Chapter 7: Other Applications of Op Amps (*preliminary*)

In this chapter we will consider some other applications of op amps, primarily current to voltage conversion, comparators and oscillators.

A: Current to Voltage Conversion

One of the two common current measurement techniques involves using an op amp to measure a current without a voltage burden. Typically one measures a current by inserting a "small" resistor, R, into the circuit and measuring the voltage across that resistor and saying that I = V/R. The problem is that introducing the resistor R into the circuit changes the circuit. The voltage drop across the resistor, V, is referred to as the voltage burden. Consider the arrangement at the right. If the battery is 0.1V and R_s = 1kΩ the current flowing in the circuit would normally be 100μA. To measure a current this small on a voltmeter, many digital multimeters would insert a 100Ω, or a 1kΩ, resistor, so that the voltage drop across the 100Ω resistor would be about 10mV. (This is called a voltage burden.) This would produce a total resistance of 1.1kΩ and reduce the actual current to 91μA, making the voltage burden 9.1mV. This changes the circuit. One can eliminate this problem by using an op amp as shown at the right. Here the ammeter is in the dashed box and the open circles represent connections to the ammeter. The feedback assures that the resistor R_s, is connected to a 0V point so that the drop across it is V_B, and the current through it is V_B/ R_s. The V_{out} represents the current scaled by the ratio of the resistors and inverted in sign.

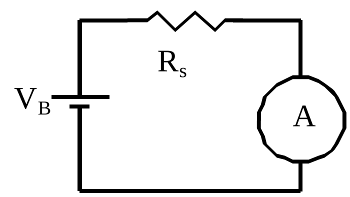


Fig. 7.1 Current Measurement

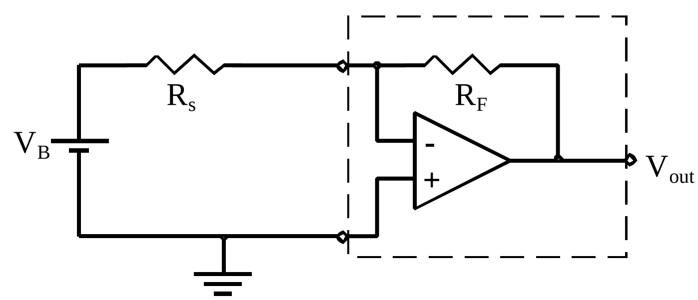


Fig. 7.2 Active Ammeter

$$V_{out} = -IR_F = -\frac{V_B}{R_s} R_F \qquad 7.1$$

If R_F = 1k, − 1V at the output represents 1mA of current and – 4.5V would represent 4.5mA. The only drawback to this type of circuit is that it effectively connects R_s to the common, i.e. it measures the current flowing through R_s to the common. If R_s does not connect to the common in the original circuit, it's not easy to use this circuit to measure the current.

B: Voltage Comparator

A comparator compares two voltages, V_1 and V_2 and figures out which one is larger. For instance, if $V_1 > V_2$, you may want an output signal to be HIGH. In this instance the output is like a logic signal, HIGH or LOW. A basic circuit that does this is shown at the right. It is just an op am with two inputs and no negative feedback. With no negative feedback, the

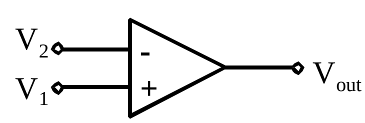


Fig. 7.3 Basic Comparator

output is either as HIGH as it can go, or as LOW as it can go. (In principle it can be between these values, but it is usually at one extreme or the other or on the way from one to the other.) The only problem is that the output will swing from one supply rail to the other. If you want the output to go between 0 and 5V, typical logic levels, you will have to take the output to a common emitter transistor like that in fig. 4.12 with the positive voltage to the collector at 5V instead of 15V. (It is often best to limit the base voltage so that it does not get more than 4-5V below the emitter voltage to prevent a "reverse breakdown of the base-emitter diode in the transistor, so sometimes I'll put a diode from the emitter to the base to prevent the base from getting more than 0.6V below the emitter voltage. A base resistor of several kΩ will also prevent this breakdown from being a serious problem.)

Very often you want to compare two signals that have some noise on them. If the two voltages are close enough to each, the noise can produce HIGH to LOW and LOW to HIGH transitions at the output. This is especially troublesome when you are counting how often one voltage goes above and then back below the other one. This often happens when you are trying to measure the frequency of a sine wave. You want to count how many times the input crosses from below 0V to above 0V in one second, see fig 7.5 below. The noise can produce false counts. The signal at the right crosses zero twice going up as shown by the circles. One way to reduce this problem is to put hysteresis into the comparator. Then the HIGH to LOW and LOW to HIGH transitions occur at different voltages. This is done by using positive feedback, i.e. from the output to the + input. In this case we will apply the signal to the – input. Normally we would ground the + input to measure transitions in the input from below 0V to above 0V. However, we now use a circuit like that in fig. 7.6. A fraction of the output is feed back to the + input through R_1 and R_2. Since the output is either HIGH or LOW, V_H or V_L, the + input is at either

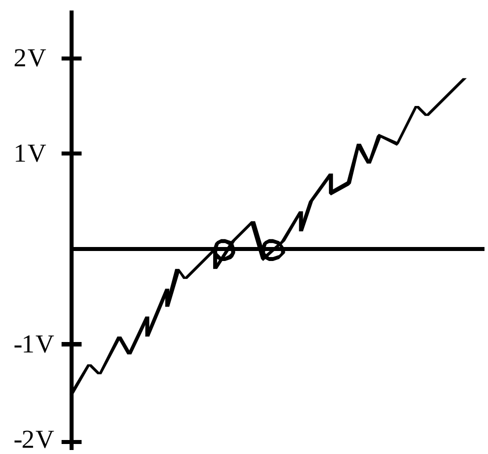


Fig. 7.4 Noisy signal

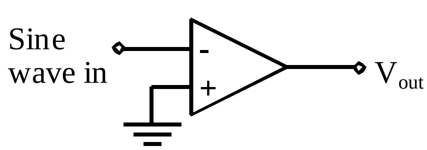


Fig. 7.5 Zero Crossing Detector

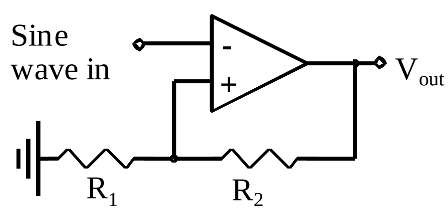


Fig. 7.6 Zero Crossing Detector with Hysteresis

$$v_+ = \frac{R_1}{R_1 + R_2} V_H \qquad \text{or} \qquad v_+ = \frac{R_1}{R_1 + R_2} V_L \qquad 7.2$$

For simplicity, let's assume $V_H = -V_L = 10V$ and that $R_1/(R_1 + R_2) = 0.1$. Then $v_+ = +1V$ if the output is HIGH or –1V if it's LOW. If the input has been low enough so the output is HIGH (remember this configuration inverts the signal's polarity) then $v_+ = +1V$. The output remains HIGH until the sine wave goes above +1V, i.e. $v_- > v_+$, at which time the output starts falling. As it falls, so does v_+. This reinforces the transition by making v_- even greater than v_+. Now the output is LOW and remains LOW until v_- becomes less than v_+, but now $v_+ = –1V$. So the sine wave has to fall below –1V before the output will swing HIGH. As the sine wave becomes less than –1V the output rises and this makes v_+ more positive, or even greater than v_-. This again reinforces the transition. The HIGH to LOW transition at the output occurs when the input crosses +1V going up and the LOW to HIGH transition occurs when the input crosses – 1V going down. They occur at different voltages. The difference between these two point is the hysteresis, so we would say the hysteresis is 2V in this case. (This is actually quite large; it's often of the order of a tenth of a volt.) Now if there is noise on the signal as it goes up past +1V and the output swings LOW, the noise would have to be large enough to get the signal below –1V before the output would swing HIGH on a false transition. The noise would have to be > 2V to do this.

An alternative circuit is shown in the figure at the right. Now the – input is grounded and the signal goes to the positive input through the resistor R_1. Again, the output is either HIGH or LOW. IF v+ is >0, the output is HIGH and if it is <0 the output is LOW. In this circuit the output is HIGH if V_{in} is high and it's LOW if V_{in} is low. If the output is HIGH, $v_+ = 0$ when

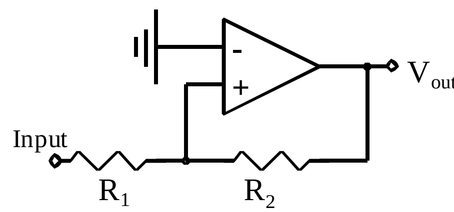


Fig. 7.7 A 2nd zero crossing detector

$$\frac{V_{in}}{R_1} = -\frac{V_H}{R_2} \qquad 7.3$$

i.e. when $V_{in} <0$. (7.3 says the current through R_1 = the current through R_2.)This will be the case when V_{in} has been high and is now going low. The output will go low if V_{in} drops below – V_{HIGH} (R_1/R_2). This $V_{in} = V_{H\ to\ L}$ is where the HIGH to LOW output transition occurs. What about when V_{in} has been low and is now going back high? The LOW to HIGH transition at the output will occur when the output is Low and $v_+ = 0$ again. This will occur when $– V_{in}/R_1 = V_{out}/R_2$, but with $V_{out} = V_L$, instead of V_H, or

$$\frac{V_{in}}{R_1} = -\frac{V_L}{R_2} \qquad 7.4$$

Therefore the two input voltages where the signal changes are

$$V_{in} = -V_H \frac{R_1}{R_2} \qquad 7.5$$

and

$$V_{in} = -V_L \frac{R_1}{R_2} \qquad 7.6$$

and the hysteresis is the difference between these two voltages, or

$$\left(V_H - V_L\right)\frac{R_1}{R_2} \qquad 7.7$$

If one wants 100mV of hysteresis and $(V_H – V_L) = 20V$, then one wants $R_1/R_2 = 1/200$. A good choice might be $R_2 = 10k$ and $R_1 = 50\Omega$.

A final consideration is that you may want to detect when the input crosses a level other than 0V, say V_{ref}. Then you would circuits like those shown below. The analysis of where the

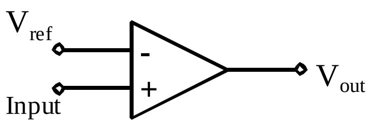


Fig. 7.8

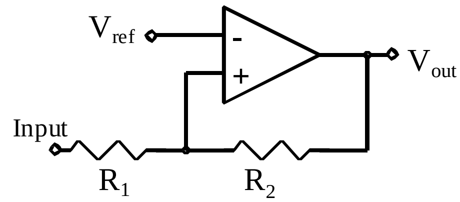


Fig. 7.9

transitions occur for fig. 7.9 is slightly more complicated, but not too bad. You should try it. Remember that the transitions occur when $v_+ = V_{ref}$. (One can also interchange the reference and the signal inputs to fig. 7.9. You might try that one too.)

C: Oscillator

One often wants to make an oscillator, either to generate a signal source, i.e. function generator, or for timing, e.g. a clock in a computer. A cheap way to produce an oscillator is based on the comparator with hysteresis. An example is shown at the right. This is sometimes called a relaxation oscillator. The positive feedback will mean that the output will be either V_H or V_L. Transitions from one to the other will occur when $v_- = v_+$. Assume that the output is at V_H . This means that v_- is less than v_+. If v_{out} is at V_H then v_- will be heading toward V_H as the capacitor

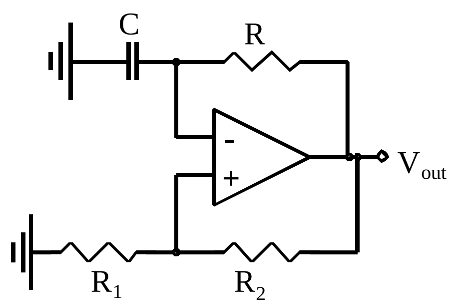


Fig. 7.10 Relaxation Oscillator

C charges up through the resistor R. When the output is at V_H, $v_+ = V_H \{R_1/(R_1 + R_2)\}$. When v_- reaches v_+ and just passes it, the output will go from V_H to V_L, and v_+ goes to $V_L\{R_1/(R_1 + R_2)\}$ (see eqn. 7.2). Now the capacitor starts discharging toward V_L through R. When it reaches v_+ and passes below it, the output will swing back high and C will start charging toward V_H again. One can estimate the frequency of the oscillation by assuming that $V_L = -V_H$, or that the swings are symmetric about 0V. This will mean that v_- and the capacitor go between $-V_H \{R_1/(R_1 + R_2)\}$ and $V_H \{R_1/(R_1 + R_2)\}$ when the output is at V_H. When v_{out} is at V_L they go from $V_H \{R_1/(R_1 + R_2)\}$ to $-V_H \{R_1/(R_1 + R_2)\}$. It should take the same amount of time to go from $V_H \{R_1/(R_1 + R_2)\}$ to $-V_H \{R_1/(R_1 + R_2)\}$ as it does to go from $-V_H \{R_1/(R_1 + R_2)\}$ to $V_H \{R_1/(R_1 + R_2)\}$. Therefore the time for one half of a cycle, or one half a period, T/2, is the time it take the capacitor to charge from $-V_H \{R_1/(R_1 + R_2)\}$ to $V_H \{R_1/(R_1 + R_2)\}$. We can estimate this if $R_2 >> R_1$. This approximation means that the capacitor only charges for a time small compared to the RC time constant, i.e. it is charging from $-V_H \{R_1/(R_1 + R_2)\}$ toward V_H, but only gets to $V_H \{R_1/(R_1 + R_2)\} << V_H$ before the output change and it starts to discharge. This will only require a small fraction of a time constant and allows us to approximate the exponential charging curve as a linear variation of voltage with time. The output is shown as a dashed line in Fig. 7.11, below. The voltage across the capacitor is the solid line in the linear approximation, i.e. small hysteresis.

As an example, consider the case where V_H = 10V and $R_2 = 9R_1$. Then the capacitor starts at –1V and charges toward + 10V, but only goes to +1V before the output switches low to –10V. Thus it only goes two elevenths of the way from its starting value toward its "final value" of 10V. If we assume it is linear, we would estimate it takes (2/11)xRC to go that far, or 0.18RC. The actual time is 0.20xRC. This would be T/2 or half a period of the oscillation.

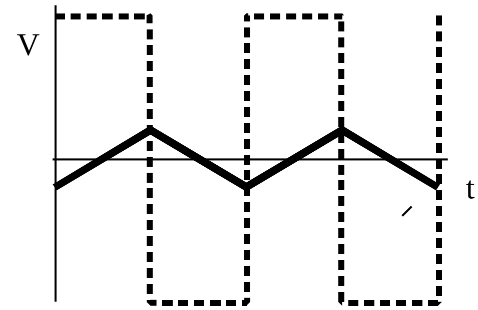


Fig. 7.11 Oscillator Output (dashed line)

We can approximate the time required for this by assuming that the capacitor is charging from $-V_H \{R_1/(R_1 + R_2)\}$ to $V_H \{R_1/(R_1 + R_2)\}$ with a current V_H/R, i.e. the current is the average of the starting current and the "final" current. (This is a slightly better approximation than the one used in the example above.) The rate of change of the voltage across the capacitor is

$$\frac{dV_C}{dt} = \frac{I}{C} = \frac{V_H/R}{C} = \frac{V_H}{RC} \qquad 7.8$$

It has to go is from $-V_H \{R_1/(R_1 + R_2)\}$ to $V_H \{R_1/(R_1 + R_2)\} = 2V_H \{R_1/(R_1 + R_2)\}$. This will take a time t such that

$$\frac{V_H}{RC} t = 2V_H \frac{R_1}{R_1 + R_2} \qquad 7.9$$

or

$$t = 2RC \frac{R_1}{R_1 + R_2} \qquad 7.10$$

Since this is one half the period, T/2, then T is

$$Period = T \approx 4RC \frac{R_1}{R_1 + R_2} \qquad 7.11$$

If you want to produce an oscillation of frequency 1000Hz, then the period is 1ms. If $R_2 = 9R_1$, then 0.4RC = 1ms, or RC = 2.5ms = 2.5×10^{-3}s. If C = 10^{-7}F = 0.1μF, then R = 25kΩ.

This also assumes that the output of the op amp changes instantly from V_L to V_H. This isn't bad at low frequencies, but at higher frequencies the finite slew rate means that the measured frequency will be a little less than the predicted frequency.

With a small hysteresis, the voltage across the capacitor is approximately a triangle wave. This may give you an inkling of how to generate a triangle wave. You can do this by charging and discharging a capacitor with a constant current source. The charging current might be 1mA and the discharging one is –1mA. A comparator then looks at the voltage across the capacitor and if the voltage is going down it switches current sources when V reaches –1V so that it starts charging. Then when it gets to +1V it switches back to the negative current source. This is very effective and all this can be integrated into a single chip that will generate a square wave, a triangle wave and even "reshape" the triangle wave to resemble a sine wave.

A simple circuit that will do this is illustrated at the right. The first op amp keeps a constant current flowing onto (or off of) the capacitor C when the voltage to the input resistor R_{in} is constant. Therefore the output voltage ramps down (or up) with time. The second op amp acts as a comparator with hysteresis and switches state whenever the output of amp 1 crosses the trigger points. The output of amp 2 goes to the input resistor to amp 1, or R_{in}. Because of the inverting nature of amp 1, if the output of amp 2 is V_H, amp 1's output is ramping down. When it gets low enough, the + input to amp 2 goes below ground and the output of 2 falls to V_L. Then the input to amp 1 changes to V_L and amp 1 ramps up. Therefore the output of amp 1 is a triangle wave and the output of amp 2 is a square wave. This circuit works fairly well. The frequency depends on the time constant $R_{in}C$ and the amount of hysteresis. (Can you find an expression for the frequency in terms of $R_{in}C$, R_1, R_2, V_L and V_H, assuming $V_L = -V_H$?)

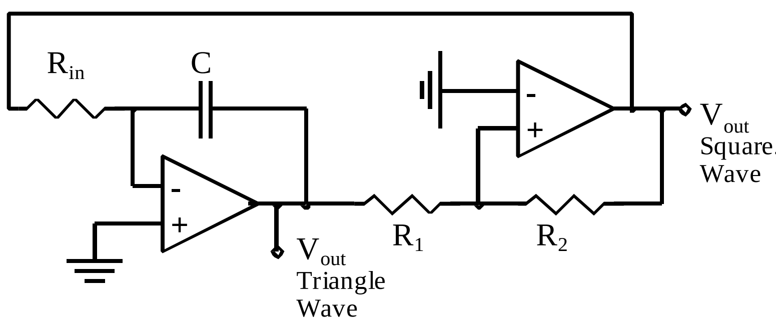


Fig. 7.11 A better oscillator

D: Power Supplies and Voltage Regulators

A DC power supply is a device that has an input from the power mains, typically $120V_{rms}$ at 60Hz, an produce a fixed or selectable output voltage. The breadboards used in our labs have a DC power supply that provides a fixed 5V supply and selectable supplies in the range of –1.2V to –15V and +1.2V to +15V. Such a DC power supply usually has three parts.

The first is a transformer that will take the power mains voltage and produce a smaller AC voltage. For a 15V supply you would want the "smaller" AC voltage to be about $15V_{rms}$. A transformer works by wrapping N_p turns around an iron core as shown at the right. The primary inputs are connected to the power mains. The N_p turns have enough inductance so that not too much current is drawn from the power mains when nothing is connected to the secondary. (Of course all of these wires are insulated to isolate them from the iron core and from each other.) The turns for the secondary are also wrapped around the core. There are N_s turns on this "side". The purpose of the iron core is to keep the magnetic field lines due to currents flowing in the primary and secondary wires inside the core. (Iron has a fairly high magnetic permeability.) This means that the flux, Φ, through one turn of the primary is the same as the flux through one turn of the secondary. Then the EMF across the input is given by

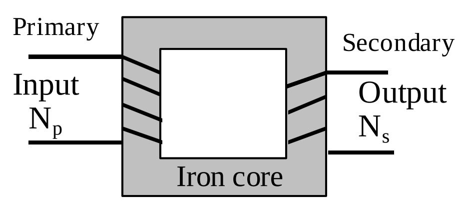


fig. 7.12

$$EMF_p = -N_p \frac{d\Phi}{dt} \qquad 7.12$$

and similarly for the secondary, except there are a different number of turns.

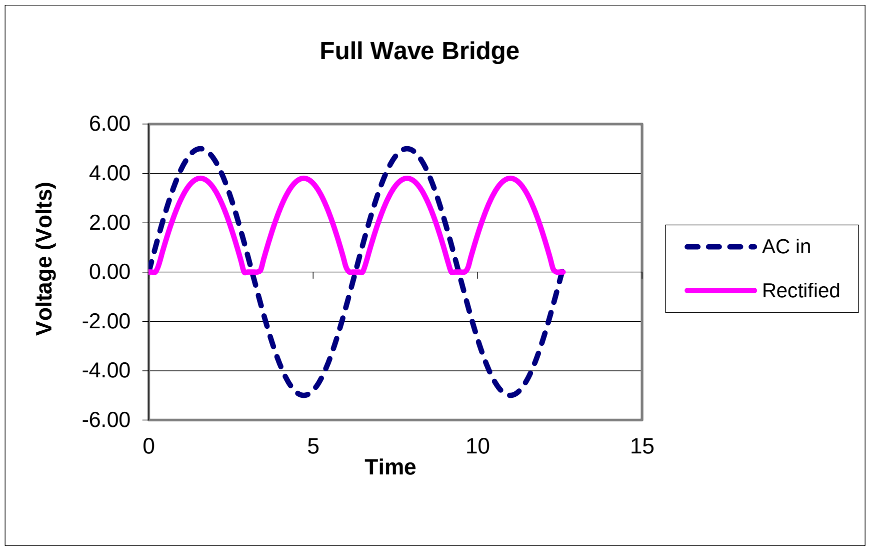
$$EMF_s = -N_s \frac{d\Phi}{dt} \qquad 7.13$$

However, $d\Phi/dt$ is the same for both. Solving for $d\Phi/dt$ from both of these and equating them yields

$$\frac{EMF_p}{N_p} = \frac{EMF_s}{N_s}, \quad \text{or } EMF_s = EMF_p\left(\frac{N_s}{N_p}\right) \qquad 7.14$$

If the primary's EMF = $120V_{rms}$ and $N_p = 10N_s$, then the EMF of the secondary is $12V_{rms}$. The primary EMF or voltage has been stepped down by a factor of 10. The ratio of the turns determines how the output (secondary) is related to the input (primary).

The output of the secondary is still an AC voltage at 60Hz though. To turn it into a DC-like voltage is to run it through a full wave diode bridge. (See chapter 4.) This will convert it into a non-negative voltage, but still one that varies as shown at the right for an AC input of 10V peak to peak. This variation can be reduced by attaching a large filter capacitor across the output of the full wave bridge. This will produce an output that looks like fig. 7.13 with the original rectified signal shown as well and fig. 7.14 with just the filtered signal. These assume that there



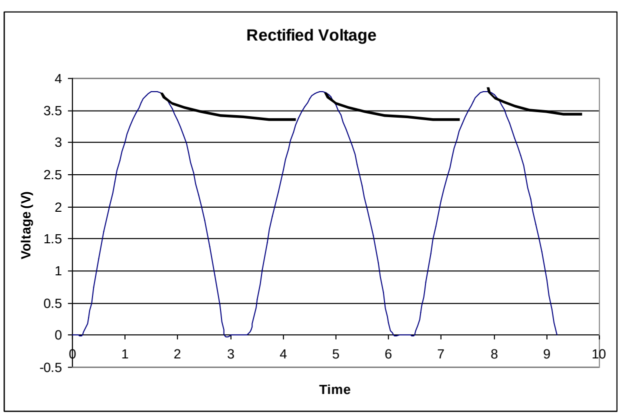


fig. 7.13

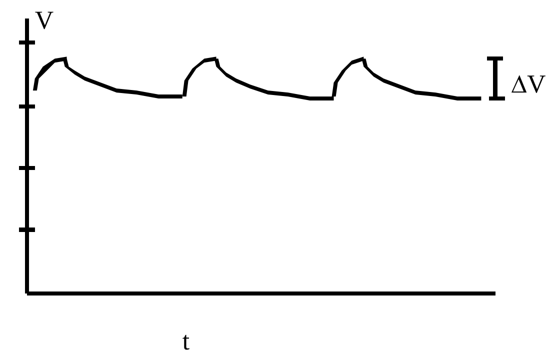


fig. 7.14

is some resistive load that causes the capacitor voltage to undergo RC decay when the "input" rectified voltage drops below the capacitor's voltage. ΔV represents how far the capacitors voltage will drop due to the RC decay until the "input" again reaches the capacitors present voltage and recharges. (The time scale in fig. 7.13 is arbitrary, and not in seconds if this is to represent a rectified 60Hz sine wave.) For a 60Hz sine wave, the time between the full-wave rectified peaks is 8.3ms. If the load resistor is 30Ω and C = 2,200μF and the peak voltage is V_p, the RC time constant is 66ms >> 8.3ms. Then the capacitors voltage would drop by about

$$\Delta V \approx -Vp\,(8.3ms/RC) \qquad 7.15$$

If V_p = 16V and RC =66ms (as above) then ΔV = – 2.0V. Your output voltage would vary between 14V and 16V, not exactly a constant DC voltage. To make the voltage more constant you would need to use a voltage regulator. (In this situation I would normally use a larger filter capacitor, for example 3,300μF.)

A common regulator is a three terminal regulator. It has three pins, an input, a ground and an output. You can think of it as a device make up of a voltage reference, an op amp and a power transistor at the output. They are usually designed to produce a fixed voltage difference between the ground pin and the output pin, the most common values being 5V, 12V, 15V, 18V and 24V for positive regulators. The designation for these is usually 78xx where the xx is the voltage difference between the ground and the output. For example a 7805 is a +5 Volt regulator and a 7812 is a +12 Volt regulator. They usually have current limiting and thermal shutdown circuits inside, but it is best not to "test" them. The 78xx series is usually limited to 1 to 1.5A of current. A typical circuit for using them is shown below.

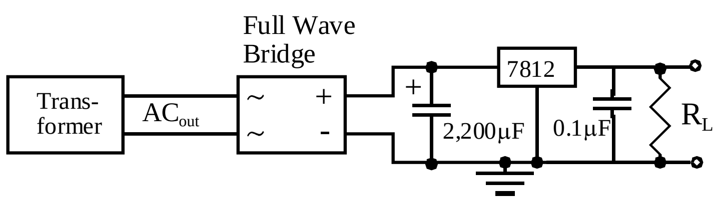


Fig. 7.15

R_L represents the load resistance, and the 0.1μF capacitor at the output is usually required for stability. Sometimes they also want a 1 μF capacitor from the input to ground if the large filter capacitor is located too far from the regulator. For this to regulate the output properly, the input to the regulator should stay above 14.6V for a 12V regulator according to the manufacturer.

There are corresponding negative regulators, e.g. the 79xx series, for regulating negative voltages. There are also adjustable voltage regulators, e.g. the LM317 for positive voltages and the LM337 for negative voltages.