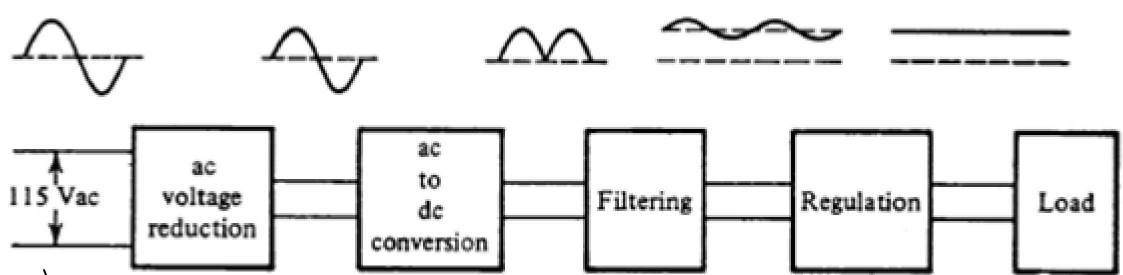
Power Supplies and Linear Regulators

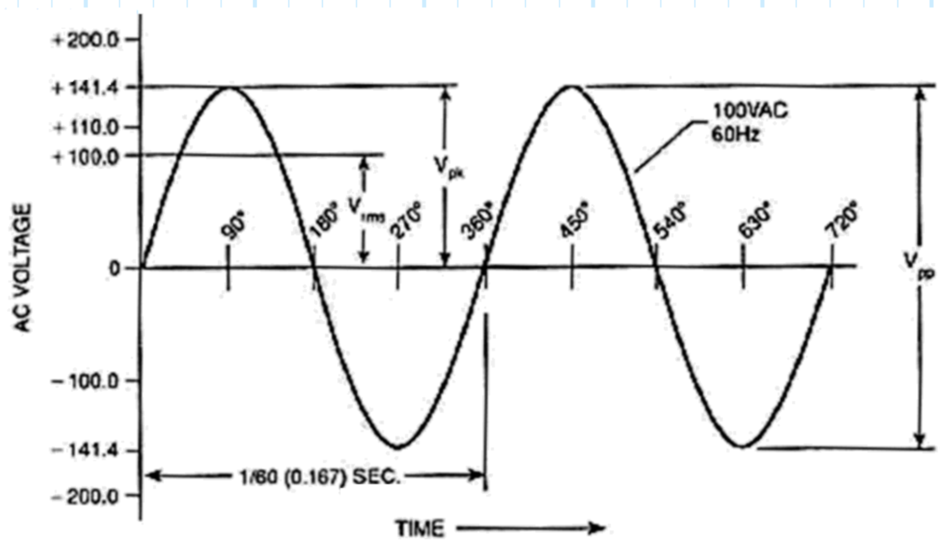
Our objective is to examine characteristics, schematics, analysis, design and limitations of practical power supplies with IC regulators. You should refer to Chapter 6 in H & H for background on this material.

The D.C. power supply block diagram:



This is a 100 Vac "line" voltage waveform. Common line voltage values are: 110, 115, 120, 125.

What line voltage do we have in the lab?



Note that the period is 167 ms.

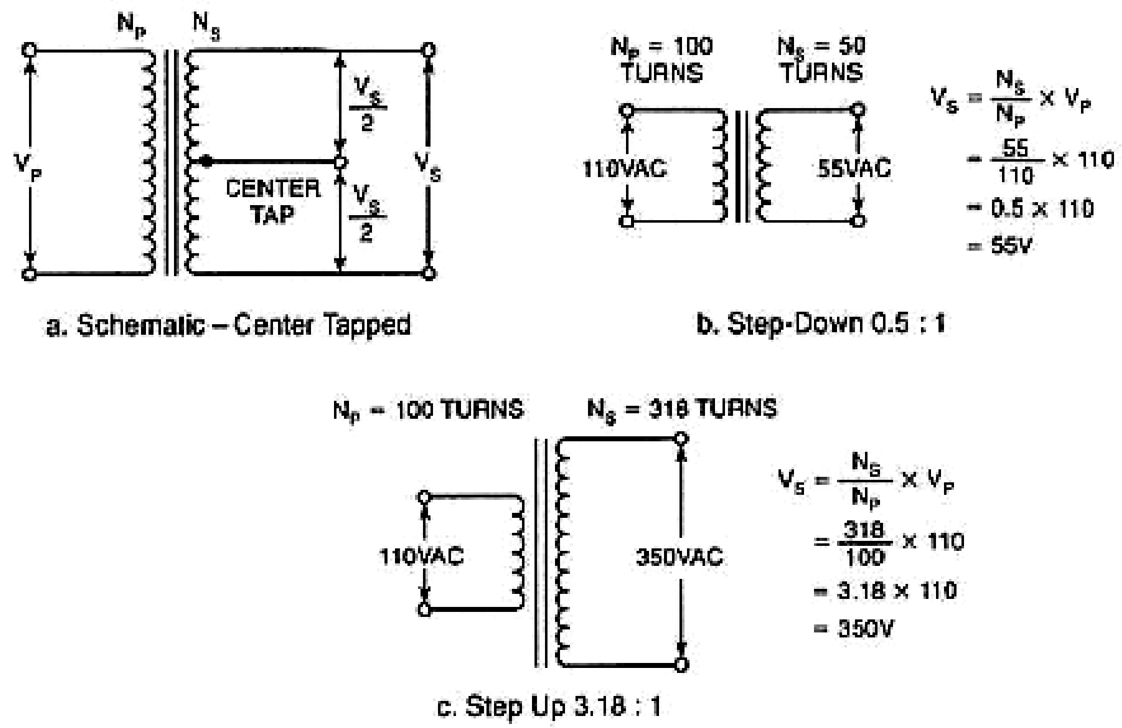
Look for this in your circuits this semester !!

Remember: $V_{pk} = \sqrt{2}V_{rms} = 1.414 \cdot V_{rms}$

Material from Prof. Prescott

AC Voltage Reduction

Transformers are used to increase or decrease the line voltage. Recall these principles of transformers:



a. Schematic – Center Tapped

b. Step-Down 0.5 : 1

c. Step Up 3.18 : 1

Remember this important principle concerning power transfer:

$$\left(V_{primary} \cdot I_{primary}\right) = \left(V_{secondary} \cdot I_{secondary}\right) \cdot \eta$$

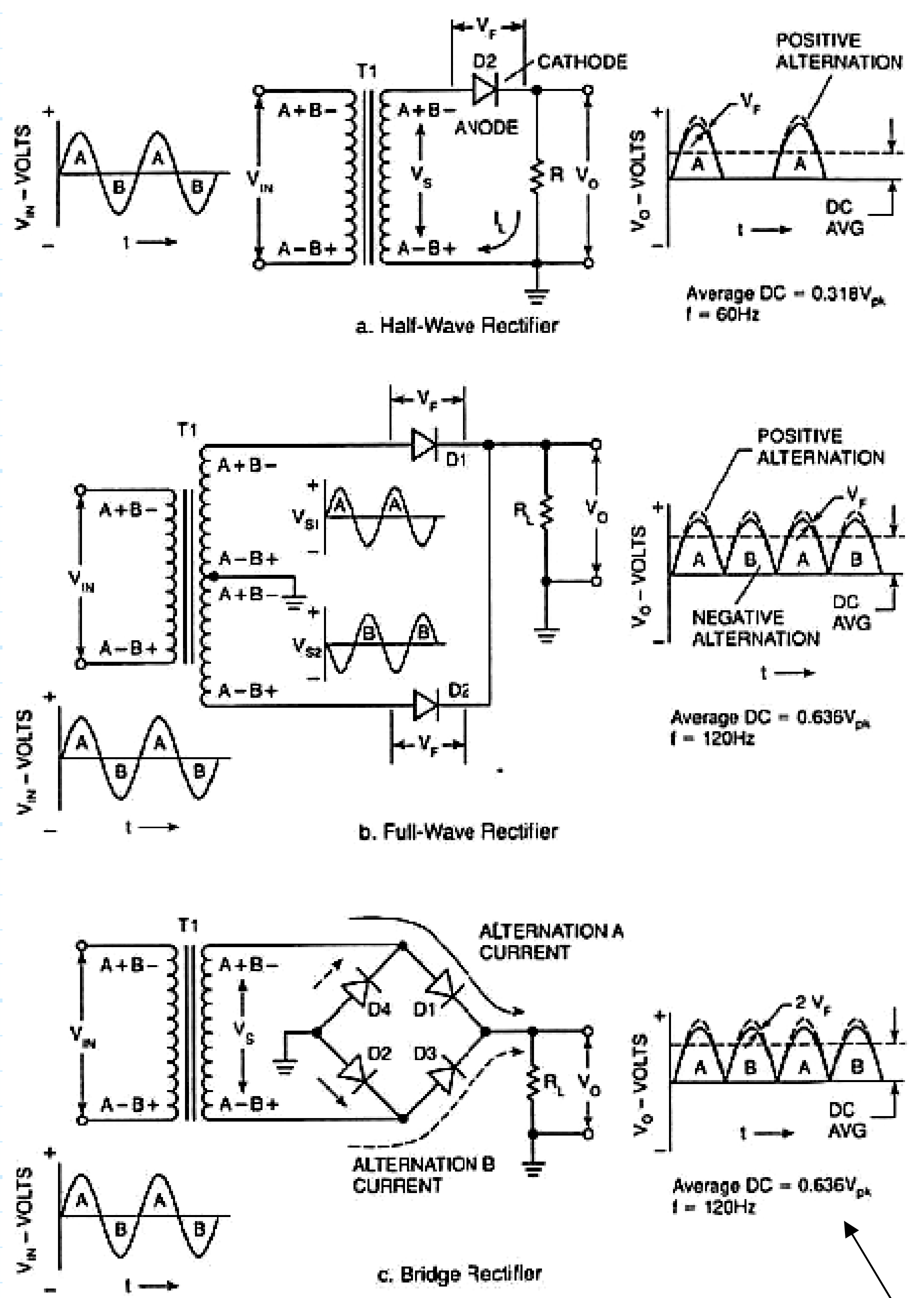
efficiency

If the primary (110 Vac) is fused, what value of fuse will be required to limit current flow in the secondary (28 Vac) to 2 amps?

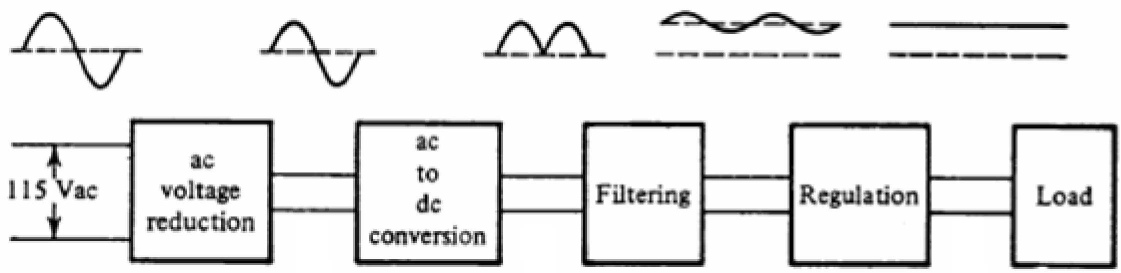
What is the difference between slow-blow and fast-blow fuses, and when are they used?

AC to DC Conversion

We will use a bridge rectifier in our power supply designs.

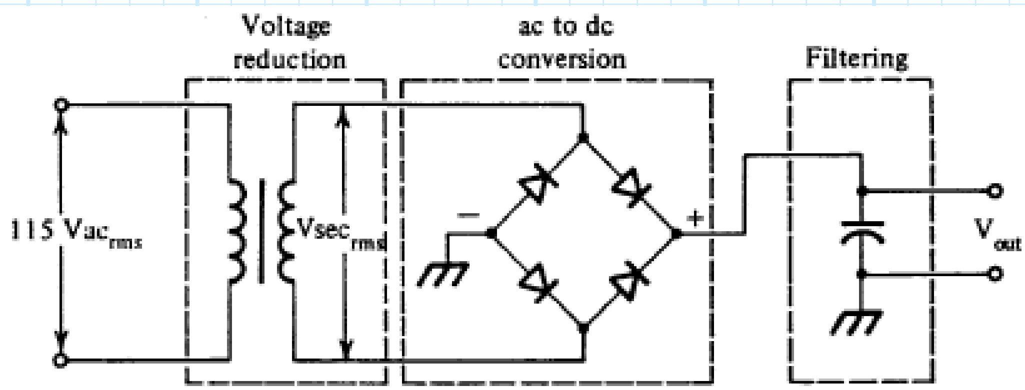


How are these DC values computed?

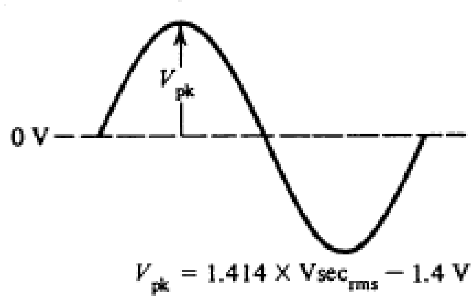


Filtering

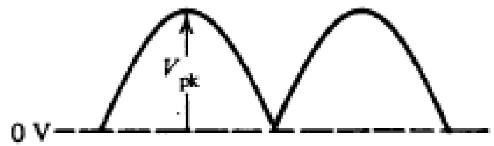
Capacitive and inductive filters are used, but capacitive filters are more common due to size, weight and cost. Let's put these concepts together and look at a power supply:



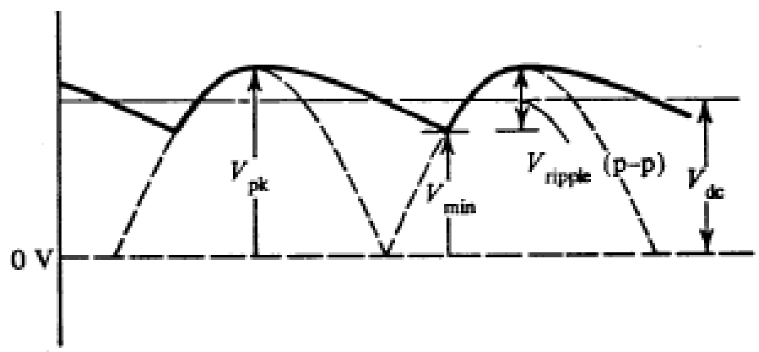
AC voltage reduction



AC to DC Conversion (without filter)



The output of the capacitive filter:



As the input rectified sinusoid starts to drop, the capacitor discharges through the load.

$$V_{ripple(p-p)} = V_{pk} - V_{\min}$$

The minimum level to which the capacitor's voltage falls is called V_{min} and depends on the size of the capacitor, V_{pk} and the load current.

Heavy and Light Load Conditions

Light load conditions exist when the ripple voltage is less than 10% of the output DC voltage.

For light load conditions, the following approximation holds:

$$\boxed{V_{\min} = V_{pk} - \frac{I_{DC}}{fC}}$$

I_{DC} - load current

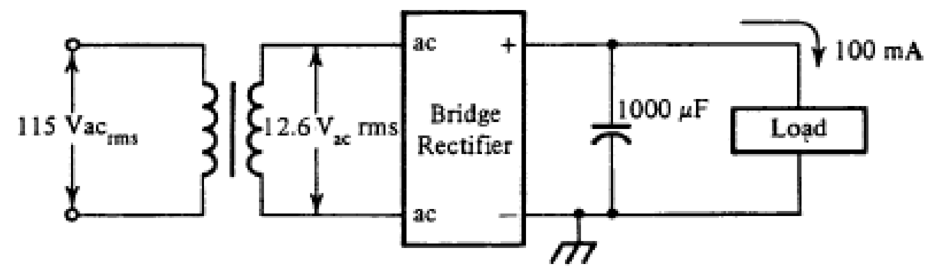
f - 120 Hz for full wave

The DC value of the output from the filter lies half way between V_{pk} and V_{min}, or:

$$V_{DC} = V_{pk} - \frac{1}{2} V_{ripple(p-p)}$$

Example:

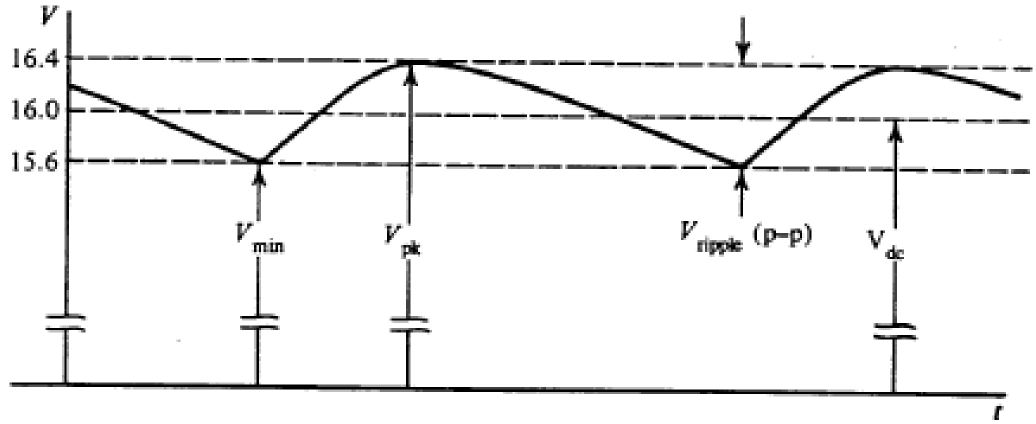
Given the power supply below, calculate V_{pk}, V_{min}, $V_{ripple(p-p)}$, V_{DC} .



$$\begin{aligned} V_{pk} &= (1.414) \cdot V_{\sec(rms)} - 1.4 \\ &= (1.414) \cdot 12.6 - 1.4 \\ &= 16.4 \text{ volts} \end{aligned}$$

$$\begin{aligned} V_{\min} &= V_{pk} - \frac{I_{DC}}{fC} \\ &= 16.4 - \frac{0.1}{(120)(1{,}000 \cdot 10^{-6})} \\ &= 15.6 \text{ volts} \end{aligned}$$

$$\begin{aligned} V_{ripple(p-p)} &= V_{pk} - V_{\min} \\ &= 16.4 - 15.6 \\ &= 0.8 \text{ volts} \end{aligned}$$



If the circuit powered by the supply can tolerate ripple voltages in excess of 10%, the capacitor can be made smaller and the required heat dissipation by the IC regulator decreases

This condition is called "heavy load." In this case:

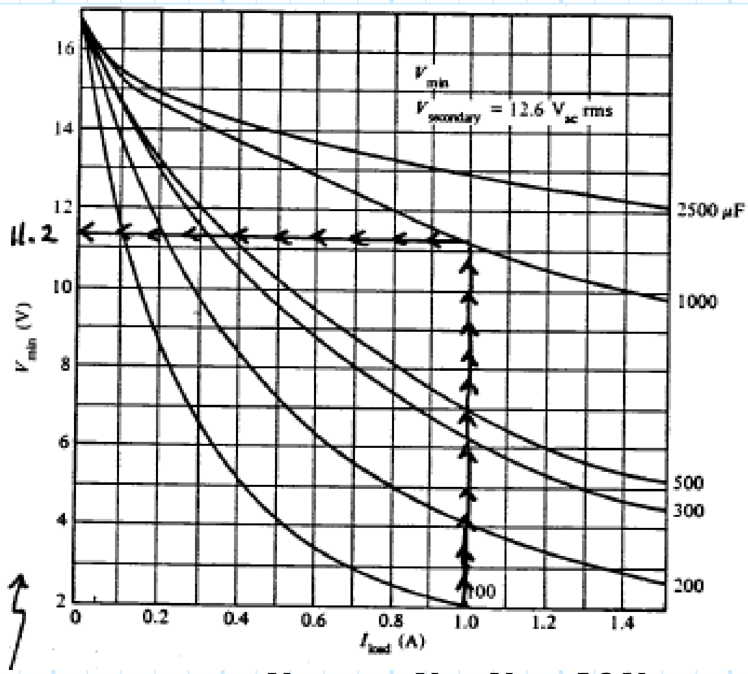
$$\left.\begin{array}{l} V_{\min} \\ V_{DC} \end{array}\right\} \text{ must be measured in the lab}$$

Example:

For the circuit in the previous example, increase the load current to 1 Amp. Then determine ***V_{pk}, V_{min}, $V_{ripple(p\text{-}p)}$, V_{DC}*** .

$$\begin{aligned} V_{pk} &= (1.414)\cdot V_{\sec(rms)} - 1.4 \\ &= 16.4 \text{ volts} \end{aligned}$$

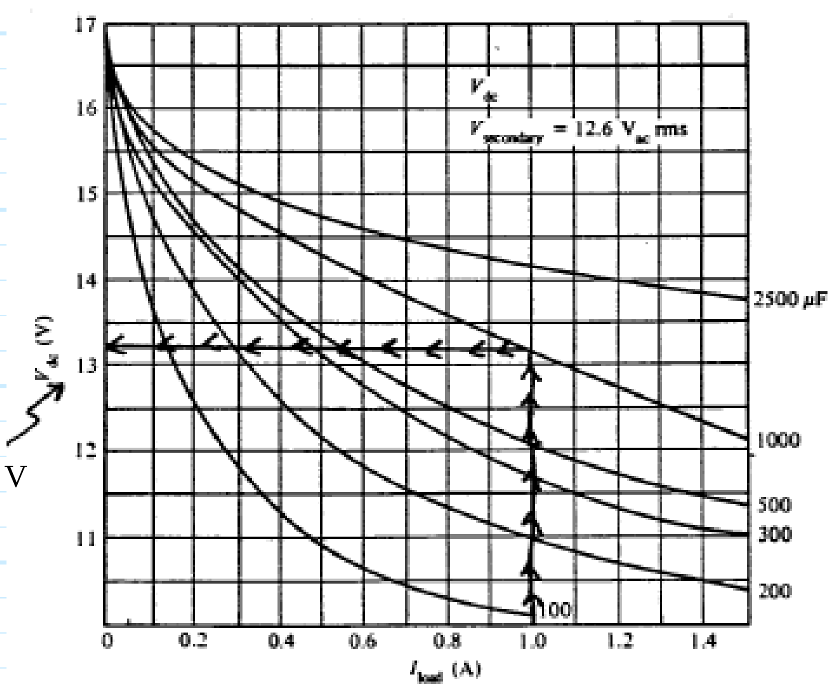
The following chart was developed using laboratory measurements. Use this table to determine V_{min}.



$V_{min} = 11.2\ V$

$V_{ripple(p-p)} = V_{pk} - V_{min} = 5.2\ V$

Finally, determine V_{DC} via laboratory measurement



$V_{DC} = 13.3\ V$

Voltage Regulators

There are two types of voltage regulators:

1. Linear regulators
2. Switching regulators

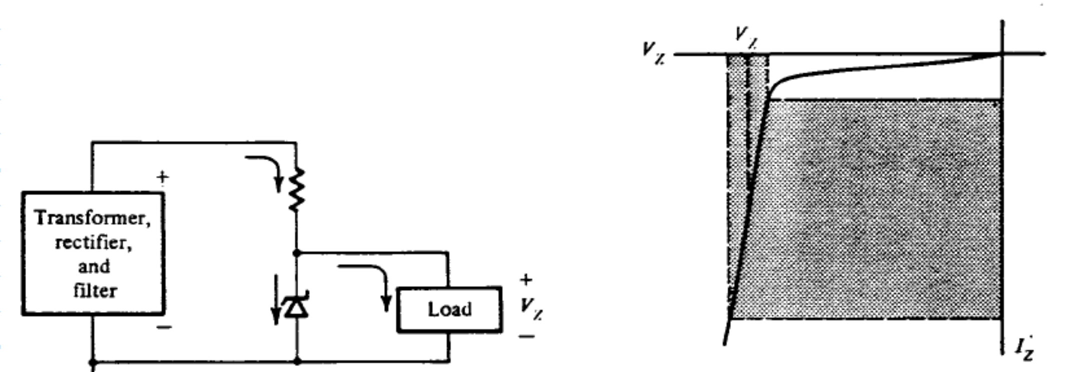
We will have the opportunity to build both types of regulators this semester. Let's begin by looking at linear regulators.

Linear Regulators

Linear regulators are notable by the fact that there is an active component (i.e., semiconductor device) in series with the load that regulates the current flow to the load, keeping the voltage across the load at a constant value. The important point is that the regulator must maintain a constant output voltage no matter how much load current is required.

Note: learn what is meant by "load" and use the term appropriately. For example, what happens when the load increases?

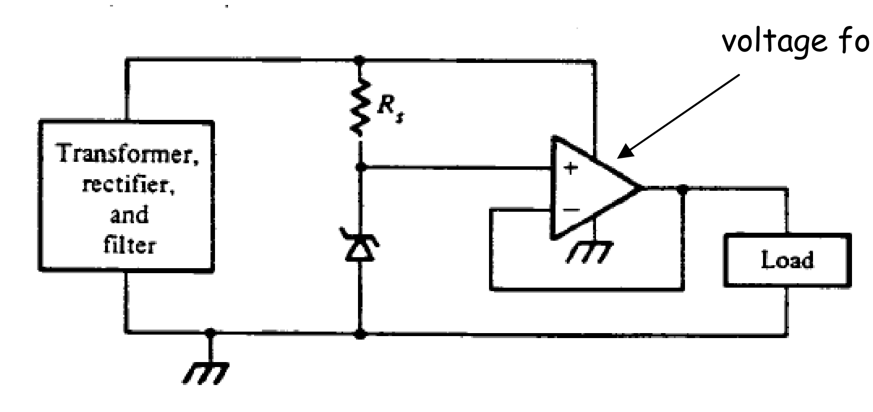
The simplest regulator consists of a series resistor and a zener diode in parallel with the load, as shown below:



(a) Zener regulator schematic

(b) Zener reverse breakdown characteristic

A better voltage regulator is shown below:



Now the op-amp provides the load current. The zener diode does not have to absorb wide variations in load current.

Two cautions on this configuration:

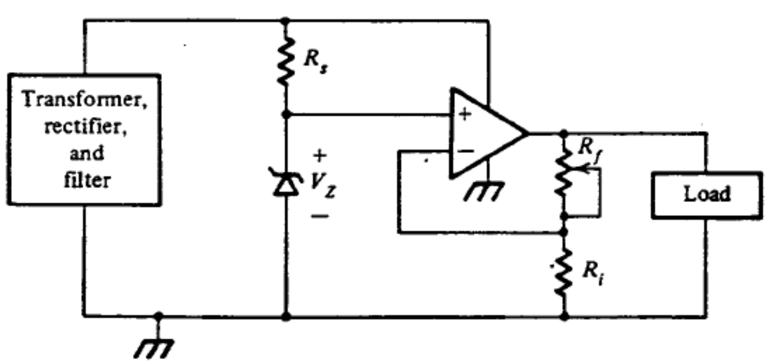
1. $V_{pk} \le \pm V_{\text{supply rating of op amp}}$
2. $V_{\min} \ge V_{load} + 2 \text{ volts}$

Keeps op-amp out of saturation and keeps the zener diode in its breakdown region.

To obtain an adjustable regulated supply, add two resistors as follows:

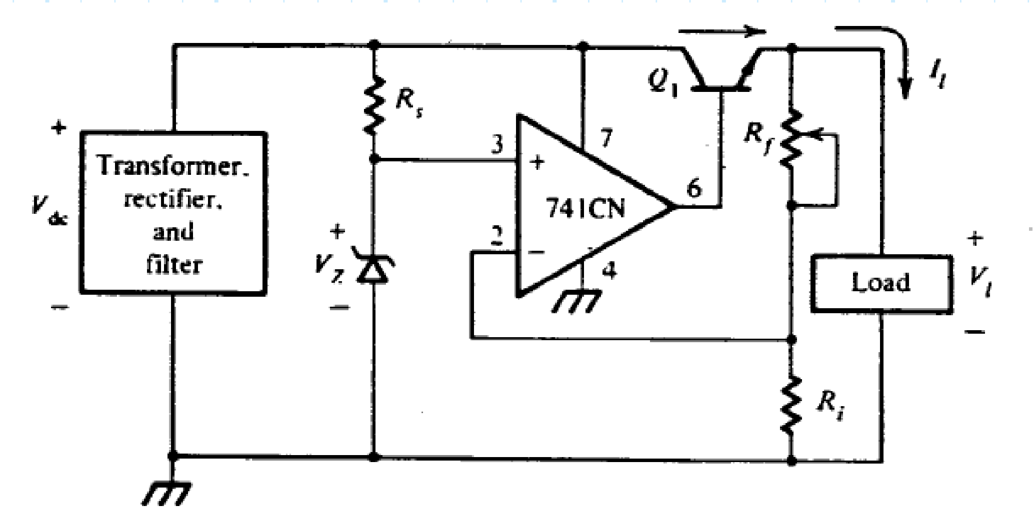
$$V_{load} = V_z\left(1 + \frac{R_f}{R_i}\right)$$

If you have trouble understanding how this formula was obtained, you need to read about op amps in H & H.



Note that the minimum output voltage is V_z

The output current is limited by the short-circuit output capability of the op-amp. Op-amps are generally not designed to serve as a current source. It is much better to use a series pass transistor for this function, and then drive the transistor with the op-amp, as shown below:



This configuration can significantly boost the load current using the series pass transistor.

The op-amp now only has to provide the base current. The transistor must be able to provide adequate current to the load. This is determined by the DC current gain (β) of the transistor.

$$\beta \geq \frac{I_{\text{Load}}}{I_{\text{op-amp output (max)}}}$$

Remember, for a transistor, $I_C = \beta I_B$

Also, the transistor must be able to dissipate all power that is not delivered to the load:

$$\begin{aligned} P_Q &= \left(V_{DC} - V_L\right) \cdot I_L \\ &= V_{CE} \cdot I_L \end{aligned}$$

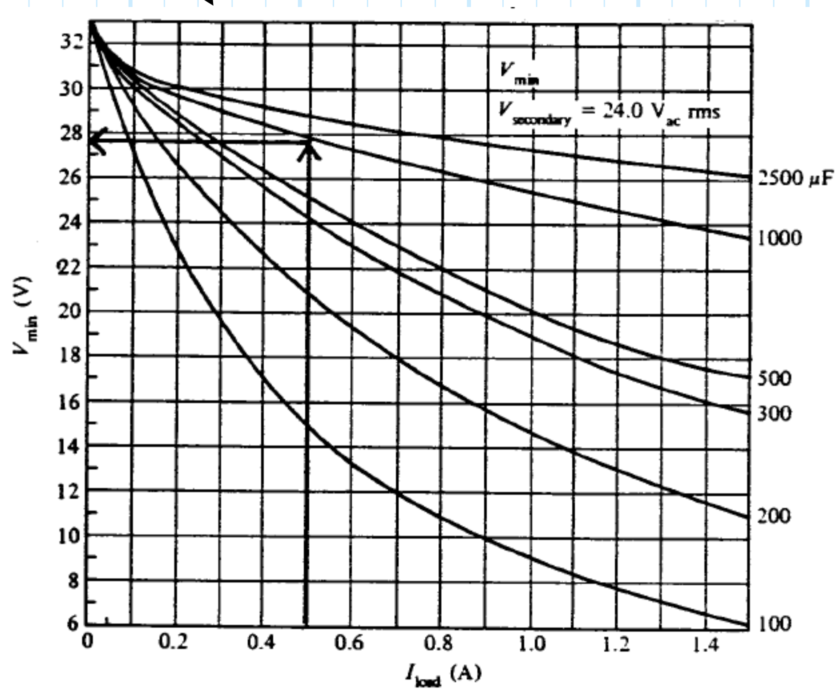
This is a very important concept. Know it well.

Example: Design a regulated power supply using a full-wave bridge rectifier and a 1000 μF capacitor. The secondary voltage on the transformer is 24 Vrms:

- V_{load} - Adjustable, 5 V to 15 V
- I_{load} – Can vary from 0 mA to 500 mA

1. First determine the filter output characteristics

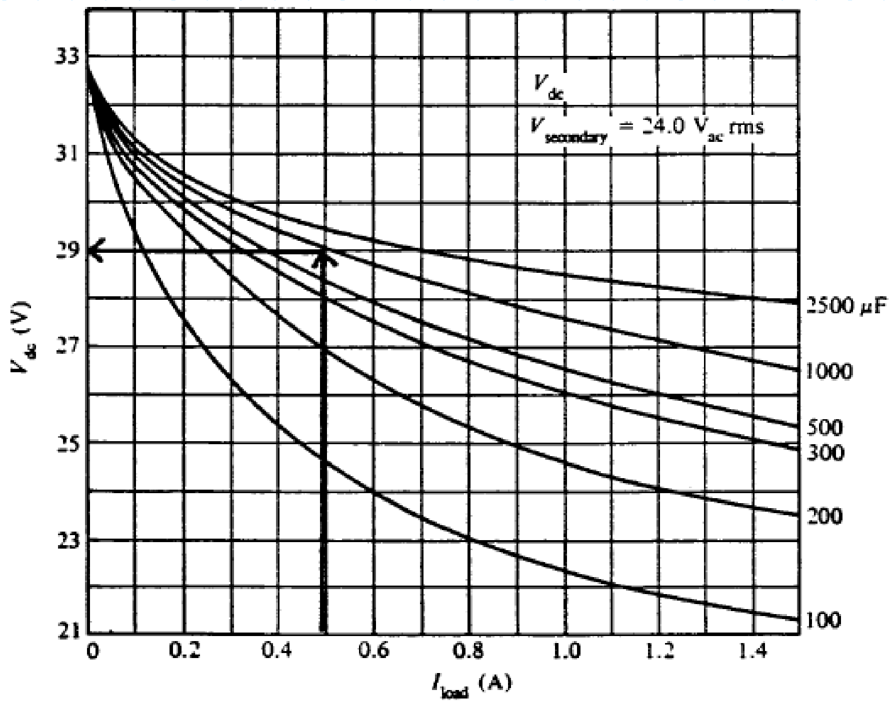
$$V_{pk} = \left(1.414\ x\ 24\ \mathrm{V_{rms}}\right) - 1.4\ \mathrm{V} = 32.5\ \text{volts}$$
$$V_{\min} = 27.8\ \text{volts}$$



Minimum output of a 24V rms capacitive filtered supply

This measurement, and the one on the next page, are made on the test bench. Can you draw a diagram showing how these measurement are made?

$$V_{DC} = 29 \text{ volts}$$



DC output of a 24V rms capacitive filtered supply

2. Next, design the reference source. Since the zener diode determines the minimum output voltage, select an appropriate component – say the 1N748. This device has a zener voltage of 3.9 volts @ 20 mA.

In order to use the zener diode, we need to determine the zener bias resistor, R_S. The bias resistor must limit the zener current to the range (from the data sheet):

$$20 \text{ mA} \le I_z \le 100 \text{ mA}$$

look-up this device on the Web and verify these parameters.

$$R_s \le \frac{V_{min} - V_z}{20 \text{ mA}} \Rightarrow \frac{27.8 - 3.9}{.020} = 1,200 \text{ Ohms}$$

$$R_s \ge \frac{V_{max} - V_z}{100 \text{ mA}} \Rightarrow \frac{32.5 - 3.9}{.100} = 286 \text{ Ohms}$$

$$286\ \Omega \le R_s \le 1200\ \Omega$$

so let $R_s = 1000\ \Omega$

3. Select the appropriate op-amp. The maximum DC output from the power supply filter (32.5 V, in this case) must be less that the op-amp's maximum supply voltage rating.

For the LM741C this value is 36 V. For the LM318 this value is 40 V. So either of these devices will meet this part of the requirement.
Let's select the LM741C.

The next question is: Is the minimum DC output from the power supply large enough to allow regulation? In other words, the following condition must be met:

$$V_{\min} > V_{load} + 2 \text{ Volts}$$

Since $\mathbf{V_{min}} = 27.8$ V and the maximum voltage across the load is not to exceed 15 V (by the original specs), then this criteria is met.

4. Determine the required DC gain for the op-amp. When we look at the op-amp as a DC amplifier, the input voltage on the non-inverting input is always 3.9 V, and the maximum voltage on the inverting input should be no larger than 15 V.

$$\frac{15}{3.9} = 1 + \frac{R_f}{R_i}$$

The choice of R_i is arbitrary, let $R_i = 3.3$ kΩ, the $R_f = 9.4$ kΩ. Since we want the supply to be variable, the choose a 10 kΩ potentiometer for $\mathbf{R_f}$.

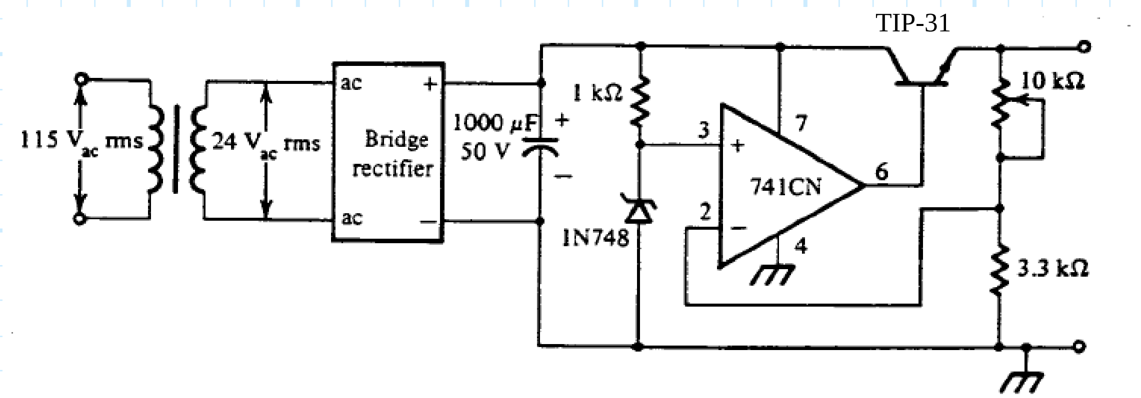
5. Determine requirements for the pass transistor. The LM741C can source (output) at least 10 mA before it begins to current-limit. Therefore, we need a pass transistor with a sufficient DC gain that 10 mA base current allows the transistor to provided the needed load current.

$$\beta_{\min} = \frac{500 \text{ mA}}{10 \text{ mA}} = 50$$

The worst-case power dissipation for the pass transistor occurs when the output voltage is at a minimum (resulting in the max voltage drop across the pass transistor) and the maximum load is being drawn.

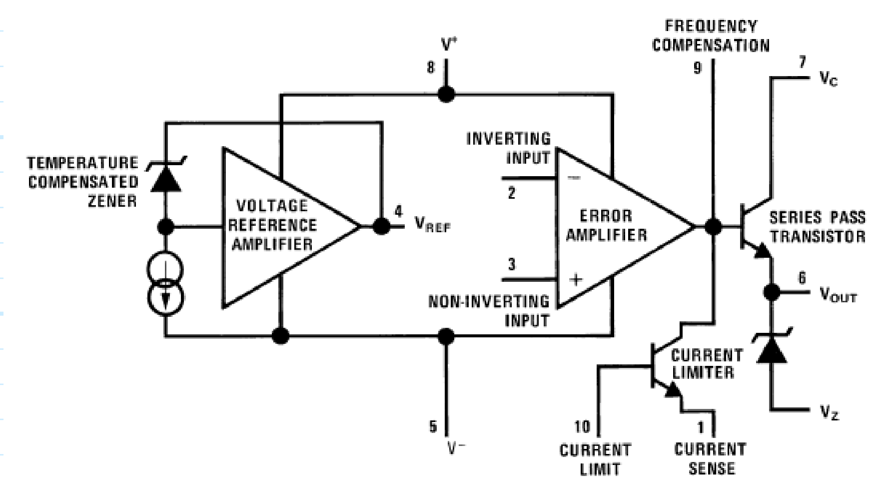
$$P_Q = \left(V_{DC} - V_{load}\right)\cdot I_{load} = \left(29.5-3.9\right)\cdot\left(0.5\right) = 12.6\ \mathrm{W}$$

Select a pass transistor with $\beta > 50$ and power dissipating ability of greater than 12.6 Watts – say 15 Watts. This is difficult to achieve using a transistor without a heat sink. If we employ a heat sink then many devices will work. We can chose the 2N3055 or its equivalent, the TIP-31. The final result of our design is shown below:

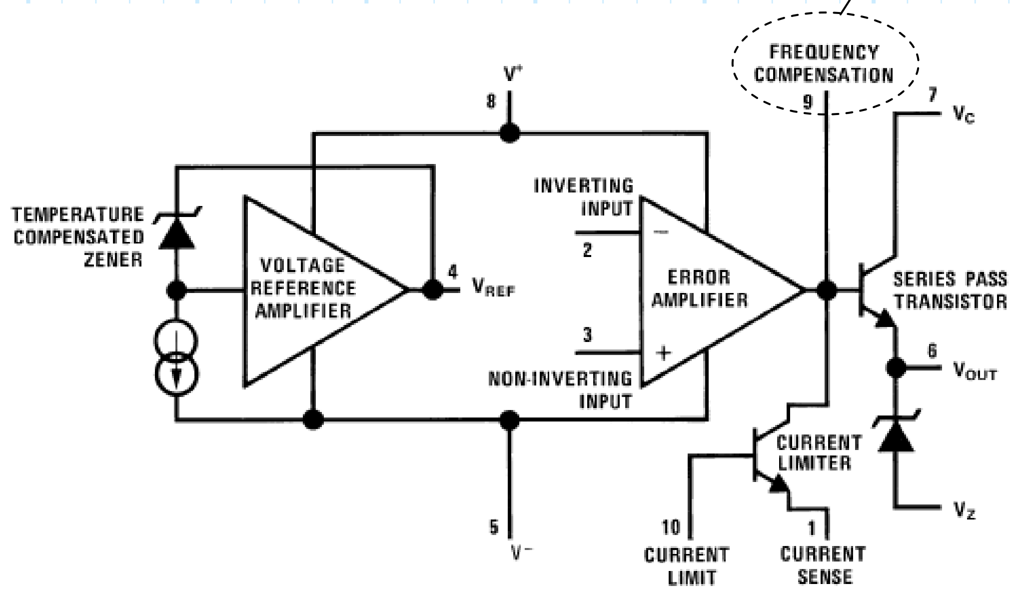


The 723 Integrated Voltage Regulator

Many of the function of the linear voltage regulator have been integrated into a sinale IC. as shown below:

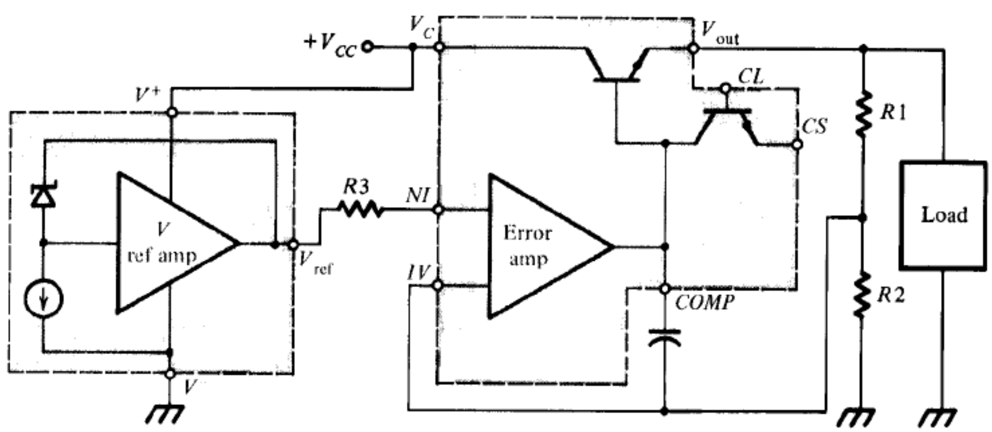


Pay attention to this. Always use compensation



Read about the 723 in Sections 6.01, 6.02, 6.03 in H & H. Understand how this circuit works and how you design regulators with it.

Here is an example of the implementation of a power supply regulator using the 723 when the desired output voltage is greater than V_{ref}.



$V_{ref} \approx 7.15$ V

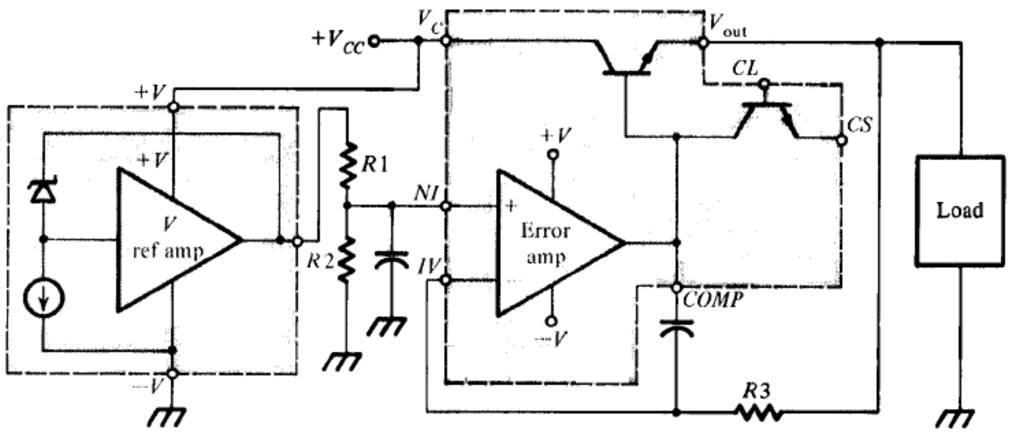
$V_{out} = 7.15 \text{ V} \times \dfrac{R1 + R2}{R2}$

$-V = \text{Gnd}$

$+V = V_{CC}$

$R3 = R1 // R2$

Here is an example of the implementation of a power supply regulator using the 723 when the desired output voltage is less than V_{ref}.



$V_{ref} \approx 7.15\ \text{V}$

$$V_{out} \approx V_{NI} = \frac{7.15\ \text{V} \times R2}{R1 + R2}$$

$-V = \text{Gnd}$
$+V = V_{in}$

$R3 = R1 // R2$ (minimum drift)

What differences do you see here, compared to the schematic on the previous page?

When you construct your power supply regulator for the first project, you will need to use an external series pass transistor. Refer to H & H and the 723 data sheet for suggestions on how to do this. Also see the diagram on the next page.

The use of a series pass transistor is essential when the output current demand is high, and/or when there is a large difference between the output voltage and the power supply voltage (i.e., the voltage from the filter capacitor).

Quite often a heat sink will be required. That is the subject of our next discussion.

Here's an example of how to add an NPN bypass transistor to the 723 integrated voltage regulator.