1. While this look does not represent all designs that could be employed, it is representative of techniques commonly seen in real-world power supplies. There is also a discussion of stability in the feedback loop of the error sensing and control circuit.

a. Voltage Sensing

The resistive voltage divider is the most used method for sensing the output voltage. The divider is simple, inexpensive and does not consume real estate. The main design consideration is to choose values that have negligible impact on the load. Resistors should be chosen that are "large" compared to the load resistances that the power supply is designed to drive. Figure 2 represents the series pass transistor, voltage sense and load resistance under steady state. R_1 and R_2 should be selected to be at least 10 times the maximum load resistance that will be seen by the power supply.

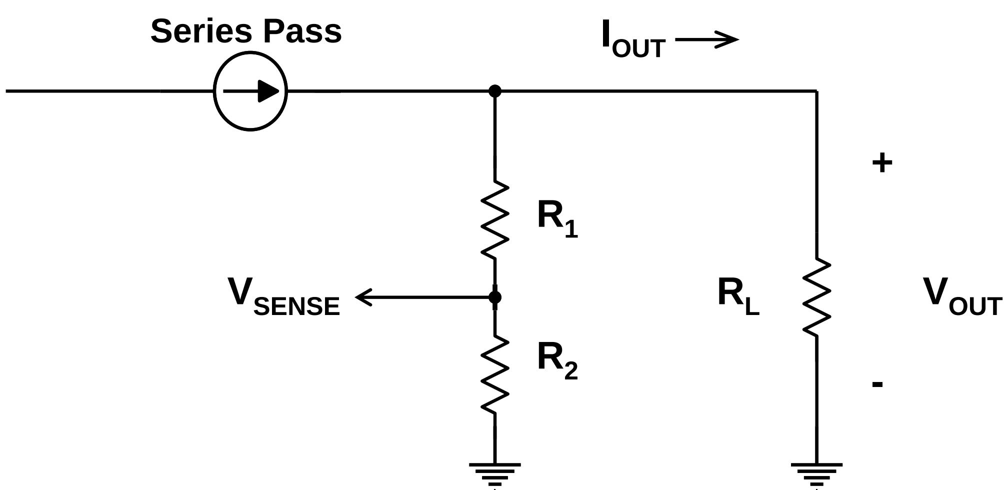

Figure 2 – Model of Voltage Sense and Load Resistances

For example, if a power supply has a nominal output voltage, V_{OUT}, of 5V and can provide output currents, I_{OUT}, over the range of 1 mA to 1 A, The range of effective load resistances, R_L, can be found from Ohms Law.

$$R_{LMIN} = \frac{V_{OUT}}{I_{MAX}} = \frac{5}{1} = 5\,\Omega$$

$$R_{LMAX} = \frac{V_{OUT}}{I_{MIN}} = \frac{5}{0.001} = 5\,k\Omega$$

The sum of R_1 and R_2 should be at least 50 kΩ. The ratio of R_1 to R_2 is selected such that $V_{SENSE} = V_{REF}$ when V_{OUT} is the nominal rated output voltage of the supply. Design equations for this example are:

$$\frac{R_1}{R_2} = \frac{V_{OUT(nominal)}}{V_{SENSE}} - 1 = \frac{5}{V_{REF}} - 1 \qquad \text{and} \qquad R1 + R_2 > 50\,k\Omega$$

b. Voltage Reference

The Voltage Reference is best derived from a source not related to the feedback loop and output of the regulator. In the case of AC-DC power supplies, it is possible to select an AC transformer with a separate winding dedicated to the Voltage Reference. It is also common to derive the reference source from the Unregulated DC Input to the regulator. This has the advantage of lower cost than the extra winding on the transformer.

Most techniques rely on characteristics of semiconductors to derive the reference. Three techniques for generating a voltage reference are.

1. Forward Voltage Drop
2. Zener Diodes
3. Bandgap Reference

The Forward Voltage Drop technique uses multiple forward voltage drops of diodes or other PN junctions to set the reference voltage. With this technique, a number of forward biased diodes are stacked in series to produce some multiple of the inherent voltage drop of the semiconductor being used. In some circuits it is possible to combine a forward biased PN junctions of transistors in this stack, For example the forward biased Base-Emitter junction of a BJT (approximately 0.7 V) can be part of the stack. In the case of silicon diodes and transistors, the reference voltage would be some multiple of the typical voltage drop of 0.7 V.

A more common technique is the use of a Zener Diode. This technique takes advantage of the Zener effect in diodes that result in a fixed voltage across the reverse biased diode. The value of this voltage is based on internal doping characteristics of the device. A key to this technique is that the reversed bias voltage does not change much over a large range of reverse currents. Figure 3 shows a Zener diode circuit where the voltage source is the Unregulated DC Input Voltage to the regulator.

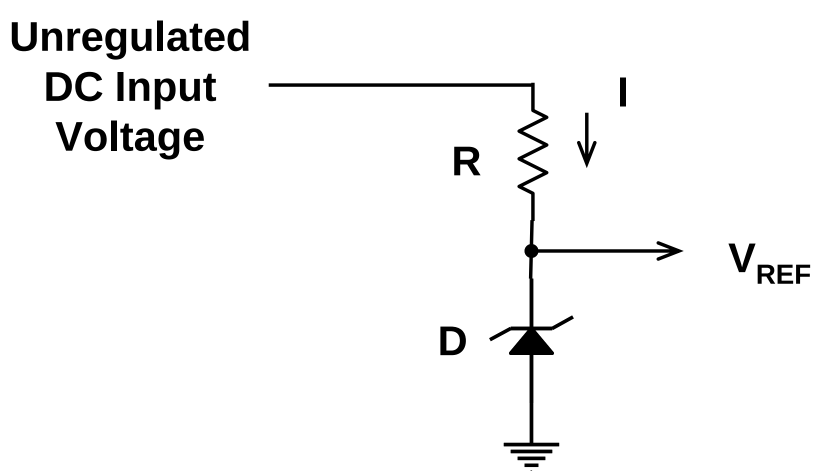

Figure 3 – Zener Diode Voltage Reference

In this circuit we assume V_{REF} is connected to a high impedance device such as the input to an operational amplifier (Op Amp). In that case, the voltage across the Zener Diode, D, will be the Zener Voltage of the diode and will be constant as long as the current through R and D keeps the diode operating in the Zener region of its IV characteristics. A typical Zener Diode will be in the Zener region with tens of milliamps reverse current.

Take the example where the Unregulated DC Input Voltage is 8 VDC with a 1 VAC ripple voltage. The input varies from 7V to 9V. If the design calls for a V_{REF} of 3 V, a diode D is selected with Zener Voltage of 3V and the datasheet shows that the diode is well within the Zener region at I = 10 mA. Then,

$$R = \frac{V_{IN(min)} - V_{REF}}{I_2} = \frac{7 - 3}{0.01} = 400\,\Omega$$

Note that at the maximum input voltage of 9 V, the current, I, is larger meaning the Zener diode is still in the Zener region.

The Bandgap reference is a technique developed by Paul Brokaw at Analog Devices in the 1970's. It was initially employed in integrated circuits to provide a very high precision voltage reference with very high temperature stability for a complex function in an integrated circuit. The technique has migrated to dedicated components whose sole purpose is generating a stable reference voltage. The technique combines a positive temperature coefficient device and a negative temperature coefficient device that complement each other in such a way that the reference is essentially fixed over a wide temperature range. The name comes from the original circuits that produced a 1.25 V fixed reference, which is derived from the 1.22 electron-volt energy bandgap of silicon at 0 degrees Kelvin. The technique has been used in three terminal devices produced by companies such as Linear Technologies and Analog Devices to provide a wider range of voltage than just 1.25 V.

c. Error Detect / Amplifier

The Error Detect/Amplifier has two functions:

1. Detect changes in the output voltage and generate an error signal.
2. Provide drive and bias for the series pass transistor.

Figure 4 shows a circuit for detecting changes in the output voltage. The Op Amp is biased from V_{OUT} and Ground. In the steady state, where $V_{REF} = V_{OUT}$, its output is at half the difference in the supply voltage, i.e. $V_{ERR} = ½\ V_{OUT}$.

If the load changes and V_{OUT} increases, V_{ERR} decreases providing a negative feedback signal for use in biasing the series pass transistor. The opposite is true if V_{OUT} decreases. This circuit would be used if the drive and bias required a signal of the opposite polarity as the change in V_{OUT}. If the drive and bias circuit requires a signal of the same polarity as the change in V_{OUT}, V_{REF} and V_{SENSE} would be connected to the – and + input respectively.

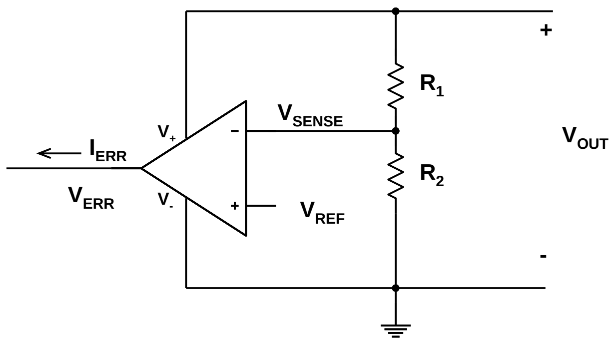

Figure 4 – Error Detect Circuit

The drive and bias function requires converting the I_{ERR} and V_{ERR} signal to a form usable by the series pass transistor. The series pass transistor can be of two forms. The first is a current amplifier where the error and control input is a current and the output is also a current. In this case, I_{ERR} is the drive current for a device such as a BJT or Darlington pair. Figure 5 shows some examples of drive and bias circuits.

Figure 5(a) shows the Op Amp driving the series pass transistor, Q, directly. The important factors here are the forward current gain, h_{FE} (or sometimes called β_F) of Q and the drive capability of the operational amplifier chosen. When the maximum current is being drawn by the output of the supply, the operational amplifier must be able to provide I_{OUT} / Q to the base of the transistor. R_3 can be added to bring the output voltage of the operational amplifier to a value closer to ½ V_{OUT} and have more range to react to changes.

Figure 5(b) shows an NPN series pass transistor, Q_1, where the base drive is being supplied by transistor Q_2. The important factors are to consider the h_{FE} parameters for each transistor as compared to the maximum output current of the power supply and the operational amplifier. R_3 provides bias for Q_2 to keep it in the active region.

Figure 5(c) shows the PNP equivalent with an NPN transistor provides base drive. Note that the V_{SENSE} and V_{REF} inputs are into the opposite polarity inputs to the operational amplifier.

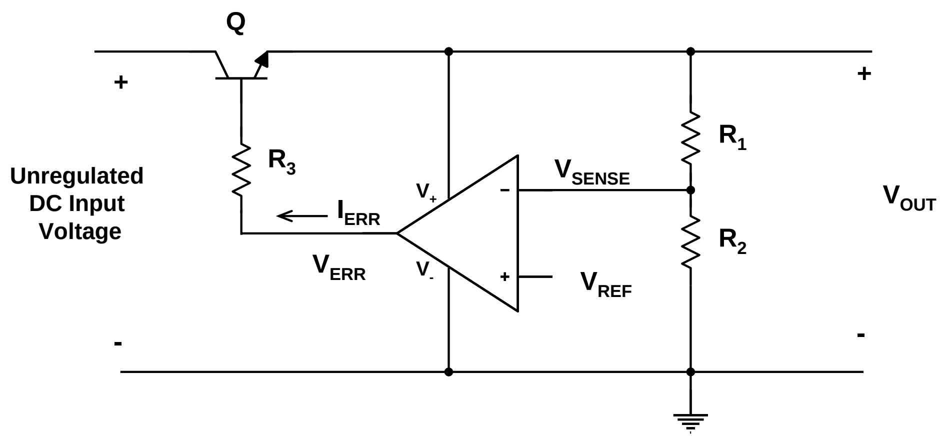

Figure5 (a) Direct Drive

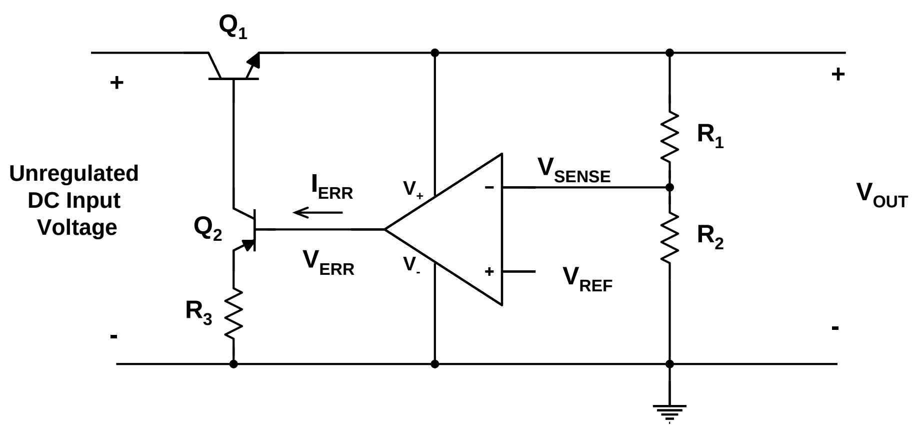

Figure 5 (b) NPN Series Pass with PNP Base Drive Transistor

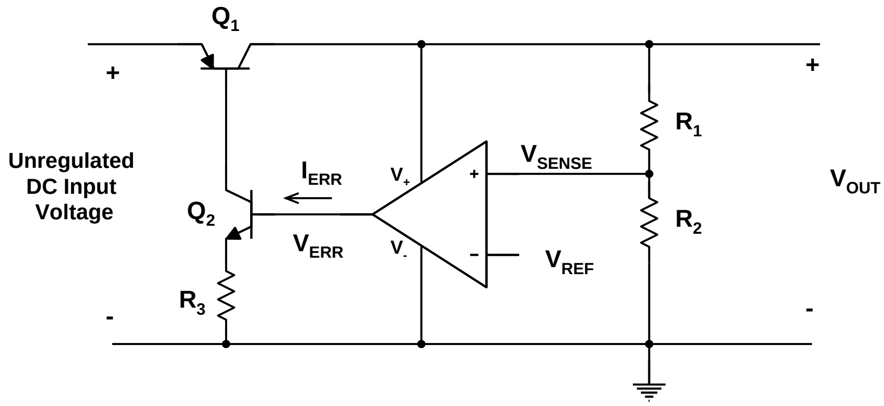

Figure 5 (c) PNP Series Pass with NPN Base Drive Transistor

The second form of series pass transistor is the transconductance amplifier. The control or error input is a voltage and the output is a current. In this case the error input, V_{ERR}, is applied to the gate of a MOSFET or IGBJT to adjust the output current to the load. Figure 6 shows a circuit with an N-channel, depletion-mode MOSFET as the series pass transistor. A depletion-mode device is used here because negative gate to source voltage is needed since V_{ERR} will be negative as compared to V_{OUT} due to the powering arrangement of the operational amplifier. R_3 and R_4 form a simple voltage divider. The ratio allows the gate voltage on Q to be adjusted to match its IV characteristics and keep the transistor operating in an active region.

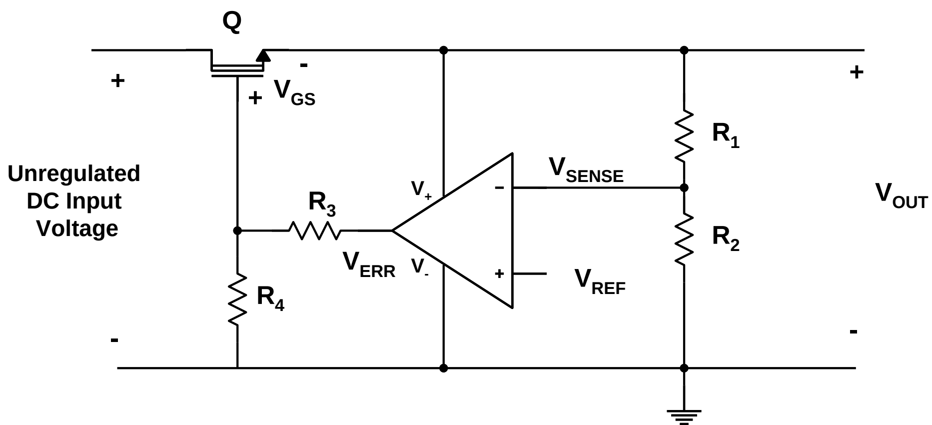

Figure 6 – N-channel, depletion-mode MOSFET series pass transistor

As with the BJT examples, other combinations of P-channel and N-channel devices could be used here with the appropriate detection of the difference between V_{SENSE} and V_{ERR}.

d. Series Pass Transistor

In the last section, the drive circuits for various transistor configurations were shown and some of the considerations in designing those circuits were discussed. To complete the detailed design, the series pass transistor needs to be selected to drive the rated output currents of the power supply. Three important considerations for deciding this are:

1. IV characteristics of the pass transistor?
2. Maximum and minimum output current of the supply?
3. Variation in voltage of the Unregulated DC Input Voltage?

With answers to these questions, an operating range on the IV characteristics of the series pass transistor can be established. That in turn allows the selection of components and completion of the drive and bias circuit from the error amplifier.

Figure 7 represents and equivalent circuit for the series pass transistor. R_L represents the variable load resistance and is related to the range of I_{OUT} and the nominal V_{OUT} by Ohms Law. $V_{DC\ IN}$ is the average unregulated DC input voltage and $V_{AC\ IN}$ is the magnitude (peak to peak) of the AC ripple voltage. The Control Input is a current or voltage depending on the type of transistor chosen.

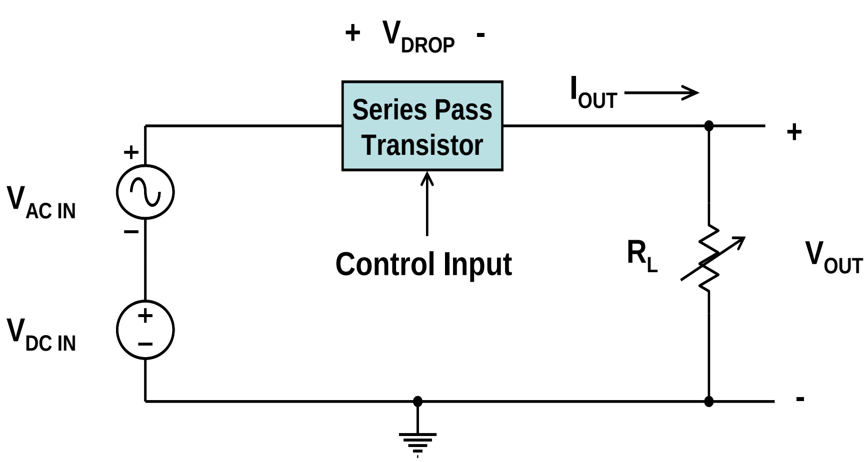

Figure 7 – Equivalent Circuit for Series Pass Transistor

If a BJT is used as the series pass transistor, V_{DROP} would be the collector-emitter voltage, V_{CE}, of the transistor and I_{OUT} would be I_C. Looking at Figure 7,

$$V_{DROP\ MAX} = V_{CE\ MAX} = \left(V_{DC\ IN} + 1/2\ V_{AC\ IN}\right) - V_{OUT}$$

$$V_{DROP\ MIN} = V_{CE\ MIN} = \left(V_{DC\ IN} - 1/2\ V_{AC\ IN}\right) - V_{OUT}$$

By specification, $I_{OUT\ MAX}$ and $I_{OUT\ MIN}$ are given, so;

$$I_{OUT\ MAX} = I_{C\ MAX} \quad \text{and} \quad I_{OUT\ MIN} = I_{C\ MIN}$$

In Figure 8, these values have been mapped onto IV characteristics of a typical BJT. These curves are simplified by the assumption that the Early voltage of the BJT is large and the relationship between the base current, I_B, and the collector current, I_C, is simply:

$I_C = h_{FE} \times I_B$ where h_{FE} is the DC Current Gain of the transistor

DC Current Gain is represented by h_{FE} in most transistor datasheets, however, it is called β_F in many text books.

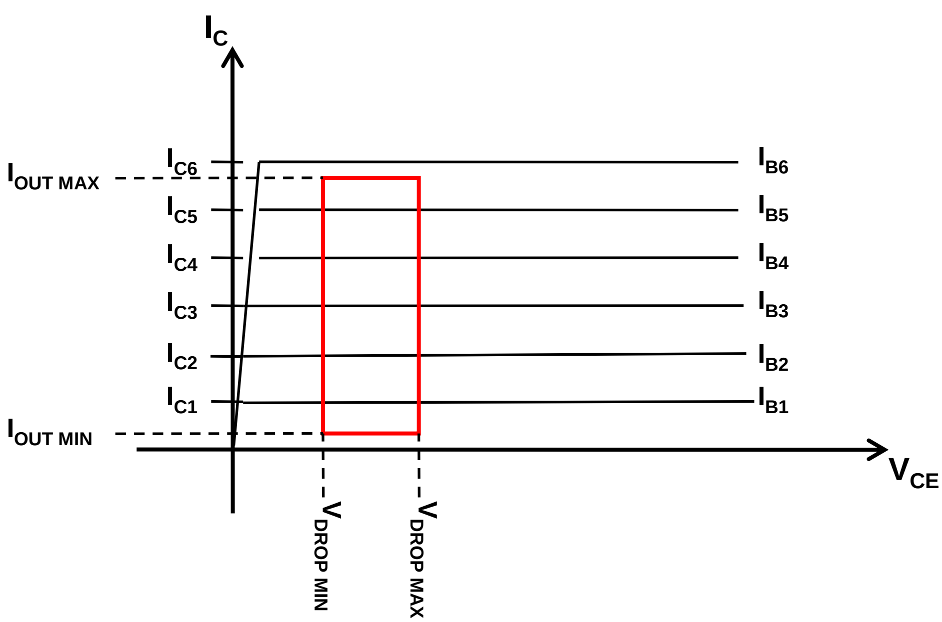

Figure 8 - Supply Specifications on IV characteristics of BJT

The red box represents the limits of operation that the power supply design specifications dictate. The red box is such that the transistor will operate in a linear region. By superimposing these on the IV characteristics, the limits of operation of the base drive circuit can be determined that will keep the transistor from saturating or being cutoff in trying to adjust the output voltage to the nominal voltage.

The starting point for the design is selecting a transistor such that the limits of the power supply can be superimposed on the linear region of the IV characteristics. Then the base drive circuit of the Error Detector/Amplifier can be determined that will bias the series pass transistor in this region using circuits similar to those in Figure 5 (a), (b) or (c).

If an N-channel MOSFET is used as the series pass transistor, V_{DROP} would be the drain-source voltage, V_{DS}, of the transistor and I_{OUT} would be I_D. Looking at Figure 7,

$$V_{DROP\ MAX} = V_{DS\ MAX} = \left(V_{DC\ IN} + 1/2\ V_{AC\ IN}\right) - V_{OUT}$$

$$V_{DROP\ MIN} = V_{DS\ MIN} = \left(V_{DC\ IN} - 1/2\ V_{AC\ IN}\right) - V_{OUT}$$

By specification, $I_{OUT\ MAX}$ and $I_{OUT\ MIN}$ are given, so;

$$I_{OUT\ MAX} = I_{D\ MAX} \quad \text{and} \quad I_{OUT\ MIN} = I_{D\ MIN}$$

In Figure 9, these values have been mapped onto IV characteristics of a typical MOSFET. These curves are simplified by the assumption that the modulation factor is small and the relationship between the gate to source voltage, V_{GS}, and the drain current, I_D, in the region of interest, the active region, is:

$I_D = K_N/2\ (V_{GS} – V_{TN})$ where K_N is the transconductance and V_{TN} is the threshold voltage of the transistor

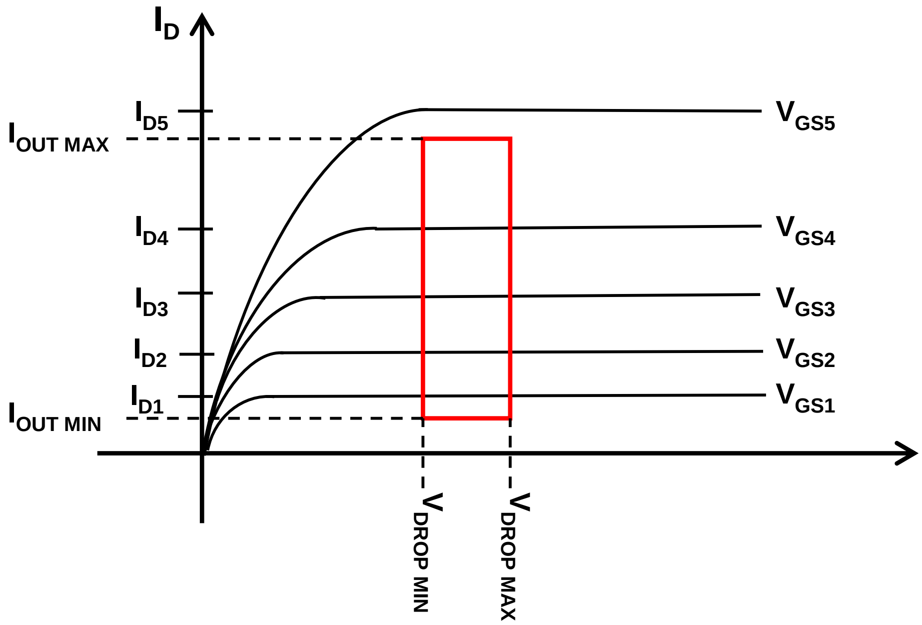

Figure 9 – Power Supply Specifications on IV characteristics of MOSFET

Again, the red box represents the limits of operation that the power supply design specifications dictate and the limits of operation of the gate voltage can be determined.

The starting point for the design is selecting a transistor such that the limits of the power supply can be superimposed on the linear region of the IV characteristics. Then the gate drive circuit of the Error Detector/Amplifier can be determined that will bias the series pass transistor in this region using a circuit similar to Figure 6.

e. Stability

Stability of the feedback loop is an important consideration in designing a regulator. Regulators are used in applications where the output load can change dramatically. For example, the power supply could be the source for a DC Motor Drive where the motor turns on and off upon demand from an intelligent controller. In such a case, the current load on the supply changes “instantly” from the relatively small amount to run the controller to a relatively large amount when the motor is operating. The linear regulator is a feedback control system that must react to these large, fast changes in the output load current and is subject to the same instability issues as any control system.

There are a number of ways to deal with stability in the feedback loop and they are based on low pass filtering of the high frequency components in the feedback loop. By suppressing high frequency components due to these abrupt changes in load they will not become a source of instability. With linear regulators there are three places that might be filtered:

1. Add a filter to the voltage divider in the Voltage Sense circuit.
2. Use the operational amplifier in the Error Detector/Amplifier as a low pass filter by adding a capacitor.
3. Add a filter to the output of the power supply.

In some designs, a combination of all these techniques is used. However, the most common technique is number 3, filtering the output of the supply.

Figure 10 shows a generalized voltage regulator with two capacitors added to the output. C_{BU} is a bulk capacitor and provides a dominant low frequency pole to the output. C_{BY} is a bypass capacitor that provides a high frequency pole to the output and is added to the design under the conditions explained below. R_O is the output resistance of the series pass transistor and R_{OF} is the output resistance of the feedback loop.

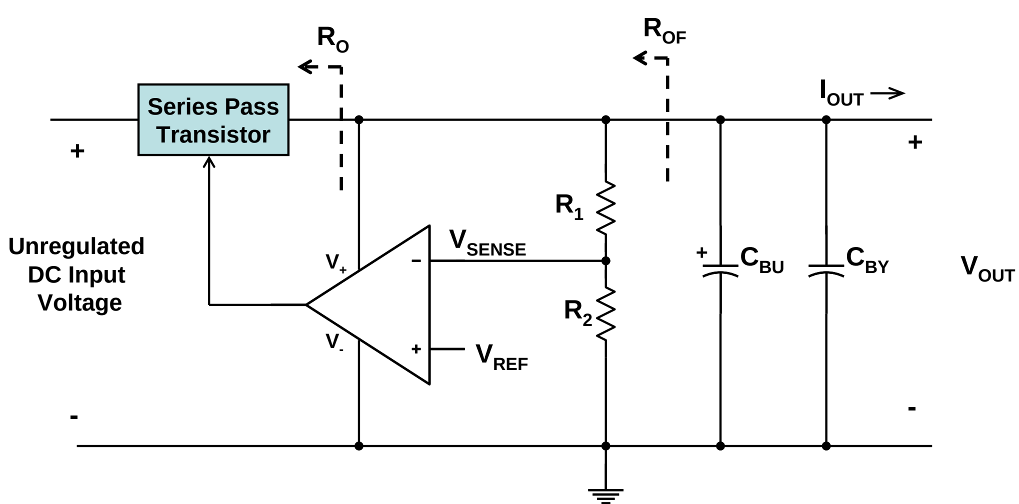

Figure 10 – Generalized Voltage Regulator with Output Filtering

The poles of the output filter are determined by the parallel combination of R_{OF}, C_{BU} and C_{BY}. From control system analysis;

$$R_{OF} \cong R_O \left(\frac{V_{OUT}}{V_{REF}}\right)\left(\frac{1}{A_{OL}}\right)$$ where A_{OL} is the open loop gain of the feedback loop.

When a BJT is used as the series pass transistor as in figure 5b, A_{OL} is the current gain of the amplifier, h_{FE}, and R_O is the output resistance of the common collector configuration which is:

$$R_O \cong \frac{1}{g_m} \cong \frac{V_T}{I_{OUT}}$$ where g_m is the AC transconductance

and V_T is the thermal voltage (25.9 mV)

When a MOSFET is used as the series pass transistor as in Figure 6, A_{OL} is half the transconductance parameter, $K_N/2$, and RO is the output resistance of the common drain configuration which is:

$$R_O \cong \frac{1}{g_m} \cong \sqrt{2K_N I_{OUT}}$$ where g_m is the AC transconductance

This leads to output resistances in the tens of milliohms.

In selecting C_{BU}, the important factor is to establish a dominant low frequency pole so that the response rolls off fast enough to have good gain and phase margins. Rule of thumb design goals for stability are that the loop gain plot has:

1. Phase margin greater than 45° at the 0dB crossover
2. Gain margin greater than –20dB at a phase of 180°

Figure 11 shows a typical loop gain for a regulator with C_{BU} only. The rolloff of the loop gain response is due to the parallel combination of R_{OF} and C_{BU}. Aluminum Electrolytic or Tantalum capacitors are often used here and values are selected to produce a pole at P1. At P1, the Equivalent Series Resistance (ESR) of C_{BU} is negligible. However, selecting values of C_{BU} that will produce a pole at P1 means the ESR will become significant in the 1 KHz to 10 KHz. Then equivalent impedance of the filter is:

$$R_{OF} \parallel \left(R_{ESR} + \frac{1}{sC_{BU}} \right) = R_{OF} \left(\frac{1 + sR_{OF}R_{ESR}C_{BU}}{1 + s\left(R_{OF} + R_{ESR}\right)C_{BU}} \right)$$

The zero at Z1 and the response at higher frequencies is due to the ESR being a significant value at higher frequencies. This often will not allow a negative DB gain margin at 180°. P2 represents the frequency range where capacitances of traces and the series pass transistor occur.

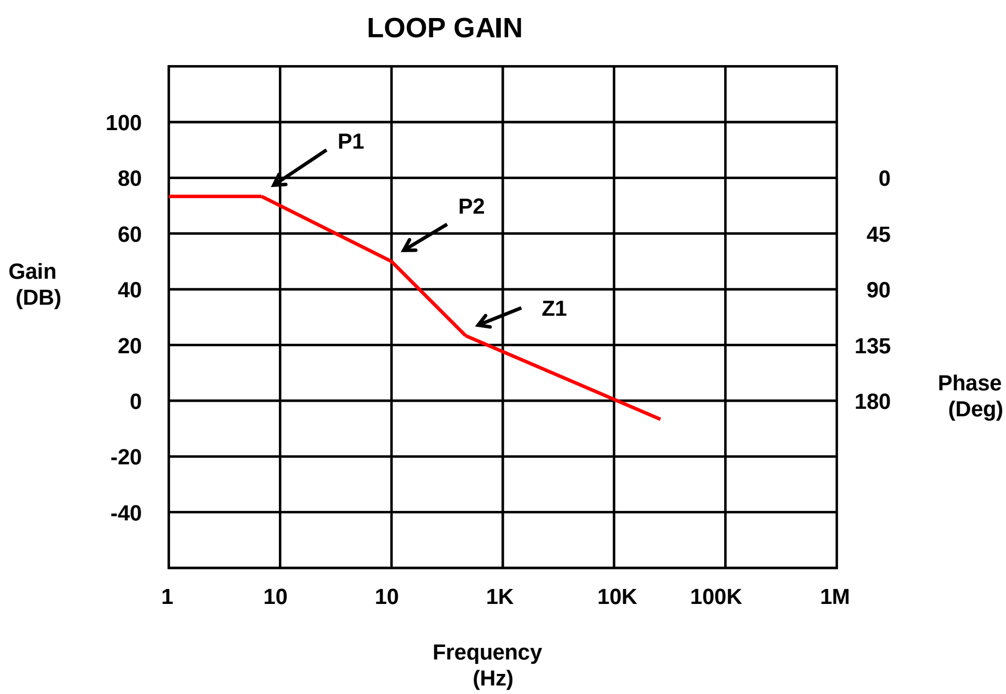

Figure 11 – Loop Gain with Bulk Capacitor Only

Figure 12 represents that loop gain when a bypass capacitor, C_{BY}, is added. This is usually a ceramic capacitor with good high frequency characteristics and a resonant frequency in the megahertz range. C_{BY} is chosen to product a pole at P_3. Adding C_{BY} compensates for Z1 caused by the ESR of C_{BU} and brings the gain margin to a value that will prevent high frequency oscillations.

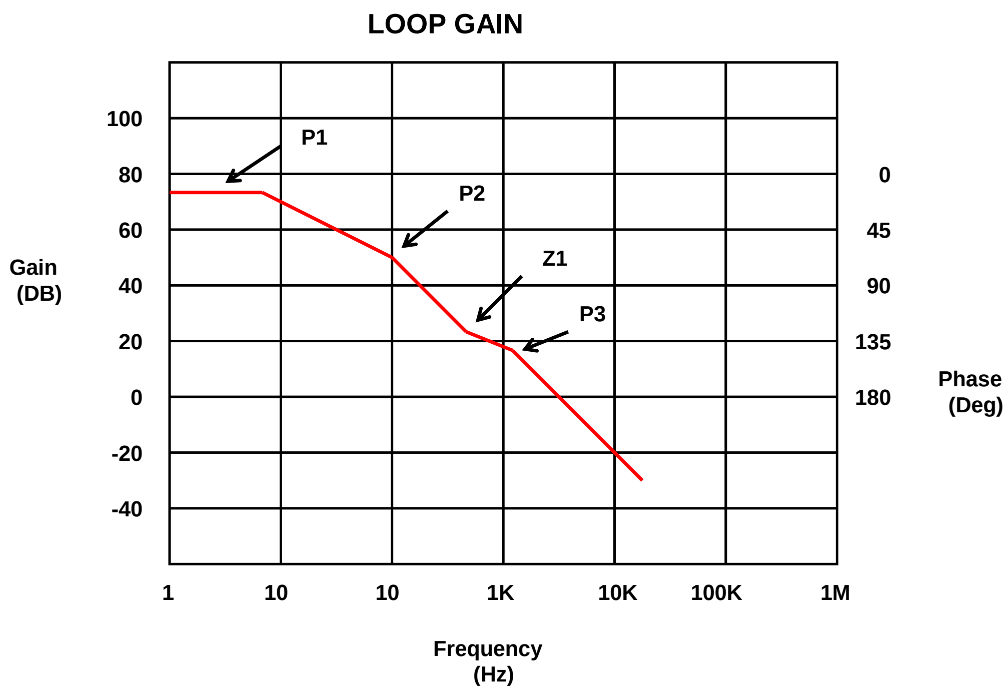

Figure 12 - Loop Gain with Bulk and Bypass Capacitor

These guidelines are a starting point in selecting capacitors to stabilize the feedback loops, however, a simulation of the response should be done using capacitor models that include ESR and ESL (Equivalent Series Inductance) for each capacitor.

4. Integrated Linear Regulators

Custom designed power supplies as described in Section 2 have the potential to be designed to very tight tolerances and can be adapted to the characteristics of a specific application. However, in many applications Integrated Linear Regulators are good choices in that they are inexpensive and do not take up much real estate. Integrated Linear Regulators perform all of the functions of the linear voltage regulator in Figure 1 except the Sensing function. There are two general classifications of integrated linear regulators: 3 Three Terminal and 4 Terminal. The main difference between the two is the relationship between the internal voltage reference and the other terminals on the device.

Figure 13 shows the basic functions within a 3 Terminal positive, adjustable regulator. The unregulated input voltage is applied to the IN terminal, the regulated output voltage is taken from the OUT terminal and the voltage sense is applied to the ADJ terminal.

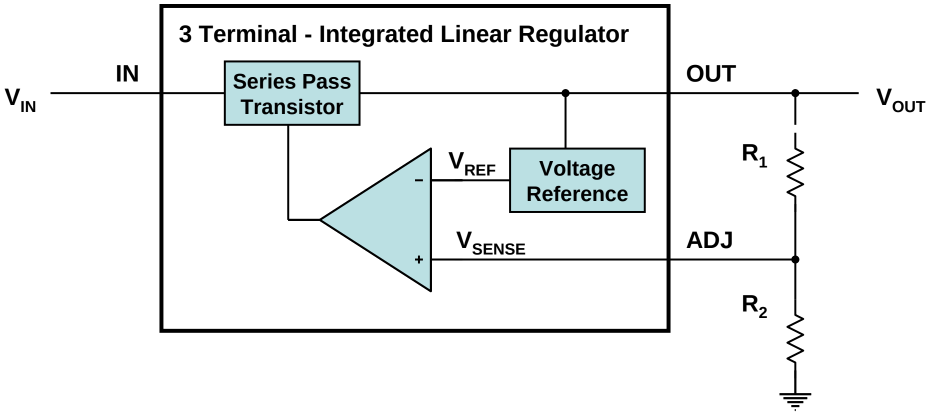

Figure 13 – Functions within a 3 Terminal – Integrated Voltage Regulator

In this case, the Voltage Reference is defined in relation to OUT terminal. An example of this type regulator is the LM117/317 series of regulators. Figure 14 shows the circuit for biasing the LM317. To determine the values of R_1 and R_2, two assumptions can be made. These assumptions are based on the fact that the input to the ADJ pin and the internal voltage reference are applied to operational amplifier type of inputs. So the basic steady state Op Amp model can be used where:

1. The inputs to the operational amplifier draw no current
2. The plus and minus inputs are a virtual short

Applied to Figures 13 and 14: $I_{ADJ} = 0$ and $V_{REF} = V_{ADJ}$.

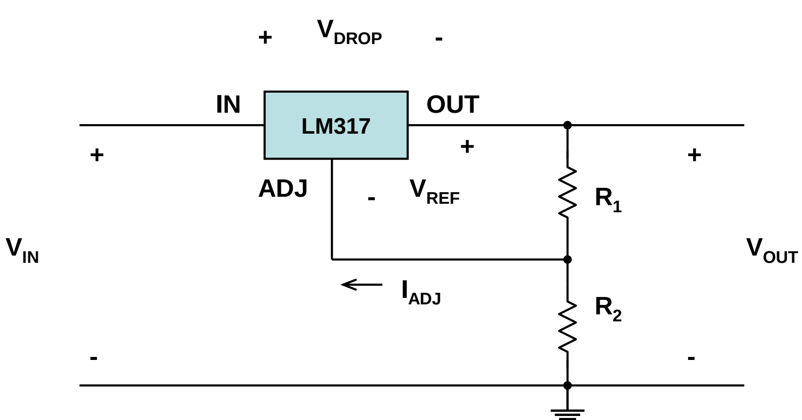

Figure 14 – LM317 Positive, Adjustable Voltage Regulator

Then the voltage across R_1 in the steady state is V_{REF} and the voltage across R_2 is V_{OUT} - V_{REF}. The current through the two resistors is equal. Applying Ohm's Law, the equation below is used to select R_1 and R_2 for the desired V_{OUT}.

$$V_{OUT} = V_{REF}\left(1 + \frac{R_2}{R_1}\right) \qquad \text{3 Terminal Design Equation}$$

The typical value of the reference voltage for the LM317 is 1.25 V and is generated from a bandgap circuit within the bipolar technology of the device.

There are two important limits to be aware of in using the device. The first is the dropout voltage. The dropout voltage is the minimum V_{DROP} that is required for the LM317 to maintain its specified operational characteristics. This value varies with the current being drawn. At an output current of 1.5A the dropout voltage is 2.25 V. At 20mA it is 1.5V. So precautions should be taken to stay within the minimum value for the maximum current draw of the power supply.

The second limitation is the maximum input-output voltage. This is the largest value of V_{DROP} that the device can withstand. For the LM317 it is 40V.

Refer to an LM317 datasheet for recommendations about capacitors to stabilize the feedback loop and protection diodes to protect against discharges into the terminals of the device.

Figure 15 shows the basic functions within a 4 Terminal positive, adjustable regulator. The unregulated input voltage is applied to the IN terminal, the regulated output voltage is taken from the OUT terminal and the voltage sense is applied to the ADJ terminal. The fourth terminal is a GND terminal. The internal Voltage Reference is in relation to the ground of the device and provides a common ground for the external circuitry.

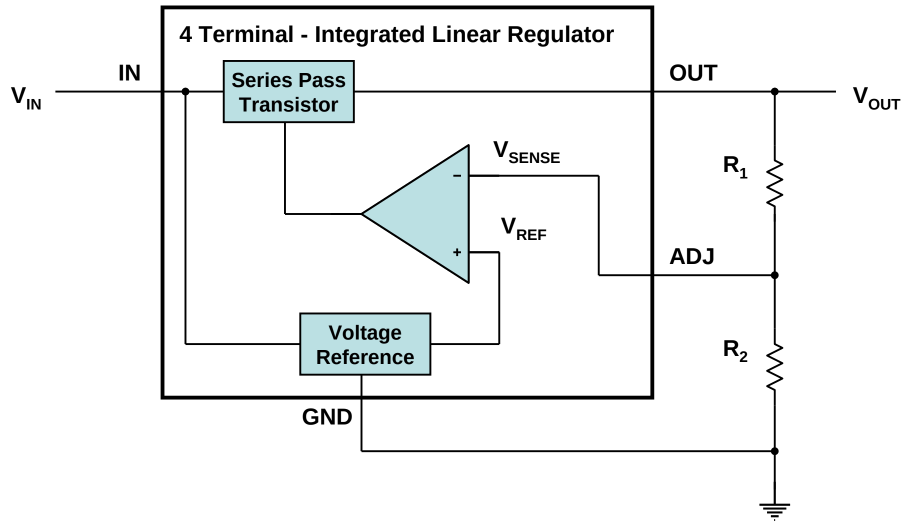

Figure 15 – Functions within a 4 Terminal - Integrated Voltage Regulator

The MCP1824 is an example of a positive liner voltage regulator that uses this method. Figure 16 shows the device used in a circuit. In this case, the voltage across R_2 is designed to be equal to the reference voltage, V_{REF}.

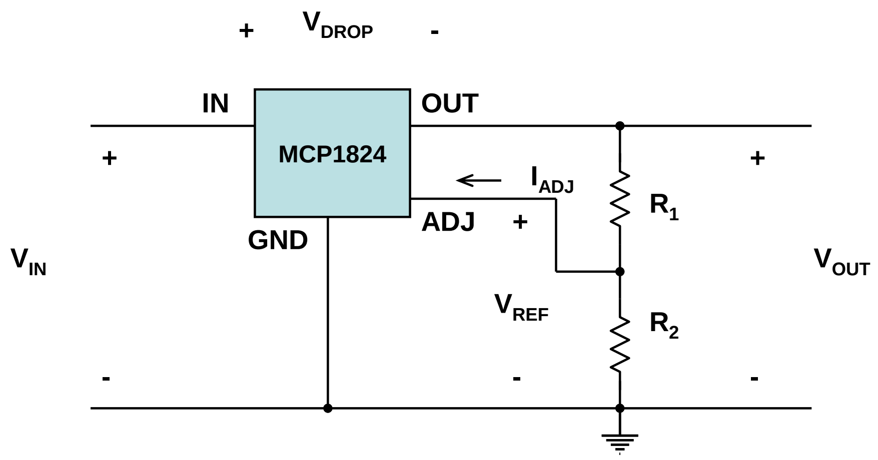

Figure 16 -

Using the same Op Amp model as before, the current into the ADJ is 0, the output voltage of the supply can be selected by a simple voltage divider equation.

$$V_{OUT} = V_{REF}\left(1 + \frac{R_1}{R2}\right) \qquad \text{4 Terminal Design Equation}$$

In the MCP1824, the reference voltage is generated from a Schottky diode based bandgap circuit and the typical value is 0.41V.

The MCP1824 device has the added capability to shutdown the output voltage and current when a low voltage is applied to a shutdown pin. Recommendations for stability and bypass capacitors are given in the datasheets.

These two devices generated their references from bandgap circuits and their values are derived from the technology used. A third reference voltage that is common in integrated circuits and regulators uses CMOS technology and is typically 1.4V. With most adjustable regulators the minimum output voltage can be set very close to the internal reference voltage.

5. Additional Functions in Linear Regulators

In most integrated regulators there are protection mechanisms included to prevent the device from being destroyed when it is operating beyond its limits. Three inter-related mechanisms are:

1. Current Limit
2. Thermal Overload Protection
3. Safe Operating Area Protection

All three are designed to protect the series pass transistor from failing when overstressed. The Current Limit varies with the junction temperature but will shut off the regulator when the limits are exceeded. Usually a graph in the datasheet will show this relationship.

Thermal Overload Protection will shut off the regulator when the junction temperature limits are exceeded. While current limit and thermal limits are sometimes exceeded at the same time, thermal limits can be exceeded even when operating within the current range of the device. For example, if the device is not properly heat sinked or the heat dissipation mechanism fails.

Safe Operating Area Protection takes into account both the V_{DROP} across the series pass transistor and the current through it to ensure the transistor is operating within its power limits.

It is very practical to build a current limit circuit for a discrete power supply also by sensing the current to the output and using the output of the sensor to clamp the feedback voltage to the series pass transistor to a known level.

6. High Current Power Supplies

The power supplies we have discussed are limited by the IV characteristics or the series pass transistor. Whether designing a discrete supply or using integrated regulators, it is easy to run into limits on current where it is difficult to find a series pass transistor or integrated regulator for low voltage, high current applications. One technique is to configure multiple low voltage regulators we have discussed in parallel. Figure 17 shows the general principle of a high current, discrete regulator using parallel BJTs.

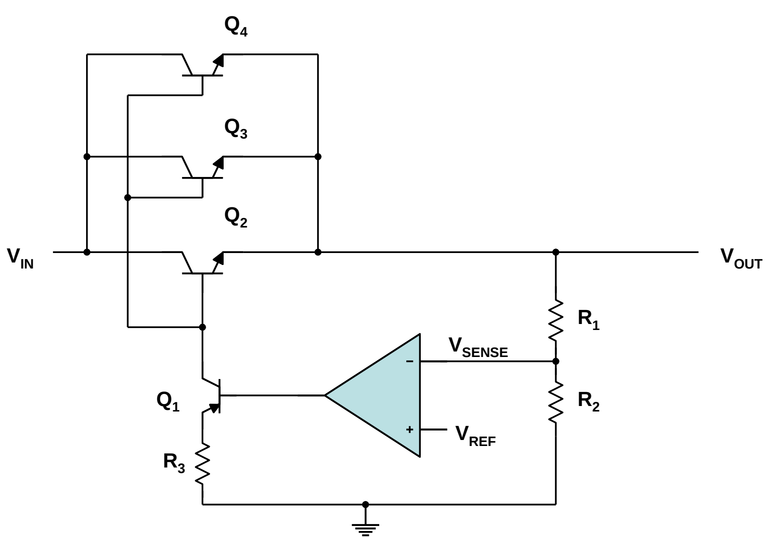

Figure 17 – High Current Regulator using Multiple Series Pass Transistors

A common reference voltage and error detect/amplifier are used to generate an error signal which is applied to all three series pass transistors effectively tripling the current drive by three over a single pass transistor.

Figure 18 shows the general principle using LM117s.

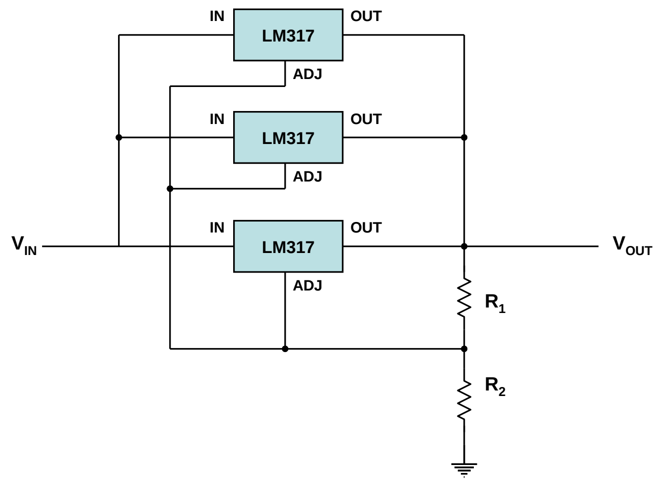

Figure 18 - High Current Regulator using Multiple LM117s

In this configuration the voltage across R_1 is the reference voltage and R_2 sets the nominal output voltage. The current handling capability is effectively tripled.

7. Conclusions

In this course, the design considerations were presented that give the audience an approach to designing linear voltage regulators pointing out key aspects of the design and their importance in the design process. Building on a basic knowledge of transistor circuit design and electronic circuit analysis, linear voltage regulators can be built from discrete components. These discrete voltage regulators can be fine tuned for responsiveness and regulation characteristics.

Integrated linear voltage regulators are available that provide most of the operational functions and are easily incorporated in power supply designs. These integrated regulators include protection mechanisms and very precise voltage references as a fundamental feature using bandgap techniques.

Advantages of linear power supplies are that they are reliable and relatively noise free. One disadvantage of the linear supply is that large components such as transformers are required increasing weight and cost. The biggest disadvantage is that linear supplies are inefficient (less than 50% often) due to the loss of power across the series pass transistor.

