CHAPTER 1

# An Introduction to the Linear Regulator

**Marty Brown**

*Linear power supplies are the simplest of the DC/DC converters, but don't be fooled by the apparent simplicity of them. There are several factors in every application of linear supplies that are important for their reliable operation. These are thermal design, output regulation, stability considerations and its transient response, any of which could cause the system to behave badly.*

*Linear regulators are used much more often than switching regulators. One finds them distributed throughout products as POL (point of load) supplies, where local circuit regulation is needed, voltage bus quieting for noise sensitive circuits, and inexpensive voltage bus generation.*

*If you have done a design completely using linear regulators, you may technically call yourself a "power supply designer," but you will not fully appreciate the complexities of the field until you have experienced a switching power supply design. You have only reached the "tenderfoot" level of experience.*

*I've attempted to cover the material in a succinct and intuitive manner showing how flexible the humble linear regulator can be. The design examples can be scaled and adapted to many other applications. Related topics such as thermal design can be found in chapter 12.*

**—Marty Brown**

The linear regulator is the original form of the regulating power supply. It relies upon the variable conductivity of an active electronic device to drop voltage from an input voltage to a regulated output voltage. In accomplishing this, the linear regulator wastes a lot of power in the form of heat, and therefore gets hot. It is, though, a very electrically "quiet" power supply.

The linear power supply finds a very strong niche within applications where its inefficiency is not important. These include wall-powered, ground-base equipment where forced air cooling is not a problem; and also those applications in which the instrument is so sensitive to electrical noise that it requires an electrically "quiet" power supply—these products might include audio and video amplifiers, RF receivers, and so forth. Linear regulators are also popular as local, board-level regulators. Here only a few watts are needed by the board, so the few watts of loss can be accommodated by a simple heatsink. If dielectric isolation is desired from an AC input power source, it is provided by an AC transformer or bulk power supply.

In general, the linear regulator is quite useful for those power supply applications requiring less than 10 W of output power. Above 10 W, the heatsink required becomes so large and expensive that a switching power supply becomes more attractive.

## 1.1 Basic Linear Regulator Operation

All power supplies work under the same basic principle, whether the supply is a linear or a more complicated switching supply. All power supplies have at their heart a closed negative feedback loop. This feedback loop does nothing more than hold the output voltage at a constant value. Figure 1.1 shows the major parts of a series-pass linear regulator.

Linear regulators are step-down regulators only; that is, the input voltage source must be higher than the desired output voltage. There are two types of linear regulators: the *shunt regulator* and the *series-pass regulator.* The shunt regulator is a voltage regulator that is placed in parallel with the load. An unregulated current source is connected to a higher voltage source; the shunt regulator draws output current to maintain a constant voltage across the load given a variable input voltage and load current. A common example of this is a Zener diode regulator. The series-pass linear regulator is more efficient than the shunt regulator and uses an active semiconductor as the series-pass unit, between the input source and the load.

The series-pass unit operates in the linear mode, which means that the unit is not designed to operate in the full on or off mode but instead operates in a degree of "partially

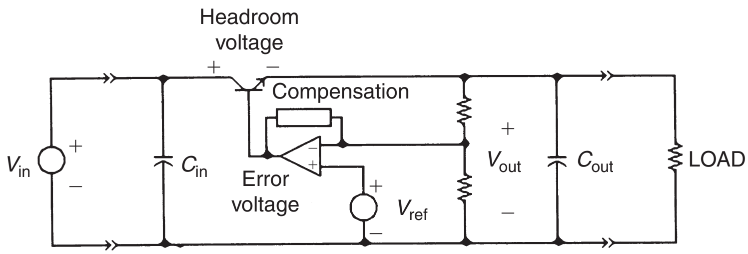


**Figure 1.1: The basic linear regulator**

on." The negative feedback loop determines the degree of conductivity the pass unit should assume to maintain the output voltage.

The heart of the negative feedback loop is a high-gain operational amplifier called a *voltage error amplifier.* Its purpose is to continuously compare the difference between a very stable voltage reference and the output voltage. If the output differs by mere millivolts, then a correction to the pass unit's conductivity is made. A stable voltage reference is placed on the noninverting input and is usually lower than the output voltage. The output voltage is divided down to the level of the voltage reference. This divided output voltage is placed into the inverting input of the operational amplifier. So at the rated output voltage, the center node of the output voltage divider is identical to the reference voltage.

The gain of the error amplifier produces a voltage that represents the greatly amplified difference between the reference and the output voltage (error voltage). The error voltage directly controls the conductivity of the pass unit thus maintaining the rated output voltage. If the load increases, the output voltage will fall. This will then increase the amplifier's output, thus providing more current to the load. Similarly, if the load decreases, the output voltage will rise, thus making the error amplifier respond by decreasing pass unit current to the load.

The speed by which the error amplifier responds to any changes on the output and how accurately the output voltage is maintained depends on the error amplifier's *feedback loop compensation*. The feedback compensation is controlled by the placement of elements within the voltage divider and between the negative input and the output of the error amplifier. Its design dictates how much gain at DC is exhibited, which dictates how accurate output voltage will be. It also dictates how much gain at a higher frequency and bandwidth the amplifier exhibits, which dictates the time it takes to respond to output load changes or *transient response time.*

The operation of a linear regulator is very simple. The very same circuitry exists in the heart of all regulators, including the more complicated switching regulators. The voltage feedback loop performs the ultimate function of the power supply—the maintaining of the output voltage.

## 1.2 General Linear Regulator Considerations

The majority of linear regulator applications today are board-level, low-power applications that are easily satisfied through the use of highly integrated three-terminal regulator integrated circuits. Occasionally, though, the application calls for either a higher output current or greater functionality than the three-terminal regulators can provide.

There are design considerations that are common to both approaches and those that are only applicable to the nonintegrated, custom designs. These considerations define the operating boundary conditions that the final design will meet, and the relevant ones must be calculated for each design. Unfortunately, many engineers neglect them and have trouble over the entire specified operating range of the product after production.

The first consideration is the *headroom voltage*. The headroom voltage is the actual voltage drop between the input voltage and the output voltage during operation. This enters predominantly into the later design process, but it should be considered first, just to see whether the linear supply is appropriate for the needs of the system. First, more than 95 percent of all the power lost within the linear regulator is lost across this voltage drop. This headroom loss is found by

$$P_{HR} = (V_{in(max)} - V_{out})I_{load(rated)} \tag{1-1}$$

If the system cannot handle the heat dissipated by this loss at its maximum specified ambient operating temperature, then another design approach should be taken. This loss determines how large a heatsink the linear regulator must have on the pass unit.

A quick estimated thermal analysis will reveal to the designer whether the linear regulator will have enough thermal margin to meet the needs of the product at its highest specified operating ambient temperature. One can find such a thermal analysis in Chapter 12.

The second major consideration is the minimum *dropout voltage* of a particular topology of linear regulator. This voltage is the minimum headroom voltage that can be experienced by the linear regulator, below which it falls out of regulation. This is predicated only by how the pass transistors derive their drive bias current and voltage. The common positive linear regulator utilizes an NPN bipolar power transistor (see Figure 1.2a). To generate the needed base-emitter voltage for the pass transistor's operation, this voltage must be derived from its own collector-emitter voltage. For the NPN pass units, this is the actual minimum headroom voltage. This dictates that the headroom voltage cannot get any lower than the base-emitter voltage (~0.65 VDC) of the NPN pass unit plus the drop across any base drive devices

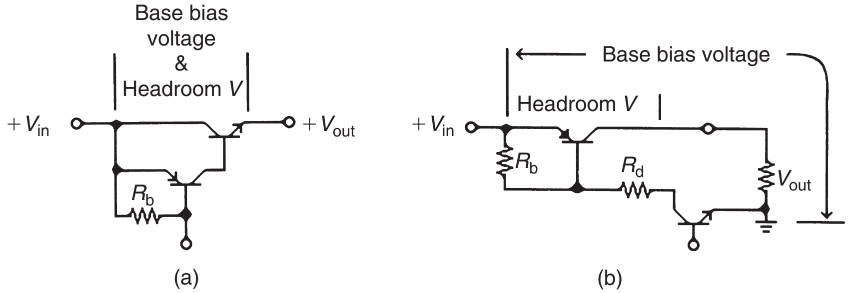


**Figure 1.2: The pass unit's influence on the dropout voltage: (a) NPN pass unit; (b) PNP pass unit (low dropout)**

(transistors and resistors). For the three terminal regulators such as the MC78XX series, this voltage is 1.8 to 1.5 VDC. For custom designs using NPN pass transistors for positive outputs, the dropout voltage may be higher. For applications where the input voltage may come even closer than 1.8 to 1.5 VDC to the output voltage, a *low dropout regulator* is recommended. This topology utilizes a PNP pass transistor, which now derives its base-emitter voltage from the output voltage instead of the headroom or input voltage (see Figure 1.2b). This allows the regulator to have a dropout voltage of 0.6 VDC minimum. P-Channel MOSFETs can also be used in this function and can exhibit dropout voltages close to zero volts.

The dropout voltage becomes a driving issue when the input to the linear regulator during normal operation is allowed to fall close to the output voltage. If operating from an AC wall transformer, this would occur at brown-out conditions (minimum AC voltages). The low dropout regulator (e.g., LM29XX) would allow the regulator to operate to a lower AC input voltage. Low dropout regulators are also widely used as *post regulators* on the output of switching power supplies. Within switching regulators, the efficiency is of great concern, so the headroom drop needs to be kept to a minimum. Here, the low dropout regulator will save several watts of loss over a conventional NPN-based linear regulator. If the application will never see headroom voltages less than 1.5 V, then use the conventional linear regulators (e.g., MC78XX).

Another consideration is the type of pass unit to be used. From a headroom loss standpoint, it makes absolutely no difference whether a bipolar power transistor or a power MOSFET is used. The difference comes in the drive circuitry. If the headroom voltage is high, the controller (usually a ground-oriented circuit) must pull current from the input or output voltage to ground. For a single bipolar pass transistor this current is

$$I_{\mathrm{B}} = I_{\mathrm{Load}}/h_{\mathrm{FE}} \tag{1-2}$$

The power lost just in driving the bipolar pass transistor is

$$P_{\mathrm{drive}} = V_{\mathrm{in/max}} \cdot I_{\mathrm{B}} \text{ or } V_{\mathrm{out}} \cdot I_{\mathrm{B}} \tag{1-3}$$

This drive loss can become significant. A driver transistor can be added to the pass transistor to increase the effective gain of the pass unit and thus decrease the drive current, or a power MOSFET can be used as a pass unit that uses magnitudes less DC drive current than the bipolar power transistor. Unfortunately, the MOSFET requires up to 10 VDC to drive the gate. This can drastically increase the dropout voltage. In the vast majority of linear regulator applications, there is little difference in operation between a buffered pass unit and a MOSFET insofar as efficiency is concerned. Bipolar transistors are much less expensive than power MOSFETs and have less propensity to oscillate.

The linear regulator is a mature technology and therefore can usually be accommodated by the integrated solutions provided by the semiconductor manufacturers. For applications beyond the limits of these integrated linear regulators alone, usually adding more components around the IC will satisfy the requirement. Otherwise, a completely custom approach would need to be utilized. These various approaches are overviewed in the design examples in the following section.

## 1.3 Linear Power Supply Design Examples

Linear regulators can be designed to meet a variety of cost and functional needs. The design examples that follow illustrate that linear regulator designs can range from the very elementary to the more complex. Designs for enhanced three-terminal regulator designs will be abbreviated, since the integrated circuit datasheets usually contain great detail. Due to the relatively large power loss of linear regulators, the thermal considerations typically represent a significant problem. Some thermal analysis and design is done in the examples. For further insight on this please refer to Chapter 12.

### *1.3.1 Elementary Discrete Linear Regulator Designs*

These types of linear regulators were commonly built before the advent of operational amplifiers and they can save money in consumer designs. Some of their drawbacks include drift with temperature and limited load current range.

#### *1.3.1.1 The Zener shunt regulator*

This type of regulator is typically used for very local voltage regulation for less than 200 mW of a load. A series resistance is placed between a higher voltage and is used to limit the current to the load and Zener diode. The Zener diode compensates for the variation in load current. The Zener voltage will drift with temperature. The drift characteristics are given in many Zener diode datasheets. Its load regulation is adequate for most supply specifications for integrated circuits. It also has a higher loss than the series-pass type of linear regulator, since its loss is set for the maximum load current, which for any load remains less than that value. A Zener shunt regulator can be seen in Figure 1.3.

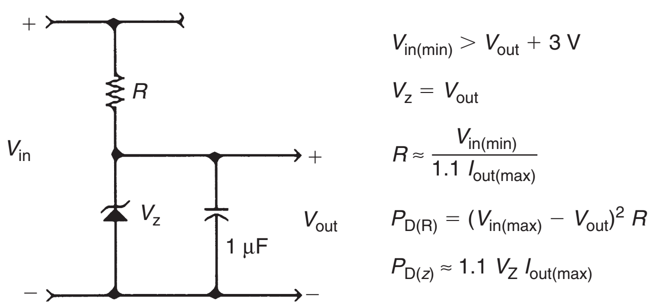


**Figure 1.3: A Zener shunt regulator**

#### 1.3.1.2 The one-transistor series-pass linear regulator

By adding a transistor to the basic Zener regulator, one can take advantage of the gain that the bipolar transistor offers. The transistor is hooked up as an emitter follower, which can now provide a much higher current to the load, and the Zener current can be lowered. Here the transistor acts as a rudimentary error amplifier (refer to Figure 1.4). When the load current increases, it places a higher voltage into the base, which increases its conductivity, thus restoring the voltage to its original level. The transistor can be sized to meet the demands of the load and the headroom loss. It can be a TO-92 transistor for those loads up to 0.25 W or a TO-220 for heavier loads (depending on heatsinking).

### 1.3.2 Basic Three-Terminal Regulator Designs

Three-terminal regulators are used in the majority of board-level regulator applications. They excel in cost and ease of use for these applications. They can also, with care, be used as the basis for higher functionality linear regulators.

The most-often ignored consideration is the overcurrent limiting method used in three-terminal regulators. They typically use an overtemperature cutoff on the die of the regulator, which is typically between +150°C and +165°C. If the load current is passed through the three-terminal regulator, and if the heatsink is too large, the regulator may fail due to overcurrent (bondwire, IC traces, etc.). If the heatsink is too small, then one may not be able to get enough power from the regulator. Another consideration is if the load current is being conducted by an external pass-unit, the overtemperature cutoff will be nonfunctional, and another method of overcurrent protection will be needed.

#### 1.3.2.1 The basic three-terminal positive regulator design

This example will illustrate the design considerations that should be undertaken with each three-terminal regulator design. Many designers view only the electrical specifications of the regulators and forget the *thermal derating* of the part. At high headroom voltages,

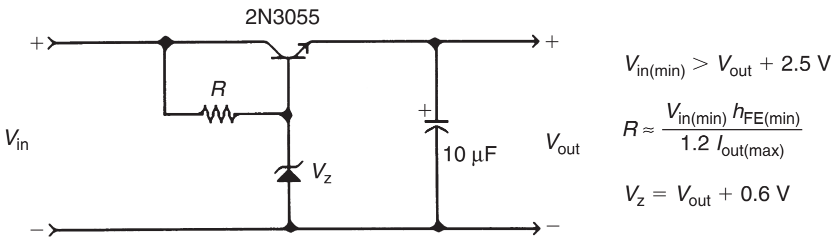


**Figure 1.4: A discrete bipolar series-pass regulator**

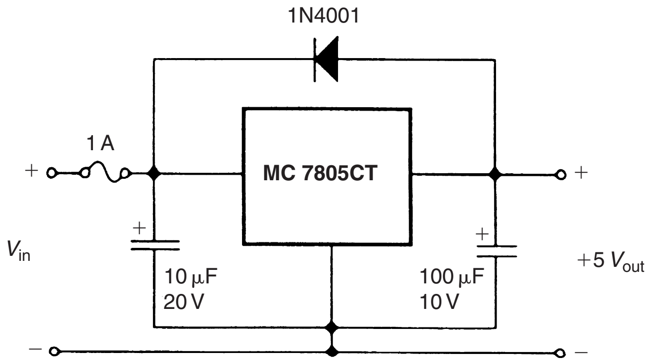


**Figure 1.5: A three-terminal regulator**

and at high ambient operating temperatures, the regulator can only deliver a fraction of its full-rated performance. Actually, in the majority of the three-terminal applications, the heatsink determines the regulator's maximum output current. The manufacturer's electrical ratings can be viewed as having the part bolted onto a large piece of metal and placed in an ocean. Any application not employing those unorthodox components must operate at a lower level. The following example illustrates a typical recommended design procedure (see Figure 1.5).

***Design Example 1. Using three-terminal regulators***

| | | |
|---|---|---|
| Specification | Input: | 12 VDC (max)<br>8.5 VDC (min) |
| | Output: | 5.0 VDC<br>0.1A to 0.25A |
| | Temperature: | −40 to +50°C |

> **Note:** The 1N4001 is required for discharging the 100 µF capacitor when the system is turned off.

***Thermal Design (refer also to Appendix A)***

Given in data sheet:

$$R_{\theta JC} = 5°C/W$$

$$R_{\theta JA} = 65°C/W$$

$$T_{j(max)} = 150°C$$

$$P_{D(max)} = (V_{in(max)} - V_{out}) \cdot I_{load(max)}$$
$$= (12 - 5\,V)(0.25\,A)$$
$$= 1.75\,W \text{ (headroom loss)}$$

Without a heatsink the junction temperature will be:

$$\begin{aligned} T_j &= P_D \cdot R_{\theta JA} + T_{A(max)} \\ &= (1.75\ W)(65°C/W) + 50 \\ &= 163.75°C. \end{aligned}$$

A small "clip-on" style heatsink is required to bring the junction temperature down to below its maximum ratings. Refer to Chapter 12 for aid in the selection of heatsinks.

***Selecting the heatsink—Thermalloy P/N 6073B***

Given in heatsink data: $R_{\theta SA} = 14°C/W$

Using a silicon insulator $R_{\theta CS} = 65°C/W$

The new worst-case junction temperature is now:

$$\begin{aligned} T_{j(max)} &= P_D(R_{\theta JC} + R_{\theta CS} + R_{\theta SA}) + T_A \\ &= (1.75\ W)(5°C/W + 65°C/W + 14°C/W) + 50°C \\ &= 84.4°C \end{aligned}$$

### *1.3.2.2 Three-terminal regulator design variations*

The following design examples illustrate how three-terminal regulator integrated circuits can form the basis of higher-current, more complicated designs. Care must be taken, though, because all of the examples render the overtemperature protection feature of the three-terminal regulators useless. Any overcurrent protection must now be added externally to the integrated circuit.

***The current-boosted regulator***

The design shown in Figure 1.6 adds just a resistor and a transistor to the three-terminal regulator to yield a linear regulator that can provide more current to the load. The current-boosted positive regulator is shown, but the same equations hold for the boosted negative regulator. For the negative regulators, the power transistor changes from a PNP to an

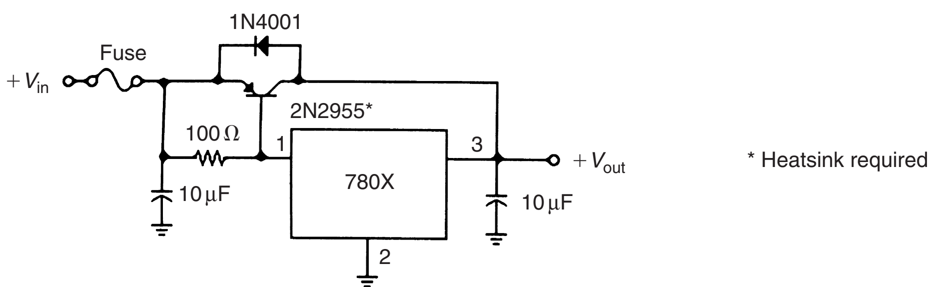


**Figure 1.6: Current-boosted three-terminal regulator without overcurrent protection**

NPN. Beware: there is no overcurrent or overtemperature protection in this particular design.

***The current-boosted three-terminal regulator with overcurrent protection***

This design adds the overcurrent protection externally to the IC. It employs the base-emitter (0.6 V) junction of a transistor to accomplish the overcurrent threshold and gain of the overcurrent stage. For the negative voltage version of this, all the external transistors change from NPN to PNP and vice versa. These can be seen in Figures 1.7a and b.

### 1.3.3 Floating Linear Regulators

A floating linear regulator is one way of achieving high-voltage linear regulation. Its philosophy is one in which the regulator controller section and the series-pass transistor "float" on the input voltage. The output voltage regulation is accomplished by sensing the ground, which appears as a negative voltage when referenced to the output voltage. The output voltage serves as the "floating ground" for the controller and the power for

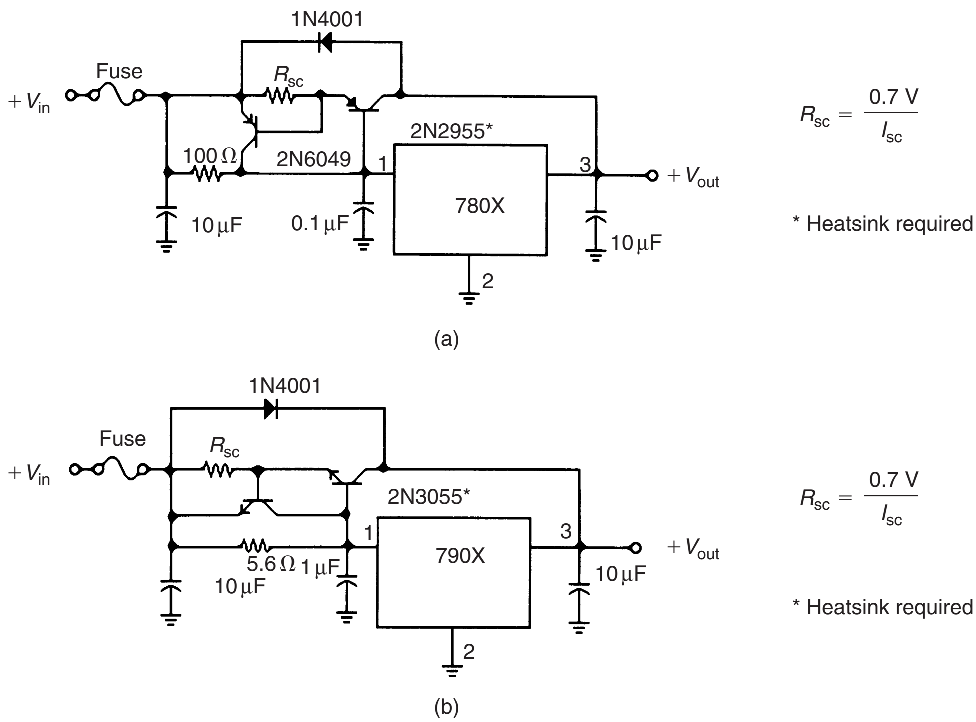


**Figure 1.7: (a) Positive current-boosted three-terminal regulator with current limiting (b) Negative current-boosted three-terminal regulator with current limiting**

the controller and series-pass transistor is drawn from the headroom voltage (the input-to-output difference) or is provided by an auxiliary isolated power supply.

The power transistor still needs to have a breakdown voltage rating greater than the input voltage, since at start-up it must see the entire input voltage across it. Other methods such as a *bootstrap Zener diode* can also be used in order to shunt the voltage around the pass transistor, but only when the input voltage itself is switched on and off to activate the power supply. Also, caution must be taken to ensure that any controller input or output pin never goes negative with respect to the floating ground of the IC. Protection diodes are usually used for this purpose. One last caution is the little-known breakdown voltage of common resistors. If the output voltage exceeds 200 V, more than one sensing resistor must be placed in series in order to avoid the 250 V breakdown characteristic of 1/4 W resistors.

A common low-voltage positive floating regulator is the LM317 (the negative regulator complementary part is the LM337). The MC1723 can also be used to create a floating linear regulator, but care must be taken to protect the IC against the high voltage.

The first example shows how an LM317 can be modified to create a 70 V linear regulator from a 100 V input voltage. Several design restrictions must be strictly followed; for example, the operational headroom voltage must not exceed the voltage rating of the bootstrap Zener diode or regulation will be lost. Also the use of the protection diode on the error amplifier is mandatory. This regulator can be seen in Figure 1.8.

The second example illustrates a 350 V floating linear regulator that can provide up to 10 mA of load current from a 400 to 450 V unregulated source. The TIP50 provides the bias supply for the controller, which must withstand the full input voltage during start-up and power supply foldback. The controller is "grounded" on the output voltage and the

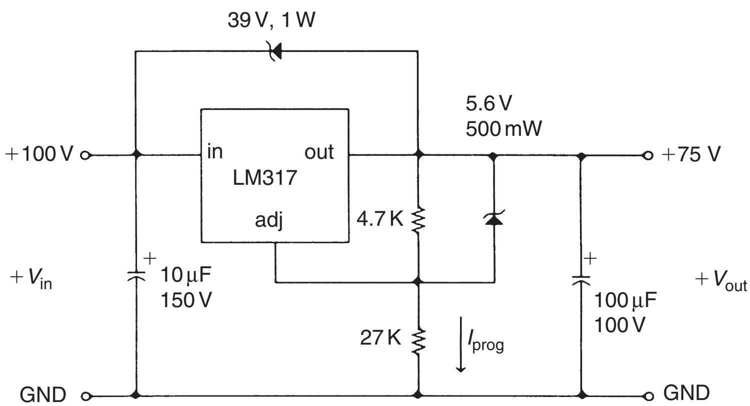


Figure 1.8: A high voltage floating linear regulator

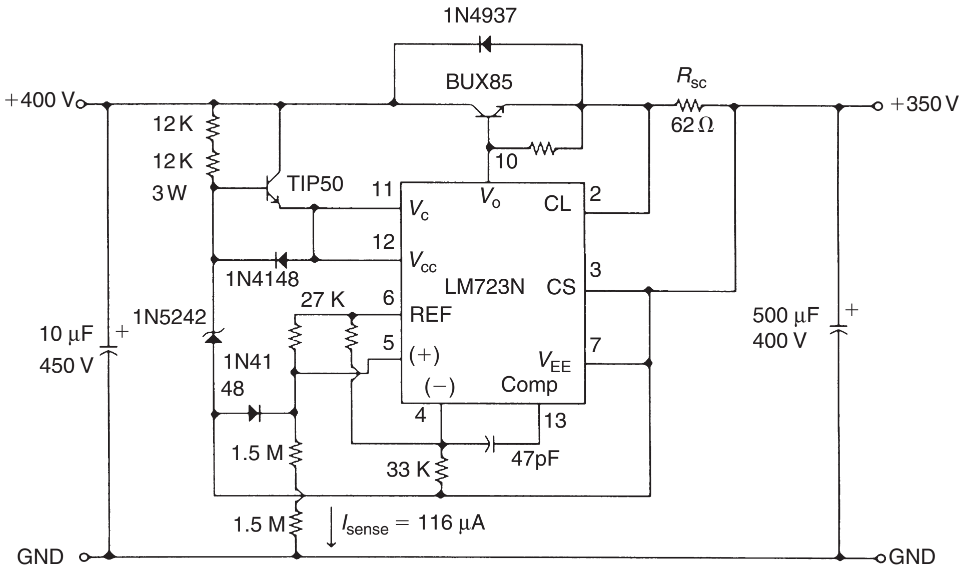


**Figure 1.9: A 350 V, 10-mA floating linear regulator**

minimum headroom voltage is 15 V. To readjust the output voltage, one changes the value of the two series resistors in the voltage sensing branch and this is set by

$$R_{sense} = (V_{out} + 4.0\text{V})/I_{sense} \tag{1-4}$$

Floating linear regulators are particularly suited for high-output voltage regulation, but may be used anywhere. This regulator can be seen in Figure 1.9.