The Power Supply

The power supply is used to convert the AC energy provided by the wall outlet to dc energy. In most electronic equipment, the power cord supplies the ac energy at 120 V_{AC} to the power supply. The power supply then provides all the dc voltages needed to run the equipment.

The basic power supply is broken down into 4 elements as shown.

1) *The Transformer*
2) *The Rectifier*
3) *The Filter*
4) *The Voltage Regulator*

Basic Power Supply -- Block Diagram

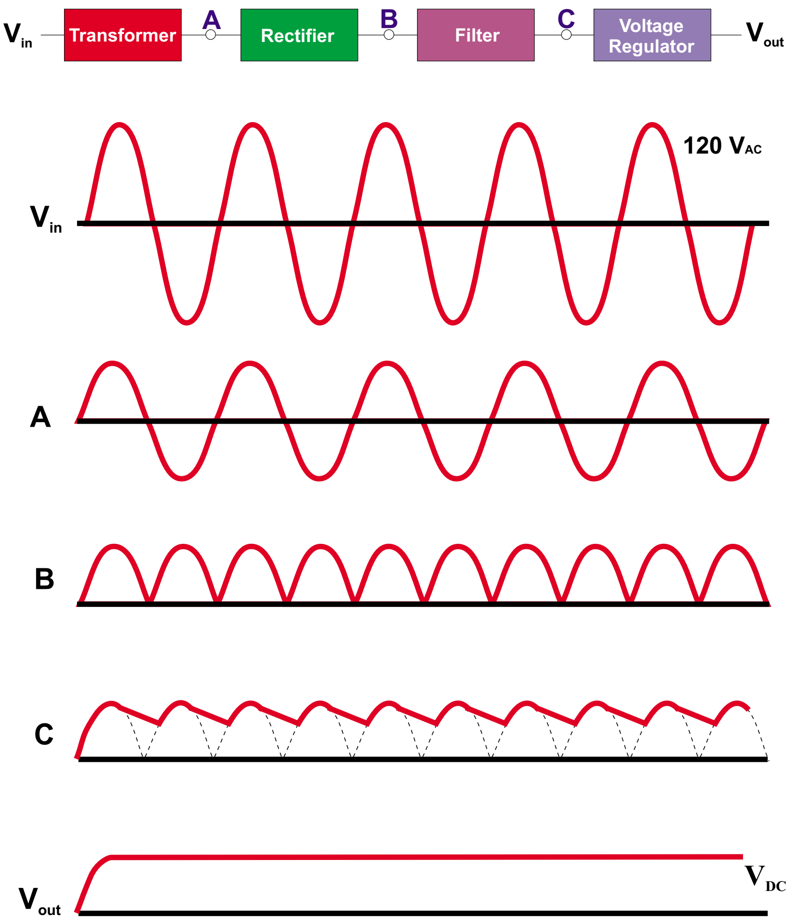


Figure 1

The Transformer

- usually steps up or steps down the incoming line voltage depending on the needs of the power supply. This alternating voltage is then fed to the rectifier.

The Rectifier

- is a diode circuit that converts the ac to pulsating dc. This pulsating dc is then applied to the filter.

The Filter

- is a circuit that reduces the variations of the in the dc voltage. It can include one or several passive components such as resistors, capacitors and inductors. We will study the capacitor as a filter. The filtered dc is then fed to a voltage regulator stage.

The Voltage Regulator

- is used to maintain a constant voltage at the power supply output. It also provides a further smoothing of the dc voltage.

We will be using a zener diode as a voltage regulator. Modern day circuits have superceded the zener diode regulator with more modern integrated circuits. Since the zener diode is the simplest of these circuits to understand, we will study it as a prerequisite to the more modern circuits available.

The Transformer

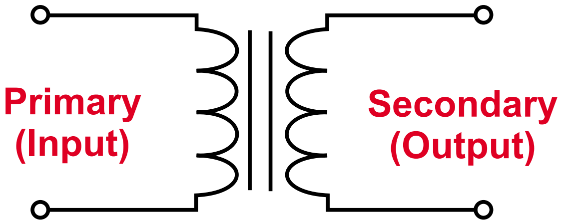


Figure 2

The basic schematic symbol for the transformer is shown in Figure 2. Note that it has two windings , the primary and the secondary. The input voltage is applied to the primary winding and the output voltage is taken from the secondary winding. The vertical lines between the windings represent an iron core transformer.

Figure 3 represents a simple transformer. Note that there is no electrical connection between the primary and secondary windings. AC is applied to the primary and this ac current creates a magnetic flux in the core of the transformer.

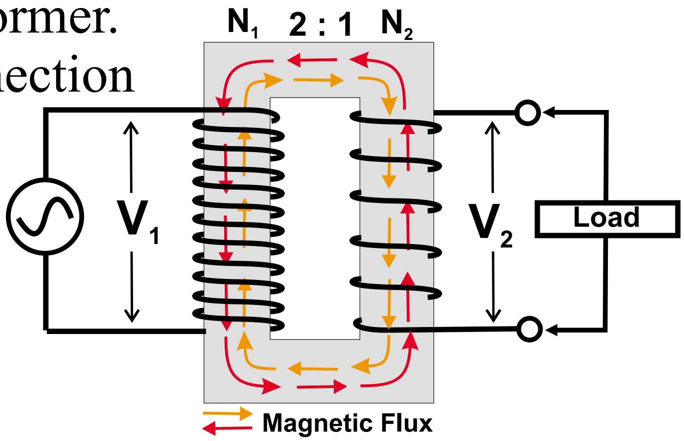


Figure 3

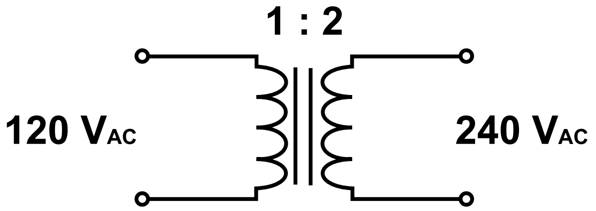
This magnetic flux grows as the ac current increases in the primary winding. As the ac current decreases, then reverses, - so does the magnetic flux.

The ac current has created a constantly changing and reversing flux in the iron core of the transformer.

This constantly changing flux also passes through the secondary winding. As it grows, collapses and reverses, it cuts through the secondary windings and induces a voltage in it. The voltage level that appears across the secondary winding is dependant on the ratio of primary turns to secondary turns.

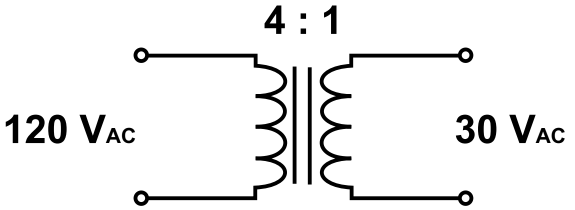
Transformer Types

Step Up



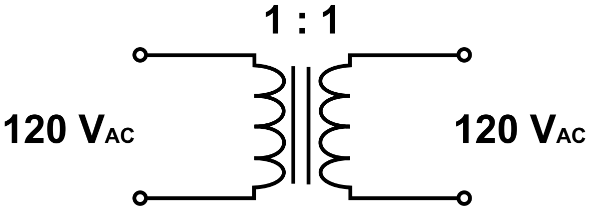
Step Up Transformers provide a secondary voltage that is greater than the primary voltage

Step Down



Step Down Transformers provide a secondary voltage that is less than the primary voltage

Isolation



Isolation Transformers provide a secondary voltage that is equal than the primary voltage. This type of transformer is used to isolate the power supply from the ac power line. ***This is often necessary with certain equipment (i.e. television sets) to protect both the equipment and the technician working on it.***

Calculating Secondary Voltage

In the simple transformer shown in Figure 4, we have 12 turns creating the magnetic flux in the core. This same flux cuts the secondary windings. Since only 6 windings are here, the induced voltage is one half of that in the primary. Since 12 windings to 6 windings is a ratio of 2:1, we can calculate the secondary voltage if the turns ratio is known and the primary voltage is known.

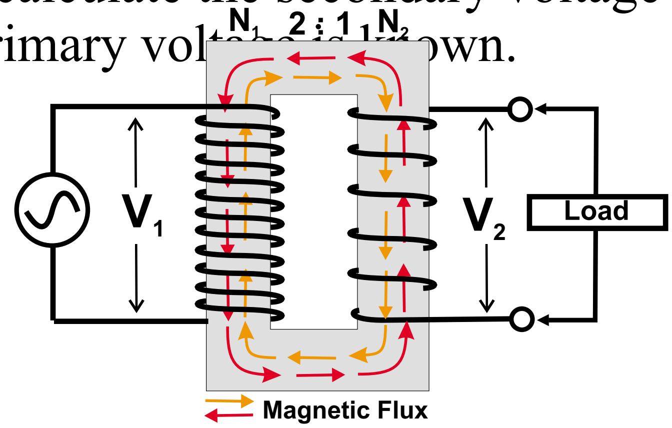


Figure 4

This gives the formula:

$$\boxed{V_2 = \frac{N_2}{N_1} V_1}$$

In our case above, if V_1 is 12Vac,
Then V_2 would calculate out to be 60 Vac.

$$V_2 = \frac{N_2}{N_1} V_1 \qquad V_2 = \frac{1}{2}\,12\text{ Vac}$$

$$= 6\text{ Vac}$$

Calculating Secondary Current

Ideally, transformers are 100% efficient. This means that the ideal transformer transfers 100% of its power to the secondary (The actual losses are small, so we ignore them).

If we assume that all the power that goes in is transferred to the output then:

$$\boxed{P_2 = P_1}$$

We know that power is voltage times current then:

$$\boxed{V_2 I_2 = V_1 I_1}$$

And

$$\boxed{\frac{I_1}{I_2} = \frac{V_2}{V_1}}$$

A quick look at this last formula should tell you that the current ratio is the inverse of the voltage ratio. This means that:

For a step down Transformer $I_2 > I_1$
For a step down Transformer $I_2 < I_1$

This simply says that if the voltage on the secondary increases, then the current in the secondary decreases.

Using our simple transformer in Fig. 4 as an example:

We found before that the secondary voltage was 6 Vac when the primary voltage was 12 Vac.

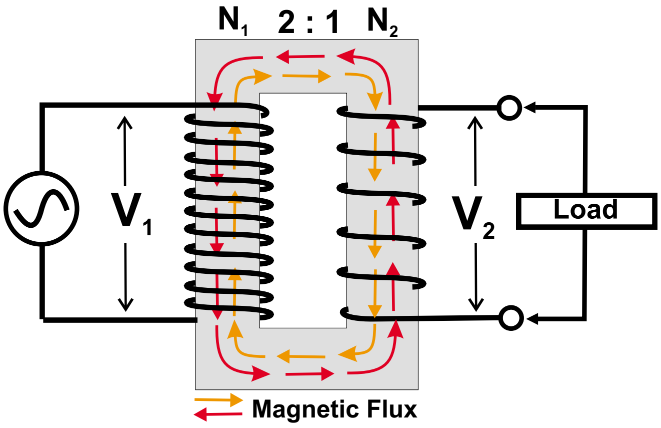


Figure 4

Let's assume that we measured the primary current and found that it was 1 Ampere. We know that the current ratio is the inverse of the voltage ratio. This means that if the voltage drops in half, then the current must increase by a factor of 2. This means that the current in the secondary winding is 2 Amperes.

By formula, if we know the primary current, the primary voltage and the secondary voltage , then the secondary current is

$$\boxed{I_2 = \frac{V_1}{V_2} I_1}$$

If we know the turns ratio then :

$$\boxed{I_2 = \frac{N_2}{N_1} I_1}$$

Example 3-1 shows an example of finding the secondary current.

Transformer Input / Output Relationships

Some transformers have their output waveform in phase with the input waveform. Others do not. While is not an important factor in the analysis of our power supply, we should be aware of it.

Note the two dots in each of the schematic diagrams. (See Figure 5) The two dots at the top of the windings indicate an "in phase" relationship between the input and output.

The lower diagram has one dot at the top and one dot at the bottom indicating a 180^{O} phase shift from input to output.

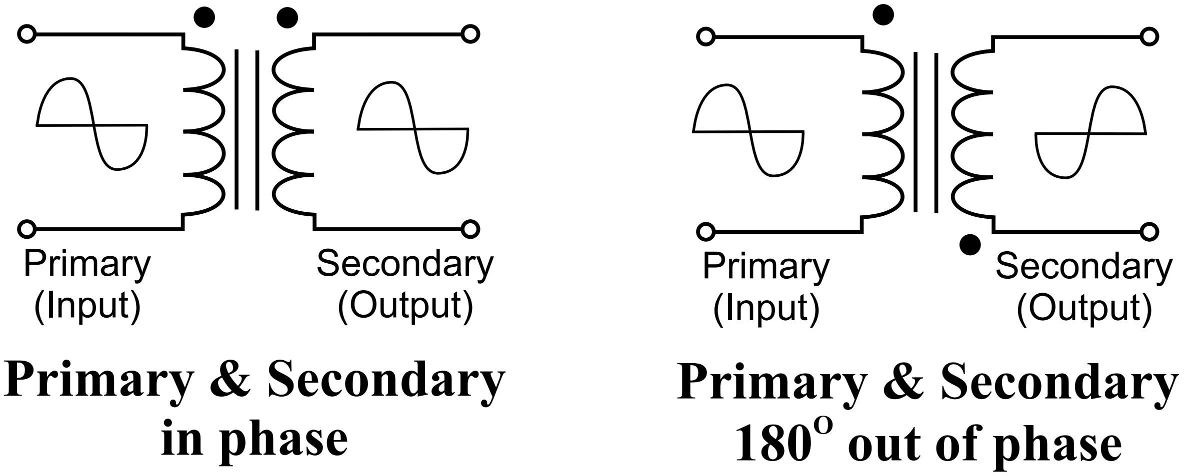


Figure 5

Transformer Ratings

While some manufacturers list their transformers by their turns ratios, others list them by secondary voltage ratings. In the lab, the transformer we use is listed as a 12.6 V transformer. This means that the secondary output will be 12.6 Vac at 120 Vac input.

It should be noted that many small transformers are designed to deliver their rated voltage at a rated current. When the transformer is operated below the rated current, it is normal for the secondary voltage to be above the rated voltage. This is because some of the output voltage is dropped across the secondary winding resistance.

Types of Rectifier Circuits

There are three basic types of rectifier circuits:

1) *The Half Wave Rectifier*
2) *The Full Wave Rectifier*
3) *The Bridge Rectifier*

The most commonly used rectifier is the bridge rectifier followed by the full wave rectifier. The half wave rectifier sees limited use in today's circuits.

The Half Wave Rectifier

The easiest rectifier to understand is the half wave rectifier. It is simply a diode and a load as shown in Figure 6.

It is used to ***eliminate*** either the ***negative swing of the ac input waveform*** or to ***eliminate the positive swing of the input waveform.***

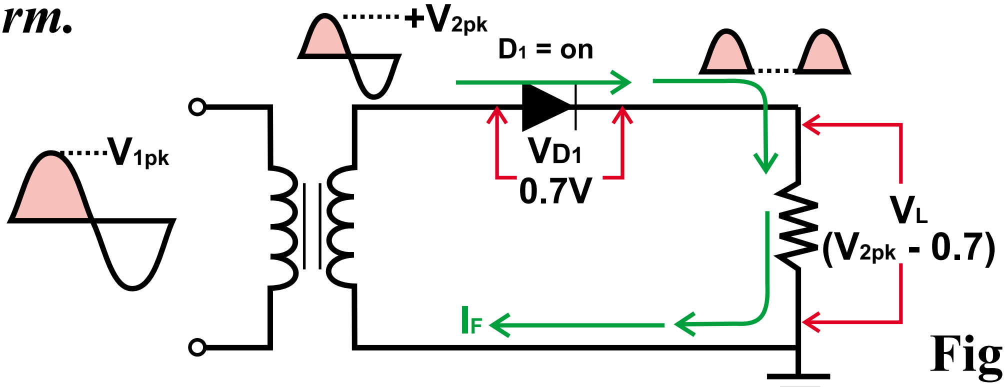


Figure 6

Positive Half Cycle

Basic Operation During the positive half cycle of the input, diode D_1 is forward biased and provides a path for the current through the load. This allows a voltage V_L to develop across the load resistor (R_L). This voltage is approximately equal to V_{2pk} - 0.7 V *(using the practical diode).*

During the negative half cycle, the diode D_1 is reverse biased and no current flows through the load resistor (R_L) Now the voltage V_L is approximately 0 and the voltage across the diode V_{D1} is the peak secondary voltage V_{2pk}.

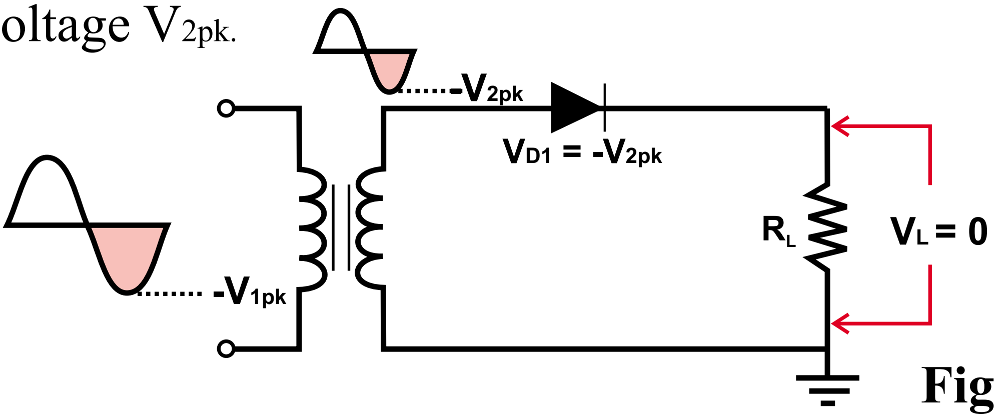


Figure 7

Negative Half Cycle

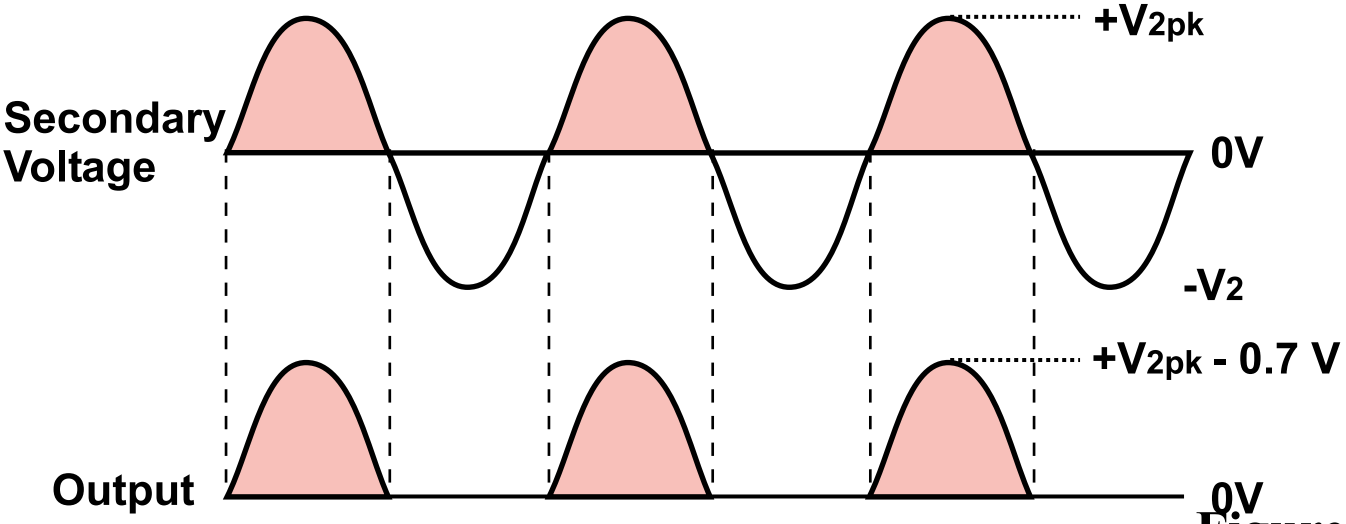


Figure 8

Input & Output Waveforms

Negative Half Wave Rectifiers

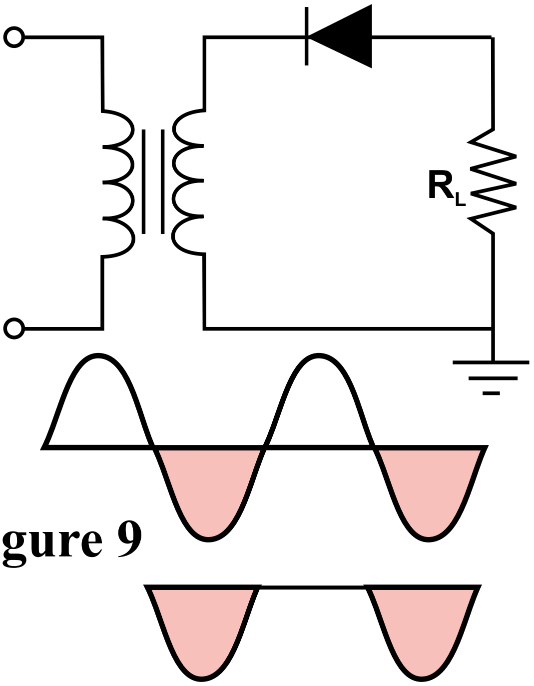


Figure 9

In Fig. 9, the diode is reversed. The diode is reverse biased on the positive half cycles and is forward biased on the negative half cycles. As a result, the positive half cycle is eliminated at the output.The operating principles are exactly the same as before, only now the output has been reversed.

The direction of the diode determines whether the output of the rectifier is positive or negative. For circuit recognition, the following statements will generally hold true:

1) When the ***diode points toward the load***, the output from the rectifier will be ***positive.***

2) When the ***diode points toward the transformer***, the output from the rectifier will be ***negative*****.**

The Half Wave Rectifier

Calculating Load Voltages and Currents

The ***peak load voltage*** is found as:

$$\boxed{\begin{array}{c} V_{L(pk)} = V_{2(pk)} - V_F \\ \text{or} \\ V_{L(pk)} = V_{2(pk)} - 0.7\ V \end{array}}$$

this uses the standard 0.7 V for V_F

The ***peak secondary voltage of the transformer*** is found as:

$$\boxed{V_{2(pk)} = \frac{N_2}{N_1} V_{1(pk)}}$$

where $\frac{N_2}{N_1}$ = the ratio of transformer turns

$V_{1(pk)}$ = the peak transformer primary voltage

Note that the formula above assumes that the input to the transformer is given as a peak value. More often than not, source voltages are given as a rms value. When this is the case, use this formula to convert it to a peak value.

$$\boxed{V_{pk} = \frac{V_{rms}}{0.707}}$$

Once the peak load voltage is determined, we can find the peak load current

$$\boxed{I_{L(pk)} = \frac{V_{L(pk)}}{R_L}}$$

Example 3-2, 3-3 and 3-4 (pages90 & 91) work with peak load voltages and currents

The Half Wave Rectifier

Average Load Voltage & Current

The ***Average Load Voltage*** - V_{ave} is the reading you would get if you used a dc voltmeter to read the pulsating dc output of our rectifier. The meter averages out the dc pulses and displays this average. The formulas to calculate V_{ave} are:

$$\boxed{V_{ave} = \frac{V_{L(pk)}}{\pi}} \quad \text{or} \quad \boxed{V_{ave} = 0.318 V_{L(pk)}}$$

Either equation will find V_{ave}. This is also called the dc equivalent voltage for our half wave rectifier. *Keep in mind that this formula finds Vave for our half wave rectifier only.*

Equivalent DC Voltage V_{ave}

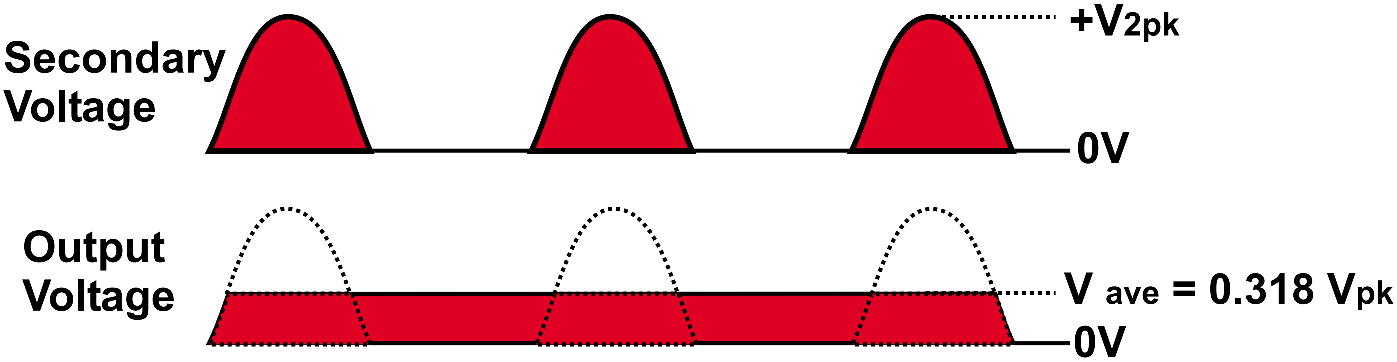


Figure 10

Example 3-5 (page 92) finds V_{ave}.for the half wave rectifier.

Average Load Current

Just as we can convert a peak voltage to average voltage, we can also a peak current to an average current. The value of the average load current is the value that would be measured by a dc ammeter. This value is called the ***equivalent dc current.***

Average Load Current (Cont)

The value of I_{ave} can be calculated in one of two ways:

1) Find I_{ave} using Ohm's Law

$$\boxed{I_{ave} = \frac{V_{ave}}{R_L}}$$

2) We can convert I_{pk} to I_{ave} using the following equations.

$$\boxed{I_{ave} = \frac{I_{pk}}{\pi}} \qquad \boxed{I_{ave} = 0.318\, I_{pk}}$$

Examples 3.6 and 3.7 use both methods (PP 93 , 94)

Negative Half Wave Rectifiers

To analyze a negative half wave rectifier -- Do the following:

1) Analyze the circuit as if it where a positive half wave rectifier.

2) After completing your calculations, change all the polarity signs from positive to negative.

See example 3-8 (Page 94)

Peak Inverse Voltage

The maximum amount of reverse bias that a diode will be exposed to is called the peak inverse voltage. or PIV. For the half wave rectifier, the value of PIV is :

$$\boxed{PIV = V_{2(pk)}}$$

Peak Inverse Voltage (cont)

The reasoning for the above equation is that when the diode is reverse biased, there is no voltage across the load. Therefore, all of the secondary voltage (V_{2pk}) appears across the diode.

The PIV is important because determines the minimum allowable value of V_{RRM}. for any diode used in the circuit. Remember that ***a replacement diode should have a*** V_{RRM} ***of at least 1.2 times the PIV*** in ordinary circumstances.

The Full Wave Rectifier

Basic Circuit Operation

The full wave rectifier consists of two diodes and a resister as shown in Figure 11

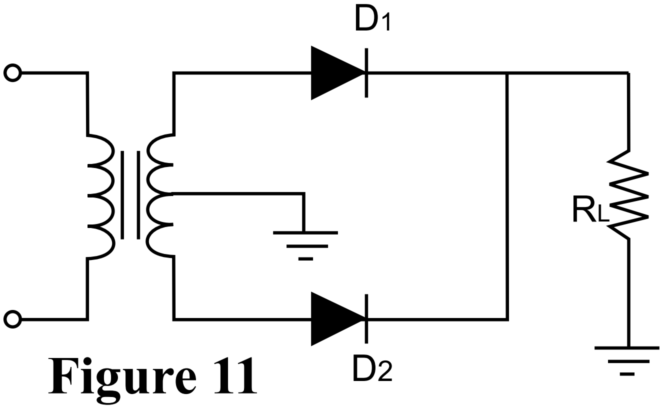
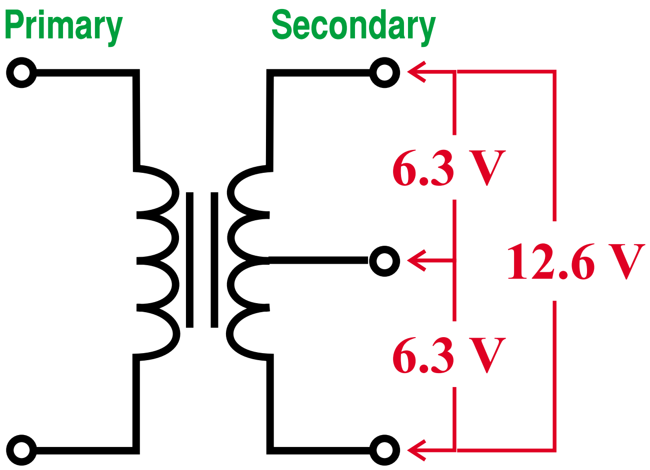


Figure 11

.The transformer has a ***centre - tapped*** secondary winding. This secondary winding has a lead attached to the centre of the winding. The voltage from the centre tap to either end terminal on this winding is equal to one half of the total voltage measured end-to-end.

For example The transformer you will be using in the lab has a 12.6 Vac centre tapped secondary winding. This means that the voltage output from the centre to each outer terminal in one half of the total voltage or 6.3 Vac. See Figure 12.



Example of a 12.6 VAC Centre-Tapped Transformer

Figure 12

The Full Wave Rectifier

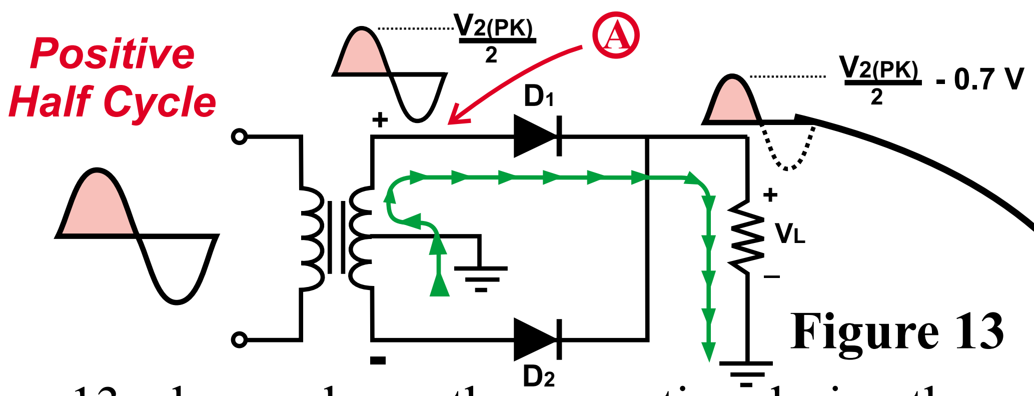


Figure 13

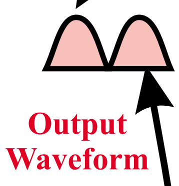


Figure 13 above shows the operation during the ***positive*** half cycle of the full wave rectifier. Note that D_1 is forward biased and D_2 is reverse biased. Note the direction of the current through the load. Also note that the voltage at point (A) is one half of V_2 when measured to ground. This is because the transformer is centre - tapped and only half of the secondary winding is in use during each half cycle. Since 0.7V is dropped across the forward biased diode, the voltage appearing across the load is one half of V_2 minus 0.7 V.

During the negative half cycle, (Fig. 14) the polarity reverses. D_2 is forward biased and D_1 is reverse biased. Note that the direction of current through the load has not changed even though the secondary voltage has changed polarity. Thus another positive half cycle is produced across the load.

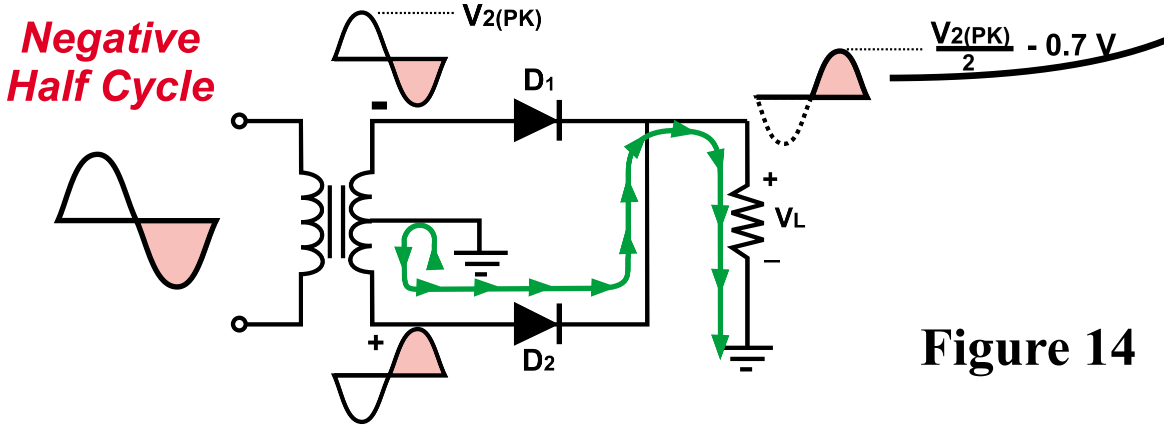


Figure 14

Calculating Load Voltage And Currents

Using the practical diode model, the peak load voltage for the full wave rectifier is found as:

$$\boxed{V_{L(pk)} = \frac{V_{2(pk)}}{2} - 0.7\ V}$$

The full wave rectifier produces twice as many output pulses as the half wave rectifier. This is the same as saying that the full wave rectifier has twice the output frequency of a half wave rectifier.

For this reason, the average load voltage is found as

$$\boxed{V_{ave} = \frac{2V_{L(pk)}}{\pi}} \quad \text{or} \quad \boxed{V_{ave} = 0.636\ V_{L(pk)}}$$

Figure 16 below illustrates the average dc voltage for a full wave rectifier.

Average DC Voltage V_{ave} for a Full Wave Rectifier

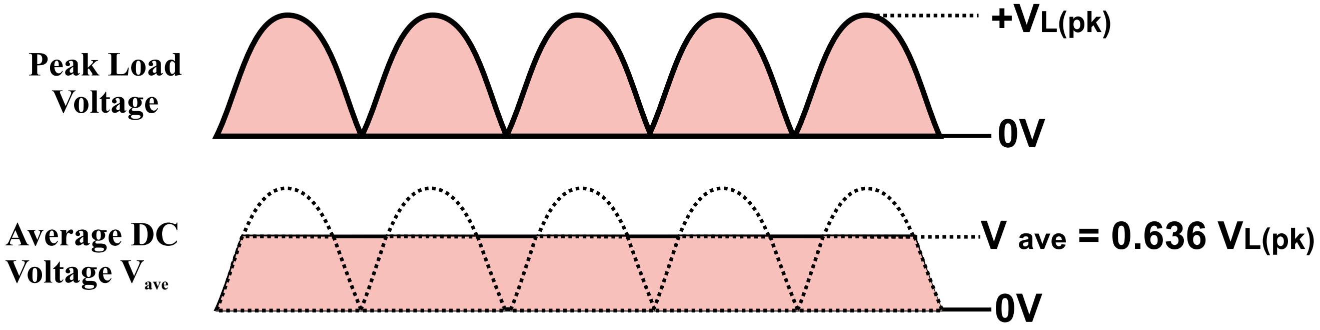


Figure 16

Example 3-9 Page 97 calculates the load voltage for a full wave rectifier. Example 3-10 determines the peak load current and the average dc voltage for a full wave rectifier.

Negative Full - Wave Rectifiers

If we reverse the directions of both diodes in a positive full wave rectifier, we get a negative output across the load.. Figure 15 shows this. Note both diodes point toward the transformer and that the output waveform is negative.

Negative Full Wave Rectifiers

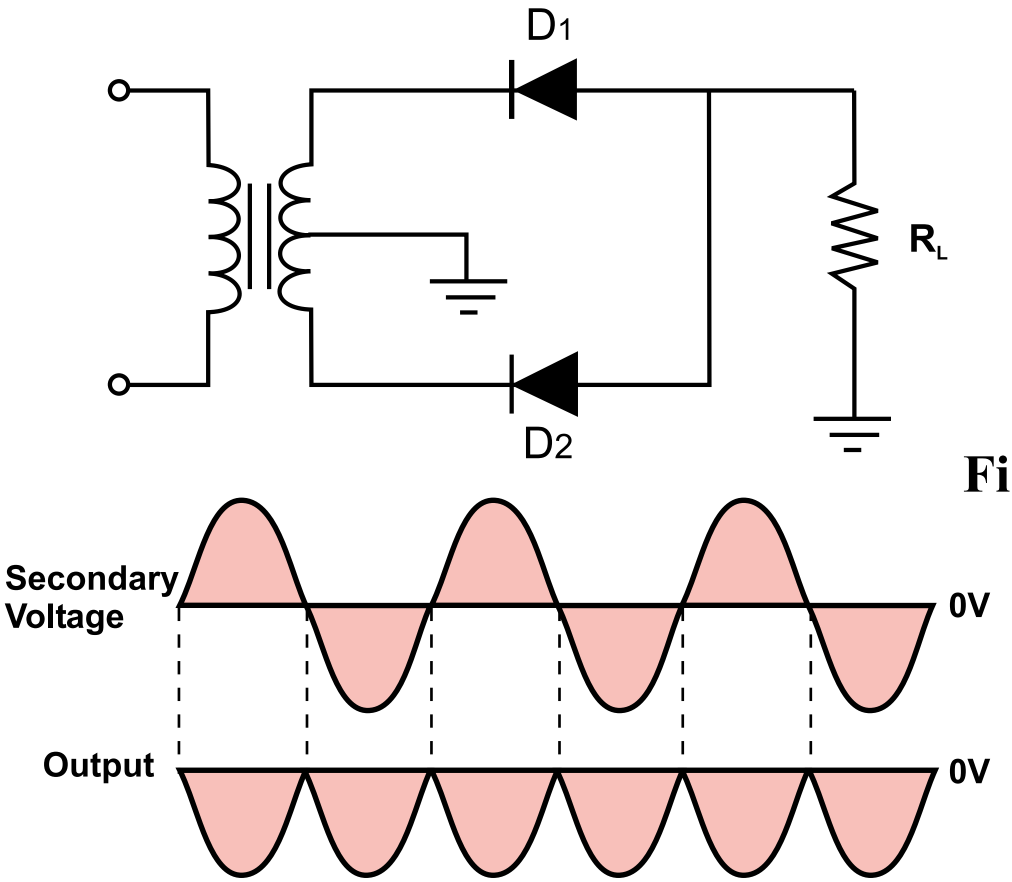


Figure 15

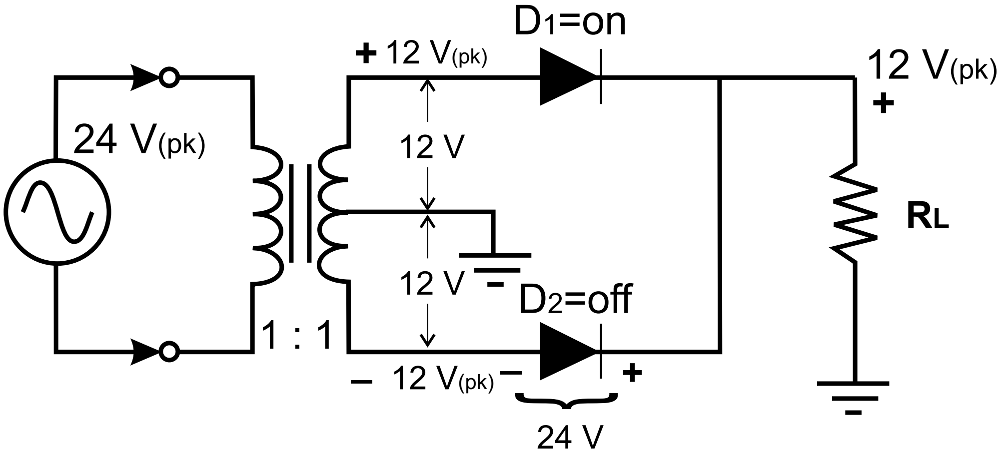
Peak Inverse Voltage

When one of the diodes in a full-wave rectifier is reverse biased, the voltage across that diode will be approximately equal to V_2 This point is illustrated in Figure 16. The 24 V_{pk} across the primary develops peak voltages of +12 V and – 12 V across the secondary (when measured from end to centre tap). Note that $V_{2(pk)}$ equals the difference between these two voltages: 24 V.

With the polarities shown, D_1 is conducting, and D_2 is reverse biased. If we assume D_1 to be ideal, the voltage drop across the component will equal 0 V. Thus, the cathode of D_1 will also be at +12 V**.** Since this point is connected directly to the cathode of D_2, its cathode is also at +12 V**.** With – 12 V applied to the anode of D_2, the total voltage across the diode is 24 V. The peak load voltage supplied by the full-wave rectifier is equal to one-half of the secondary voltage, V_2. Therefore, the reverse voltage across either diode will be twice the peak load voltage.

If we now consider the practical diode, we include the 0.7 V drop across the diode.

$$\boxed{\mathbf{PIV = V_{2(pk)} - 0.7\ V}}$$



PIV using the Ideal Diode

Figure 16

The Full Wave Bridge Rectifier

The bridge rectifier (Figure 17) is the most commonly used rectifier circuit for the following reasons:

- No centre - tapped transformer is required.
- The bridge rectifier produces almost double the output voltage as a full wave C-T transformer rectifier using the same secondary voltage.

Basic Circuit Operation

During the positive half cycle(Figure 17) , both D_3 and D_1 are forward biased. At the same time, both D_2 and D_4 are reverse biased. Note the direction of current flow through the load. On the negative half cycle (Figure 18) D_2 and D_4 are forward biased and D_1 and D_3 are reverse biased. Again note that direction of current through the load is in the same direction although the secondary winding polarity has reversed..

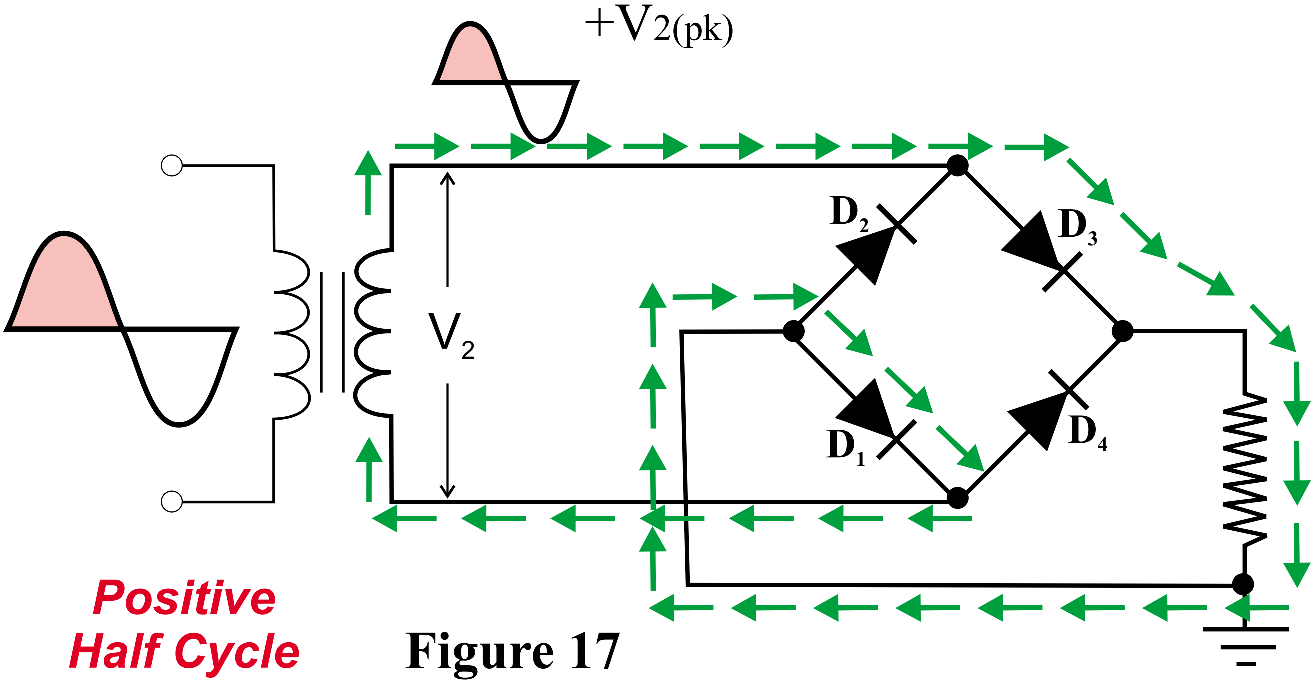


Figure 17

The Full Wave Bridge Rectifier

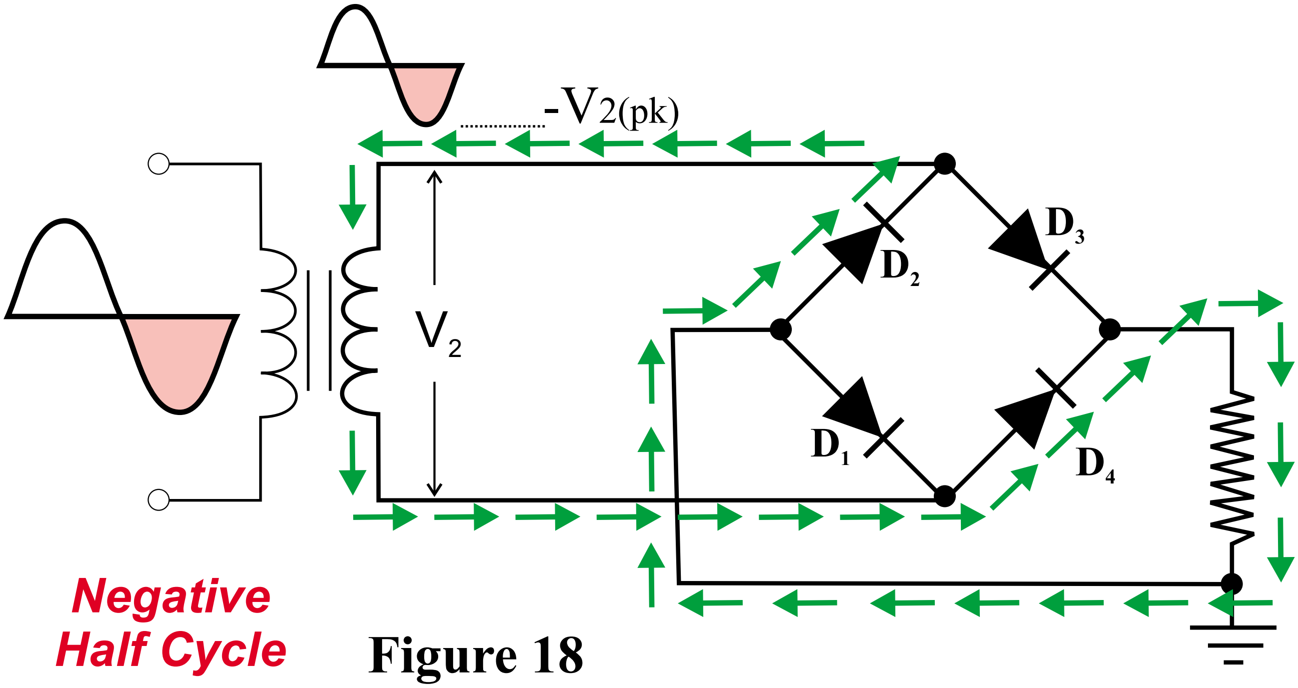


Figure 18

Note that the current passes through 2 diodes on each half cycle. This means that two diode drops must be accounted for when calculating the peak load voltage.

$$\boxed{V_{L(pk)} = V_{2\ pk)} - 1.4\ V}$$

Example 3-11 p102 shows an example of calculating the dc load voltage and current values for a bridge rectifier..

Tip

It is easy to remember how the individual diodes are placed in a bridge rectifier circuit.

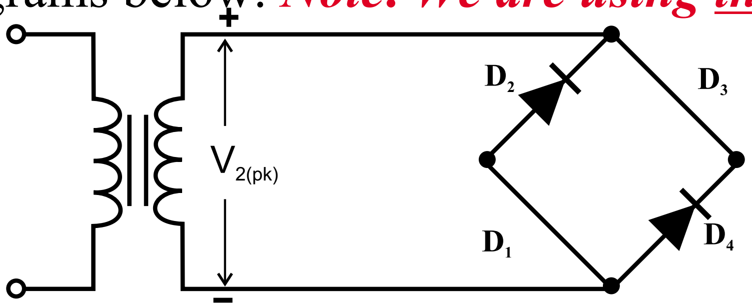
- *All diodes point toward the load.*
- *The corner opposite the load in grounded*
- *The ac is applied to the top and bottom.*

The Full Wave Bridge Rectifier

Peak Inverse Voltage

In order to understand the Peak Inverse Voltage across each diode, look at the diagrams below: *Note: We are using the ideal diode.*

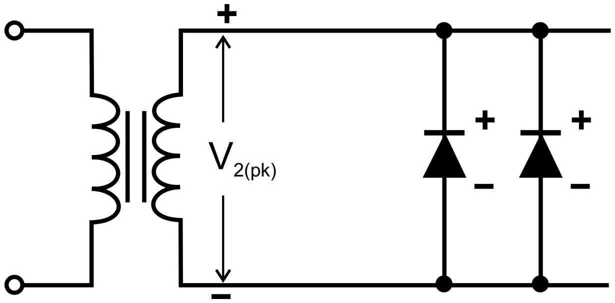
Figure 19



Consider Fig 19 above. This circuit is simplified to show the circuit conditions during the positive half cycle. The load & ground connections are removed because we are concerned with the diode conditions only. Using the ***ideal diode*** note:

- Diodes D_1 and D_3 are forward biased & act like closed switches. They are replaced with wires.
- Diodes D_2 and D_4 are reverse biased and act like open switches.

Figure 20



Consider Fig. 20 above. It is an equivalent circuit of Fig 19,, just redrawn. You can see that ***both diodes are***:

- reverse biased
- in parallel
- directly across the secondary winding

Therefore: $\boxed{PIV = V_{2(pk)}}$ ***Ideal Diode***

$\boxed{PIV = V_{2(pk)} - 0.7V}$ ***Practical Diode***

Putting It All Together

The Half Wave Rectifier

- is the simplest of the 3 types
- produces a ***single*** half cycle output for ***each input cycle***
- output polarity depends on the direction of the diode.
- ***can*** be directly connected to the ac line.

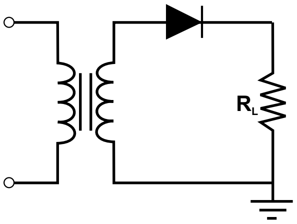
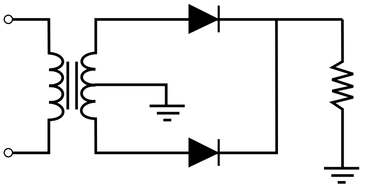
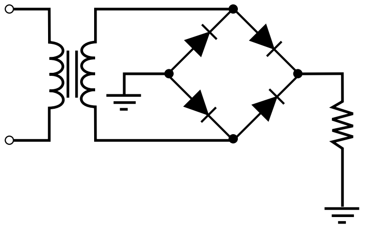
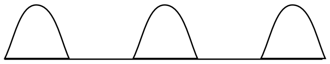
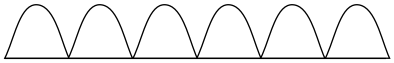
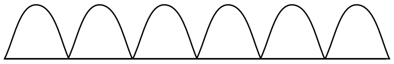
The Full Wave Rectifier

- uses 2 diodes and a centre - tapped transformer
- produces ***two*** half cycle output for ***each input cycle***
- output polarity depends on the direction of the diode.
- ***cannot*** be directly connected to the ac line.

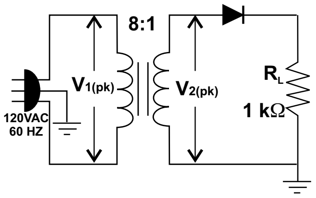
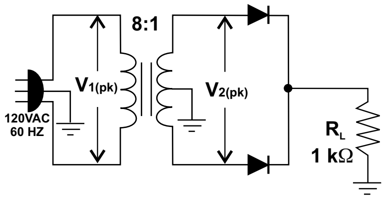
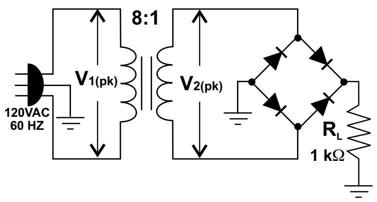
The Bridge Rectifier

- uses 4 diodes and does not require a centre tap
- produces twice the peak output voltage of the full wave rectifier above.
- ***can*** be directly connected to the ac line

Rectifier Summary

	Half Wave	Full Wave	Bridge
Schematic Diagram			
Waveform			
Peak Load Voltage $V_{L(pk)}$	$V_{2(pk)} - 0.7V$	$\frac{V_{2(pk)}}{2} - 0.7V$	$V_{2(pk)} - 1.4V$
DC Load Voltage	$\underline{V_{L(pk)}}$ or $0.318\ V_{L(pk)}$	$\underline{2V_{L(pk)}}$ or $0.636\ V_{L(pk)}$	$\underline{2V_{L(pk)}}$ or $0.636\ V_{L(pk)}$
DC Load Current	$\frac{V_{ave}}{R_L}$	$\frac{V_{ave}}{R_L}$	$\frac{V_{ave}}{R_L}$
PIV	Equal to $V_{2(pk)}$	$V_{2(pk)} - 0.7V$	$V_{2(pk)} - 0.7V$
Frequency	$f_{out} = f_{in} = 60$ Hz	$f_{out} = 2f_{in} = 120$ Hz	$f_{out} = 2f_{in} = 120$ Hz

Rectifier Calculation Example

Half Wave	Full Wave	Bridge
		
① Find $V_{1(pk)} = \frac{120\text{ V}}{.707} = 169.73\text{ V}_p$ ② Find $V_{2(pk)} = \frac{N_2}{N_1} V_{1(pk)}$ $= \frac{1}{8}\, 169.73\text{ V}_{pk}$ $= 21.21\text{ V}_{pk}$	① Find $V_{1(pk)}$ = Same = 169.73 V_p ② Find $V_{2(pk)}$ = Same = 21.21 V_{pk}	① Find $V_{1(pk)}$ = Same = 169.73 V_p ② Find $V_{2(pk)}$ = Same = 21.21 V_{pk}
③ Find the Peak Load Voltage $V_{L(pk)} = V_{2(pk)} - 0.7\text{V}$ $= 21.21\text{ V}_{pk} - 0.7\text{ V}$ $\boxed{V_{L(pk)} = 20.51\text{ V}_{pk}}$	③ Find the Peak Load Voltage $V_{L(pk)} = \frac{V_{2(pk)}}{2} - 0.7\text{V}$ $= \frac{21.21\text{ V}_{pk}}{2} - 0.7\text{ V}$ $= 10.6\text{ V}_{pk} - 0.7\text{ V}$ $\boxed{V_{L(pk)} = 9.9\text{ V}_{pk}}$	③ Find the Peak Load Voltage $V_{L(pk)} = V_{2(pk)} - 1.4\text{ V}$ $= 21.21\text{ V}_{pk} - 1.4\text{ V}$ $\boxed{V_{L(pk)} = 19.81\text{ V}_{pk}}$
④ Find the DC Load Voltage V_{ave} or $V_{DC} = V_{L(pk)}(.318)$ $= 20.51\text{ V}_{pk}(.318)$ $\boxed{V_{ave} = 6.52\text{ V}}$	④ Find the DC Load Voltage V_{ave} or $V_{DC} = V_{L(pk)}(.636)$ $= 9.9\text{ V}_{pk}(.636)$ $\boxed{V_{ave} = 6.3\text{ V}}$	④ Find the DC Load Voltage V_{ave} or $V_{DC} = V_{L(pk)}(.636)$ $= 19.81\text{ V}_{pk}(.636)$ $\boxed{V_{ave} = 12.6\text{ V}}$
⑤ Find the DC Load Current $I_{ave} = \frac{V_{ave}}{R_L}$ $= \frac{6.52\text{ V}}{1\text{ k}\Omega}$ $\boxed{I_{ave} = 6.52\text{ mA}}$	⑤ Find the DC Load Current $I_{ave} = \frac{V_{ave}}{R_L}$ $= \frac{6.3\text{ V}}{1\text{ k}\Omega}$ $\boxed{I_{ave} = 6.3\text{ mA}}$	⑤ Find the DC Load Current $I_{ave} = \frac{V_{ave}}{R_L}$ $= \frac{12.6\text{ V}}{1\text{ k}\Omega}$ $\boxed{I_{ave} = 12.6\text{ mA}}$
⑥ Find the Peak Inverse Voltage Equal to $V_{2(pk)}$ $\boxed{PIV = 21.21\text{ V}}$	⑥ Find the Peak Inverse Voltage $= V_{2(pk)} - 0.7\text{V}$ $21.21\text{ V}_{pk} - 0.7\text{V}$ $\boxed{PIV = 20.51\text{ V}}$	⑥ Find the Peak Inverse Voltage $= V_{2(pk)} - 0.7\text{ V}$ $21.21\text{ V}_{pk} - 0.7\text{ V}$ $\boxed{PIV = 20.51\text{ V}}$
⑦ Find the Output Frequency $f_{out} = f_{in}$ $\boxed{f_{out} = 60\text{ Hz}}$	⑦ Find the Output Frequency $f_{out} = 2f_{in}$ $\boxed{f_{out} = 120\text{ Hz}}$	⑦ Find the Output Frequency $f_{out} = 2f_{in}$ $\boxed{f_{out} = 120\text{ Hz}}$

The Filter Capacitor What is it?

The capacitor is a device consisting essentially of two conducting surfaces separated by an insulating material.

This insulating material, called ***a dielectric.*** can be air, mica, glass, plastic film or oil.

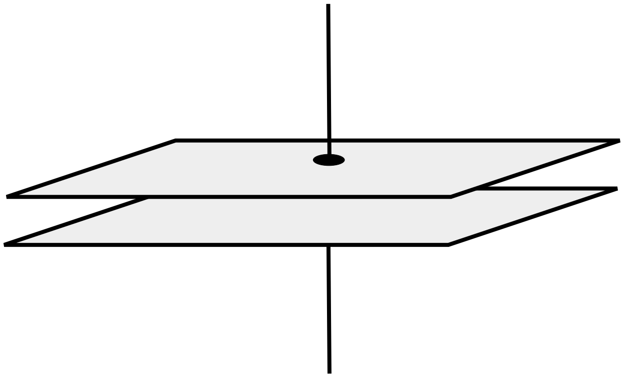
In modern day capacitors, the dielectric is generally a type of thin plastic with a very high insulating value.

Electrically, the filter capacitor acts as a storage device. It essentially blocks the flow of dc current but will allow the passage of ac current.

Its ability to pass ac current is dependant on the capacitor's size and the frequency of the ac current.

Basic Theory

In order to understand how the filter capacitor works, consider the simple capacitor shown.



It consists of two conductive plates, separated by an air space. A wire is attached to each plate.

There is no connection between the two plates.

The Filter Capacitor

Basic Theory (Cont)

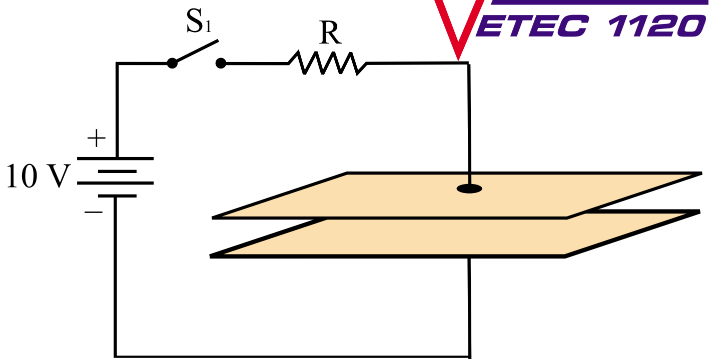


fig 1

This explanation uses ***electron flow*** ,not conventional flow.

In figure 1,we have connected our capacitor to a power supply and inserted a current limiting resistor.

With the switch open and the capacitor discharged, the electrons in the conductive plates are evenly spread throughout the plates and there are the same number of electrons in each plate.

Electrons repel each other, and this is why they spread evenly.

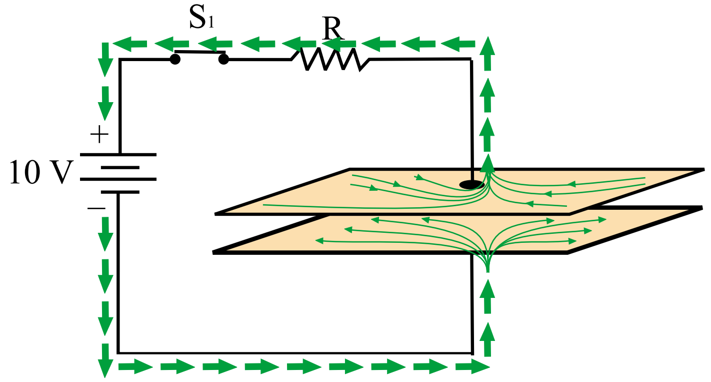


fig 2

In figure 2, we close the switch. Suddenly, there is a voltage pressure across the two plates. Electrons rush off the upper plate and gather on the lower plate. This creates a sudden high current as the electrons rush through the power supply to change plates. Remember that electrons repel each other. As more and more electrons collect on the lower plate, they are forced closer together. This causes a reverse pressure to build as more and more electrons are forced into the plate. As the reverse pressure builds, the current flows slows down and stops when the reverse pressure is equal to the power supply voltage.Now the upper plate is positive and is deficient in electrons and the lower plate is negative and has a n excess in electrons.

Basic Theory (Cont)

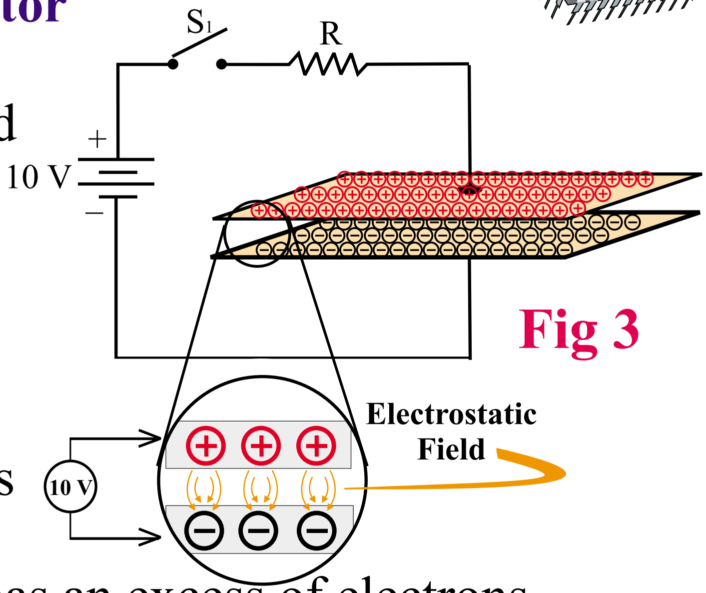


Fig 3

In Fig. 3, the switch is now opened .Even though the power supply is disconnected from the capacitor, the voltage across the capacitor remains at 10 V.

The top plate is still positive and is deficient in electrons; and the bottom plate is still negative and has an excess of electrons.

The capacitor is in a charged state and will remain there as long as there is no leakage path for the electrons to escape from the bottom plate & return to the top plate.

Between the plates, there exists an electrostatic field of attraction , since one plate is positive and the other negative.

If we were to increase the supply voltage to 20 V and then closed the switch again, a current would flow again from the positive to the negative plate.

More electrons would be forced into the negative plate and the same number of electrons would be forcibly removed from the positive plate.

The process would continue and the reverse pressure would increase until it matched the supply pressure. As the pressures become equal, the current will trickle down and stop. The voltage pressure between the plates is now 20V, double what it was before we increased the supply voltage.

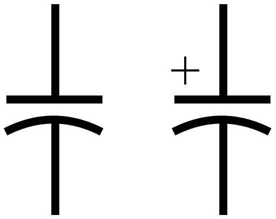
Basic Theory (Cont)

There is a limit to how high we can increase the supply voltage. If we increase it too high, the force of attraction between the plates becomes so strong that electrons on the negative plate jump across the gap and return to the positive plate.

Now our capacitor has suffered dielectric breakdown. In most cases, this event is catastrophic and will destroy the capacitor.

Important Things to Know

- The capacity of the capacitor is measured in micro Farads (μF)
- The schematic symbol is
  the (+) denotes the positive lead



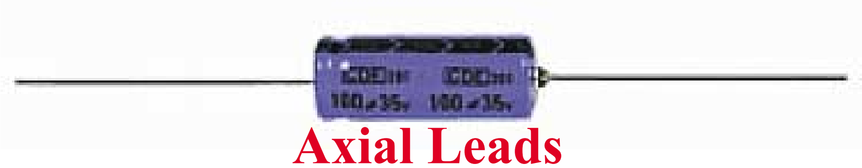
- The capacity to store energy is affected by these 3 Factors:

1) The area of the plates -larger area , larger capacity.
2) The distance between the plates -Less distance, larger capacity
3) The type of dielectric -(insulating material between the plates)

- Capacitors have a maximum working voltage. This is a ***never exceed*** value. Be careful not to exceed this voltage or catastrophic breakdown of the capacitor is likely.
  Note: Some capacitors can explode in this condition.

- Some types of capacitors are polarity sensitive. Be careful not to install this type in your circuit the wrong way. It will often destroy the capacitor.
  Note: Some capacitors can explode in this condition.

The Filter Capacitor

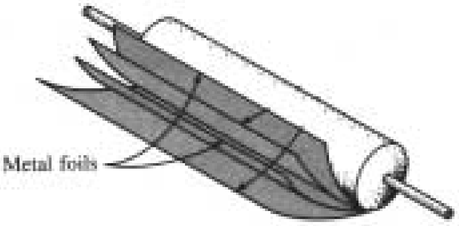


Axial Leads

Radial Leads

Your parts kit has several capacitors similar these. This type of capacitor is called an electrolytic capacitor, and is made by rolling two foils with an dielectric between them into a cigar shape as shown. Then leads are attached to each foil and the unit is inserted in a case.

Most electrolytic capacitors are polarity sensitive and will breakdown if installed wirth the wrong polarity.

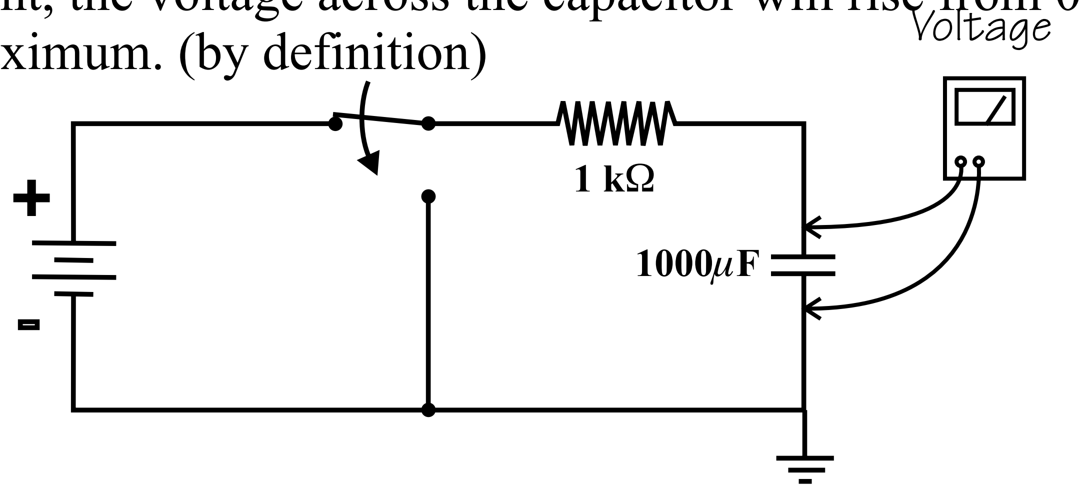


Charging & Discharging

How long does it take for the capacitor in the circuit shown to charge up once the switch is closed?

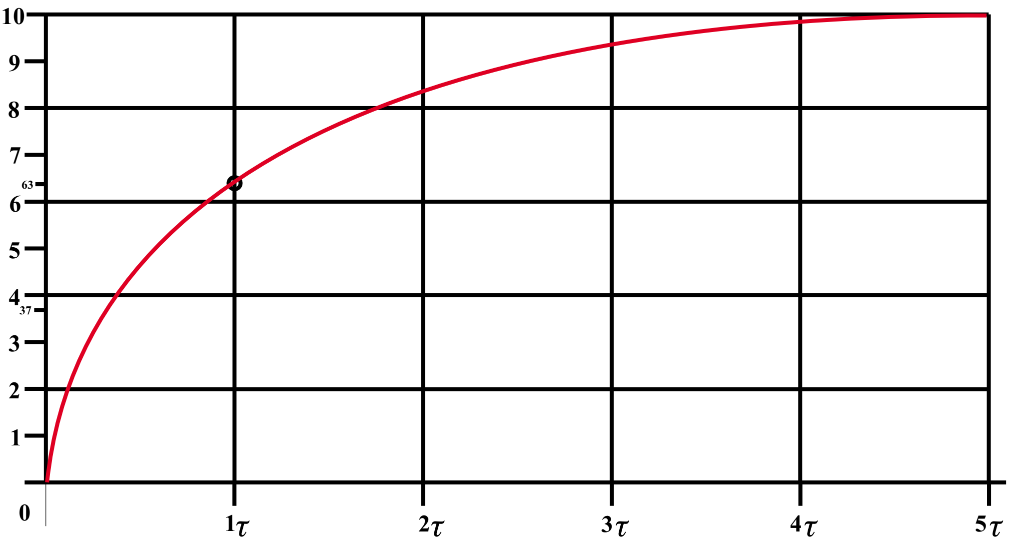
This circuit has a ***time constant*** that is determined by R times C. It is called Tau (τ) and is 1 kΩ times 1000μF = 1 Second.

In 1 time constant, the voltage across the capacitor will rise from 0 to 63.2 % of maximum. (by definition)



Charging & Discharging (Cont.)

In 5 time constants (5τ) , the capacitor has charged to 99.3 % of maximum. For our purposes we can consider the capacitor fully charged. In our example then, the capacitor will fully charge in 5 seconds (5 x 1 Sec. = 5 Sec.)



Capacitor Charging Time Constant

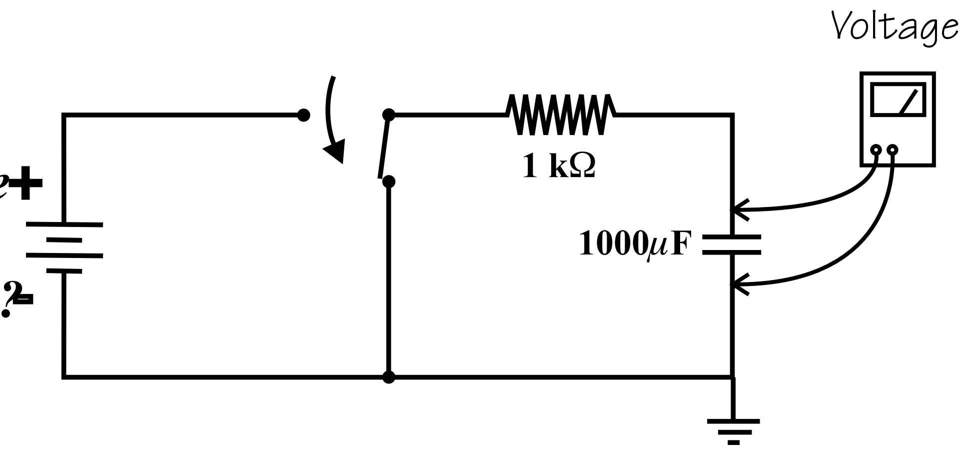
The time it takes a capacitor to charge is a function of R and C.

- If the capacitor is made larger, then the time constant increases
- If the resistance is made larger, then the time constant increases

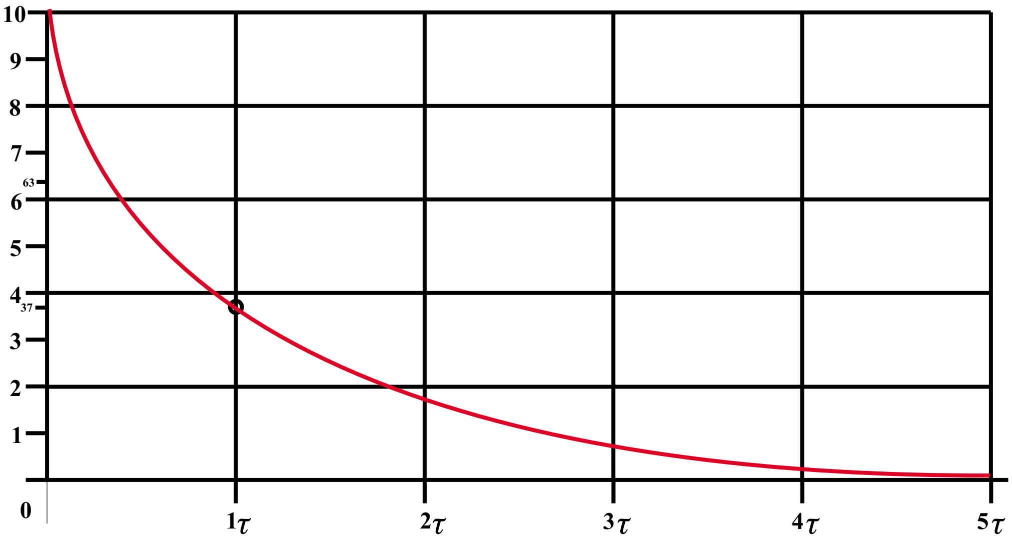
It always takes 5 time constants to reach 99.3% of maximum charge.

Discharge

How long does it take the capacitor to completely discharge?



The Filter Capacitor



Capacitor Discharging Time Constant

In 1 time constant, a fully charged capacitor will discharge to 36.8% of its full charge. In 5 time constants (5t) it will contain only 0.67% of its full charge. For our purposes we can assume that the capacitor is discharged after 5 τ. In our example, this is again 5 seconds.

The Power Supply Filter

The third circuit in our power supply is the filter.

- They reduce the variations in the rectifier output signal

Our goal is to produce a constant dc output voltage . The filter capacitor will remove most of the variations in our rectifier output waveform. The remaining voltage variation is called the ***ripple voltage Vr.***

The amount of ripple voltage left by a given filter depends on the three things:

1) Type of rectifier (half or full wave)
2) The the capacity of the fiter capacitor
3) The load resistance

The Filter Capacitor

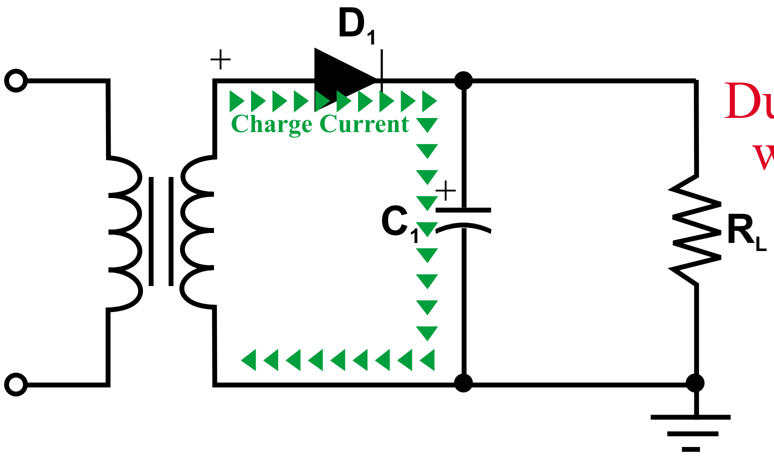
Power supplies are designed to produce as little ripple voltage as possible.

For Example

- In audio amplifiers, too much ripple shows up as an annoying 60 Hz or 120 Hz audible hum.
- In video circuits, excessive ripple shows up as “hum”bars in the picture.
- In digital circuits it can cause erroneous outputs from logic circuits.

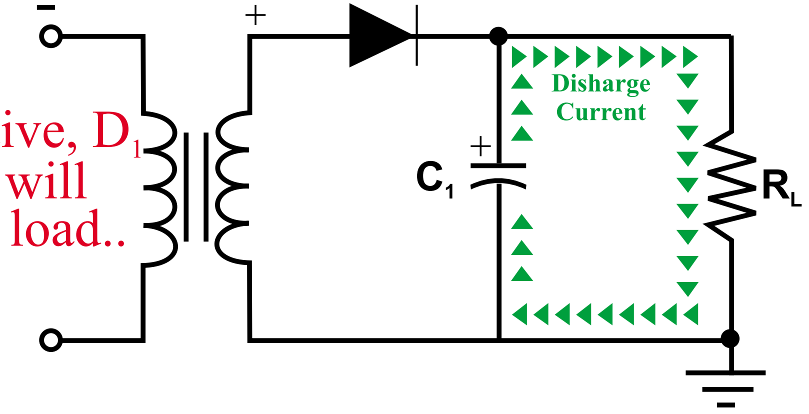
The Basic Filter Capacitor

The capacitor is the most basic filter type and is the most commonly used. It is simply a capacitor connected in parallel with the load as shown below.



During the positive half cycle, D_1 will conduct, and the capacitor charges rapidly.

As the input starts to go negative, D_1 turns off, and the capacitor will slowly discharge through the load..



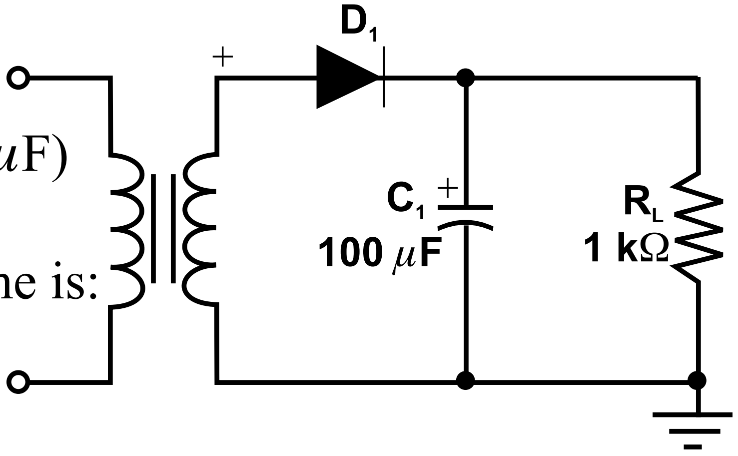
The Filter - Charge & Discharge

There are two distinct time constants in the filter circuit.

- The Charging Time Constant
- The Discharging Time Constant

The Charging Time Constant

In the diagram, if D_1 has a forward resistance of 5Ω, then the RC time constant is:



$$\begin{aligned}\tau &= RC \\ &= (5\Omega)(100\,\mu F) \\ &= 500\,\mu s\end{aligned}$$

and the total capacitor charge time is:

$$\begin{aligned}T &= 5(RC) \\ &= 5(500\,\mu s) \\ &\boxed{= 2.5\text{ ms}}\end{aligned}$$

Thus, the capacitor charges to the peak input voltage in 2.5 ms.

The Discharging Time Constant

The discharging path is through the load resistor. The discharge time constant is:

$$\begin{aligned}\tau &= RC \\ &= (1k\Omega)(100\,\mu F) \\ &= 100\text{ ms}\end{aligned}$$

and the total capacitor charge time is:

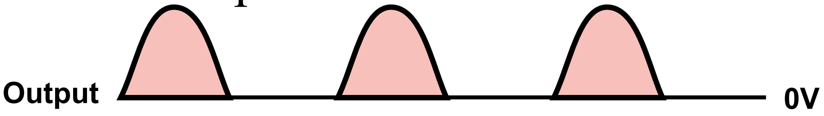
$$\begin{aligned}T &= 5(RC) \\ &= 5(100\text{ ms}) \\ &\boxed{= 500\text{ ms}}\end{aligned}$$

Note that the capacitor charges completely is short time (2.5 ms) , but it takes 500 ms to discharge. The next charging cycle is provided by the rectifier long before the capacitor is discharged.

Charging Time - Discharging Time What does it mean ?

Using the previous half wave rectifier as an example, we will examine what is happening with our filter.

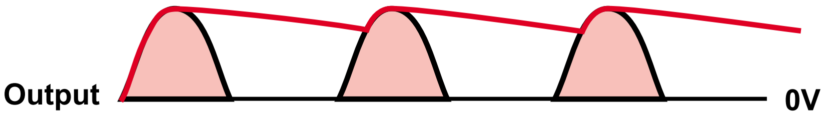
We know that our unfiltered output from the half wave rectifier looks like this.



If our capacitor charges in 2.5 ms, then it will fully charge on the first pulse from the rectifier. After the first pulse passes, there is slightly more than 8 ms before the next pulse from the rectifier arrives.

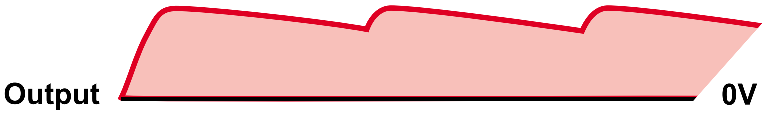
During this period of no input, the capacitor discharges through the load. If it takes 500 ms for the capacitor to completely discharge, then it will be still at a high charge after only 8 ms of discharge.

When the next pulse does arrive, it charges the capacitor back to full charge as shown. The red line shows the charge - discharge waveform at the capacitor.



What does the load see?

The load sees a reasonably constant dc voltage now, with a ripple voltage on top of it.

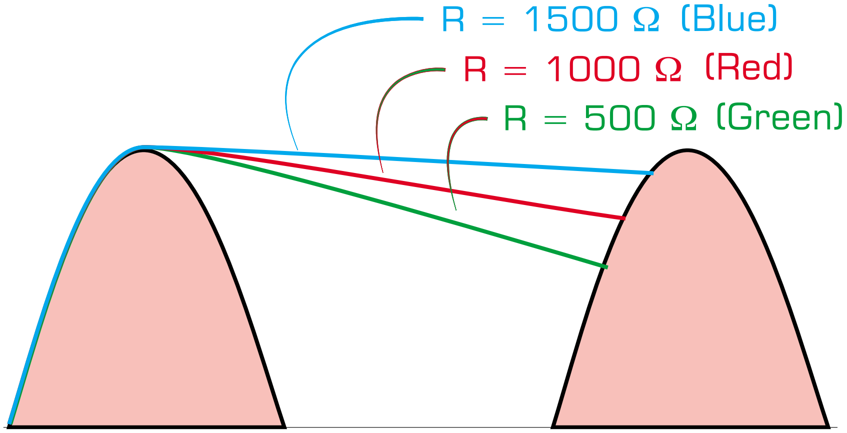


The Effects of R and C

How changing the load resistance affects Ripple.

What will happen to our ripple level if we changed the value of our load resistance. If the load resistance goes down , then a heavier current will be drawn from our supply.

Note that if R_L is 1000 Ω, then the capacitor discharges at the rate shown by the red line in the diagram.



Capacitor is constant & R_L is varied

If we decrease R_L to 500 Ω, then the capacitor discharges faster and more ripple voltage is present. This is indicated by the green line.

If we increase R_L to 1500 Ω, then the capacitor discharges at a slower rate and less ripple voltage is present. This is indicated by the blue line.

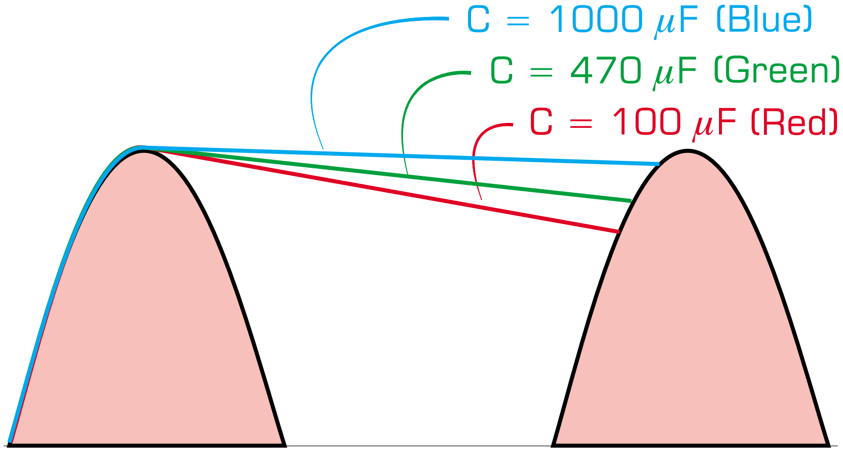
The Effects of R and C

How changing the the capacitance affects Ripple.

This time we will use a constant load resistance and we will use 3 different capacitance values to see how capacitance affects our output ripple.

The red line indicates our 100 μF capacitor that we have used in the example.

The green line indicates that by using a larger capacitance of 470 μF, that the output voltage does not drop to the level it was with 100 μF. This has reduced the ripple voltage.



Resistance is constant & C is varied

The blue line indicates that by using a larger capacitance of 1000 μF, that the output voltage does not drop to the level it was with 470 μF. This has reduced the ripple voltage further.

We can minimize ripple by:

- Using a large value of capacitance
- Using a high value of load resistance.
  There are practical limitations to both of these.

The Limits of R & C - How big (or small can they be)

The Load Resistance

Remember that, in reality, the load resistance is generally some other circuit that requires power. The resistance that it presents to our power supply is governed by its need for power.

This automatically limits the value of R_L to the needs of the load. If R_L was very high, then the output current would be very low, and our circuit being driven likely would not work.

The Capacitor

The value of C is limited by three factors:

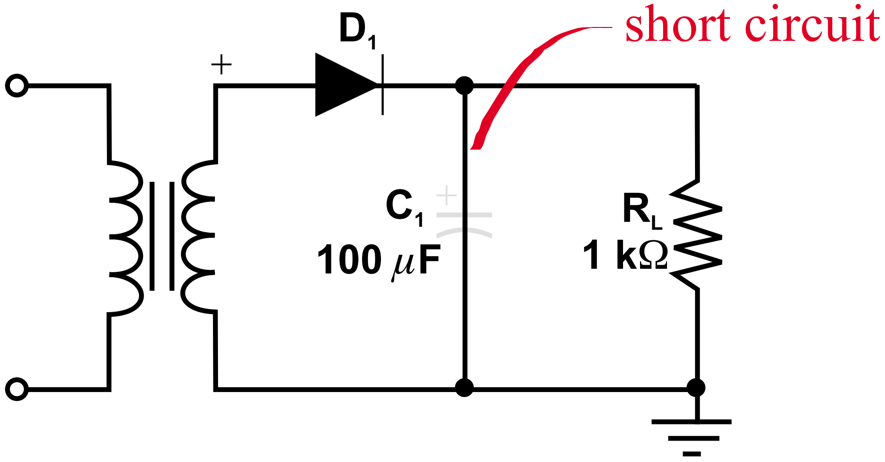
- The maximum allowable charge time for the component.
- The amount of surge current, I_{surge}, that the diodes can withstand
- The cost of "larger than needed" filter capacitors

The capacitor is not only involved in the discharge action. ***If you make the value of C too high,*** your discharge time will be greatly increased, ***but so will the charge time.***

If the charge time becomes too great, then the capacitor may never reach full charge from the incoming pulses from the rectifier.

The Filter Capacitor

When you first turn the power supply on, the filter capacitor has no accumulated charge to oppose V_2 . For the first instant, the capacitor appears as a short circuit.



This means that the current in the diodes is limited only by the transformer secondary winding resistance and the bulk resistance of the diodes. These resistances are generally very low, which means that the initial current will be extremely high.

The surge current is found as:

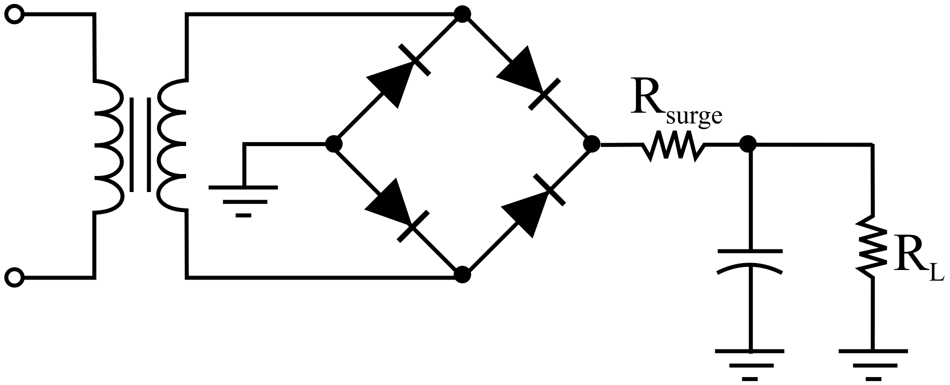
$$\boxed{I_{surge} = \frac{V_{2(pk)}}{R_W + R_B}}$$

where: $V_{2(pk)}$ = the peak secondary voltage
R_W = the resistance of the secondary windings
R_B = the total diode bulk resistance

Example 3-14 calculates the surge current. p 113

Surge Current (Cont)

The surge current can be very high but generally is not a problem. The 1N400X series of diodes has a non-repedative surge current (I_{FSM}) of 30 A. If your surge current will be above the value of I_{FSM}, then the problem can be resolved using a series current limiting resistor.



Surge current can also be limited by using a smaller capacitor Smaller capacitors charge in a shorter period of time

The formula is:

$$\boxed{C = \frac{I(t)}{\Delta V_C}}$$

where C = the capacitance in farads
I = the dc (average) charge/discharge current
t = the charge/discharge time
ΔV_C = the change in capacitor voltage during charge/discharge

If we need to find the charge/discharge time then re-arrange the above:

$$\boxed{t = \frac{C(\Delta V_C)}{I}}$$

The Filter Output Voltage

The Filter Output voltage (V_{DC}) is shown to equal $V_{(pk)}$ minus one-half of the peak-to-peak value of ripple voltage.

$$\boxed{V_{dc} = V_{pk} - \frac{V_r}{2}}$$

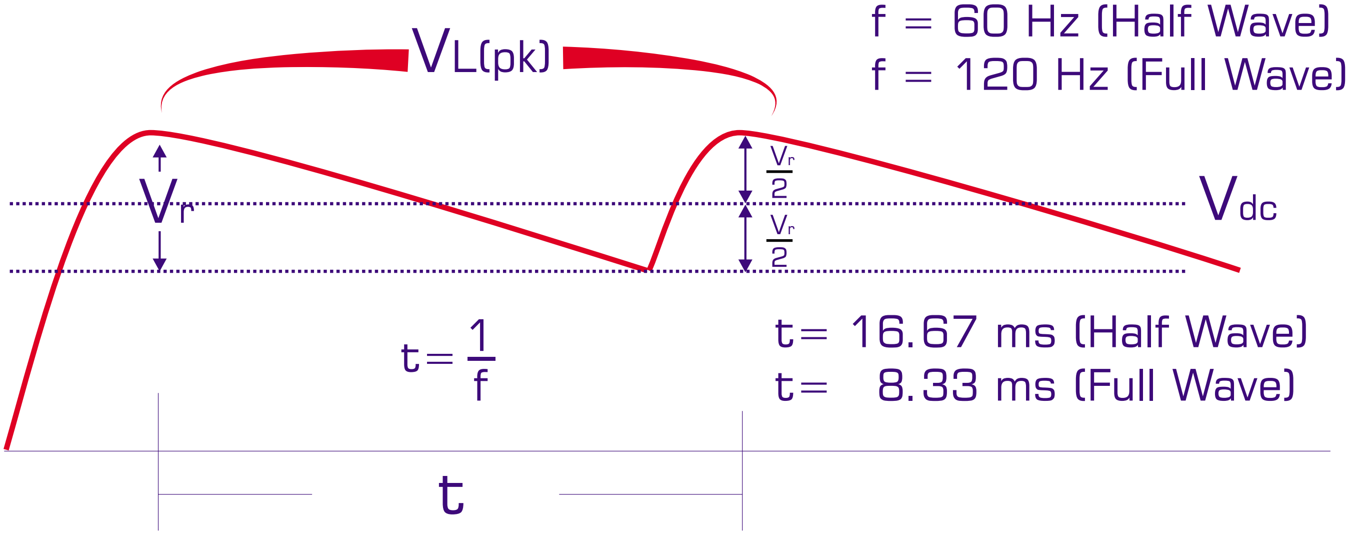
where $V_{(pk)}$ = the peak rectifier output voltage
V_r = the peak to peak ripple voltage

To find the ripple voltage Vr , use either of these two formulas:

$$\boxed{V_r = \frac{I_L t}{C}} \quad \textit{or} \quad \boxed{V_r = \frac{I_L}{f\,C}}$$

where I_L = the dc load current
t = the time between charging peaks
C = the capacitance in farads
f = the frequency in hertz

The Ripple Voltage



Finding V_{DC}

To find V_{dc}:

① Assume that $V_{dc} = V_{L(pk)}$

② Find the approximate I_L using $I_L = \frac{V_L}{R_L}$

③ Find the value of Vr $\boxed{V_r = \frac{I_L t}{C} \text{ or } V_r = \frac{I_L}{fC}}$

④ Find the new **actual** value of V_{dc} $\boxed{V_{dc} = V_{pk} - \frac{V_r}{2}}$

Example 3.15 & 3.16 page 115 - 117

Filter Effects on Diode PIV

Full Wave

The filter has no significant effect and the formulas are:

$$\boxed{PIV = V_{2(pk)} - 0.7\text{ V}}$$

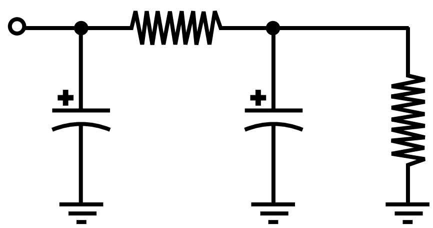
Half Wave

The half wave rectifier diode, when filtered, will have a *PIV of twice the secondary voltage*

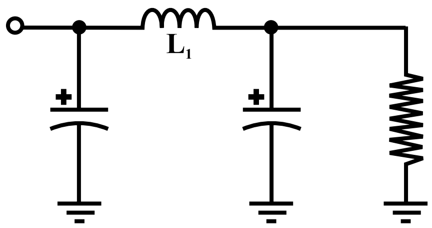
$$\boxed{PIV = 2\,V_{2(pk)}}$$

Other Filter Types

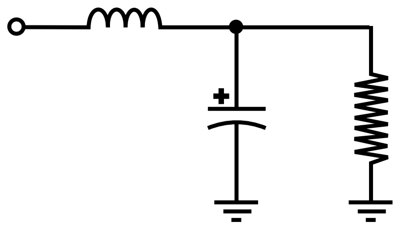
Each filter type shown here makes use of the reactance properties of capacitors and/or inductors. In each filter, the series impedance is designed to be very high, while the shunt impedance is designed to be very low Therefore, whatever ripple is not dropped by the series component is greatly reduced by the shunt component.



RC π filter



LC π filter

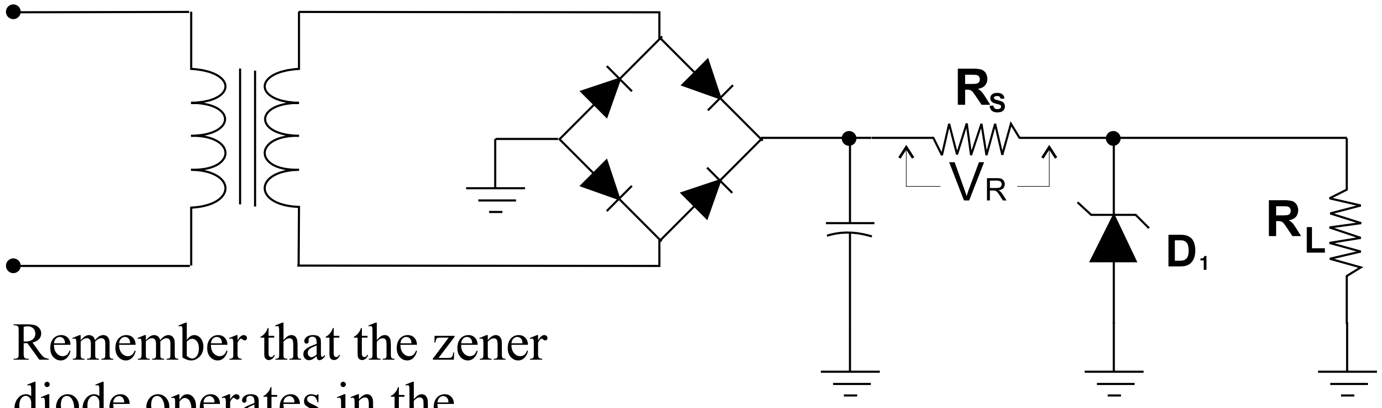


LC filter

Zener Voltage Regulators

The final circuit in the basic power supply is the voltage regulator.

Although there are many different types of voltage regulators, we will concentrate on the simple zener regulator as shown here.



Remember that the zener diode operates in the reverse breakdown region as shown in Figure 1.

The zener has almost a constant voltage across it as long as the zener current is between the knee current I_{ZK} and the maximum current rating I_{ZM}.

Since the load resistance is in parallel with the zener diode, the load voltage remains constant as long as the zener voltage remains constant.

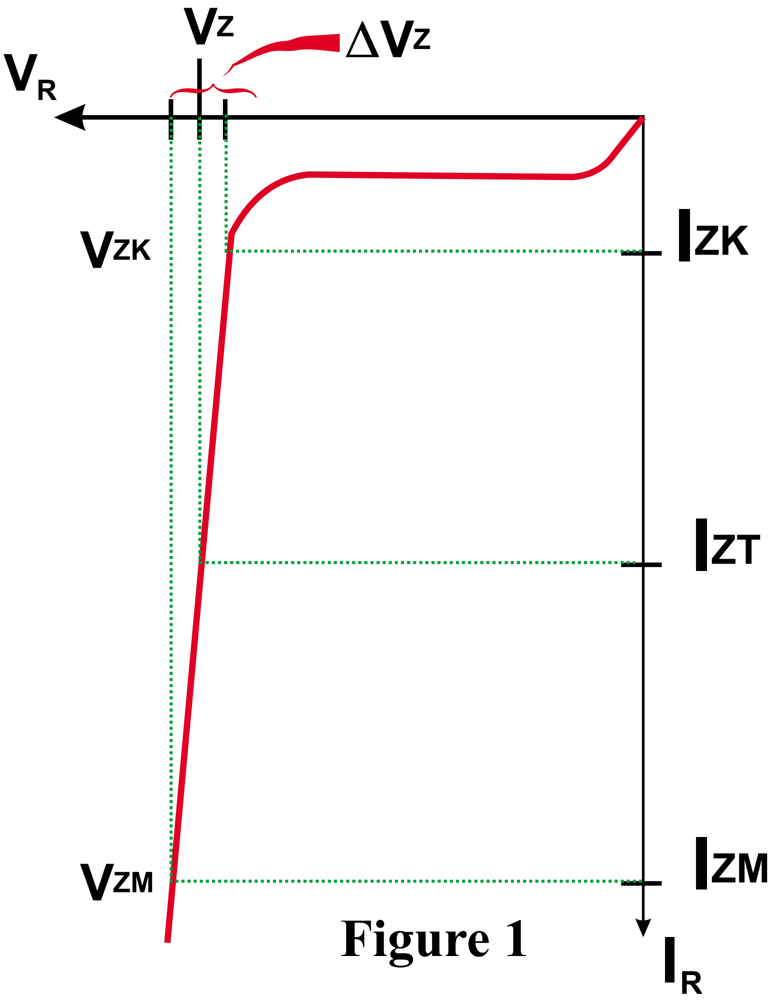


Figure 1

The Zener Regulator

If the zener current leaves the allowable range, the zener voltage, and the load voltage will change.

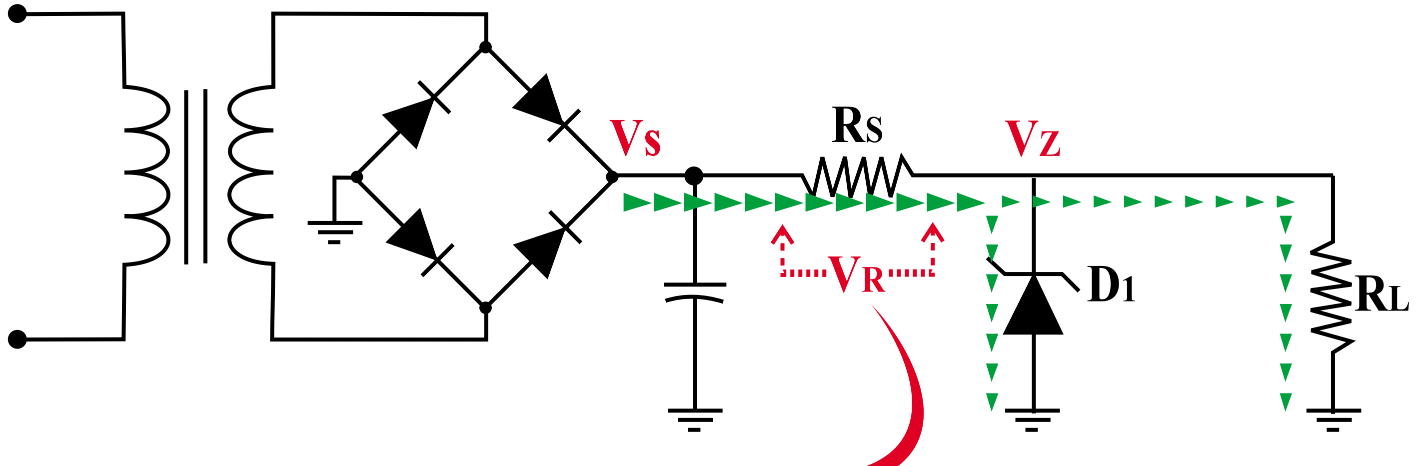
The key to keeping the load voltage constant is to keep the zener current within its specified range. (Between I_{ZK} & I_{ZM})

The Total Circuit Current

For the circuit below, the total current drawn from the source is:

$$\boxed{I_T = \frac{V_S - V_Z}{R_S}}$$

Where I_T = the total current drawn from the filtered rectifier
V_S = the source voltage
V_Z = the nominal (rated) zener voltage
R_S = the series resistor



$$V_R = V_S - V_Z$$

I_T is the total current passing through R_S. Since V_Z is known and V_S is known, then the voltage V_R can be found by subtraction. Now since the resistance of R_S is known, we can find I_T using Ohm's Law.

Example 3-17 Page 121 is an example of finding total current.

In Figure 2 below note that the total current (I_T) splits up and part passes through the zener diode and the rest passes through the load.

If we can find the load current, then finding the zener current is easy since it is simply whatever is left.

The load current is easy to find, since we know the load resistance and we know the voltage across the load is V_Z.

$$\boxed{I_L = \frac{V_Z}{R_L}}$$

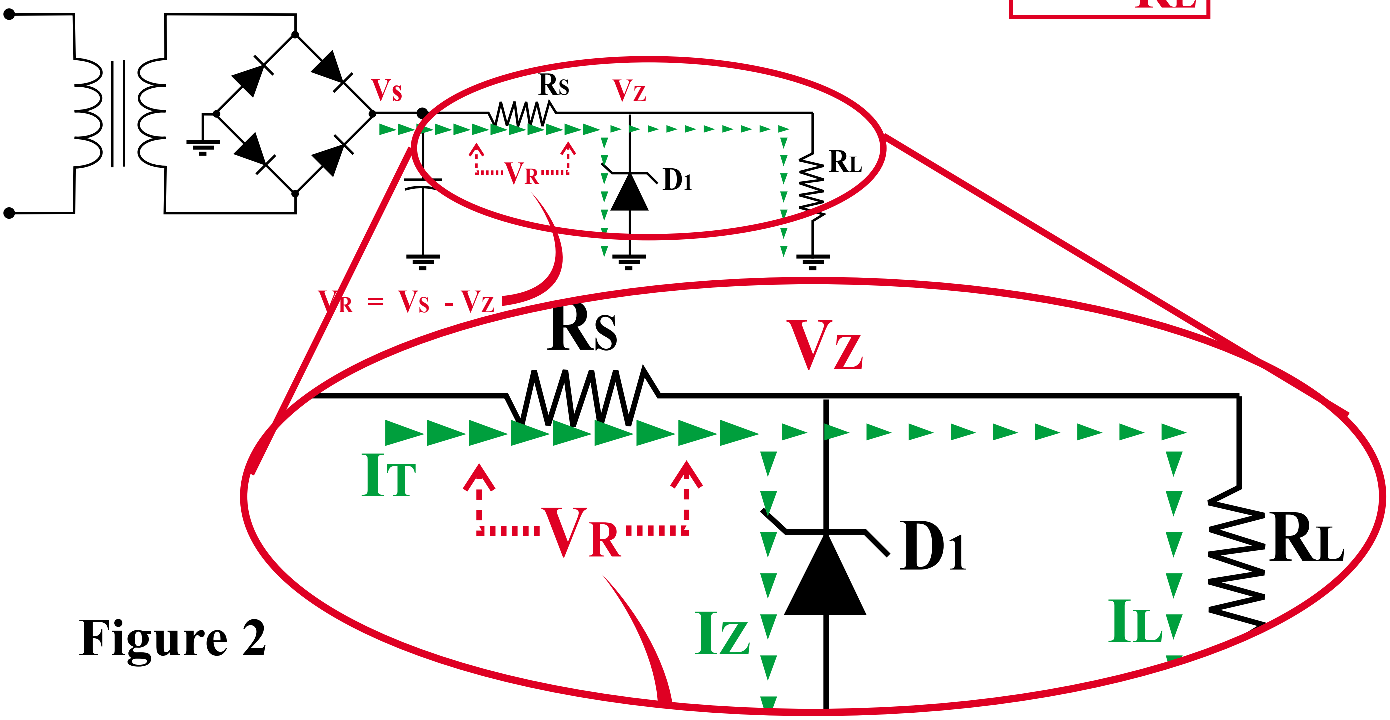


Figure 2

Now find I_Z

$$\boxed{I_Z = I_T - I_L}$$

Examples 3.18 & 3.19 find these currents.

See page 122

Load Regulation

A constant voltage will be maintained across the load if the zener current is maintained between I_{ZK} and I_{ZM}.

What happens with a varying load resistance? We will examine the two extremes.

Shorted load - In Fig. 3, the load resistance has dropped to zero. All the current now passes through the load and none passes through the zener. The zener current is now less than I_{ZK} (the knee current) and regulation is lost.

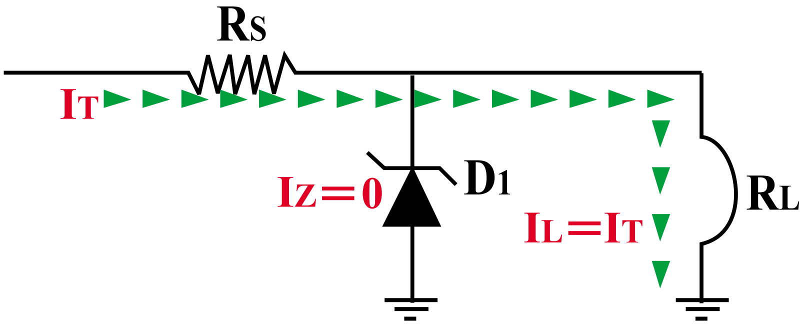


Fig 3 Load Shorted

Open Load - InFig. 4 the load resistance is infinity and no current passe through the load. Now all the current passes through the the zener diode. This is not a problem unless this current exceeds the maximum of I_{ZM}. If this happens, the zener will be destroyed. Here, R_S must be made large enough to prevent this from happening.

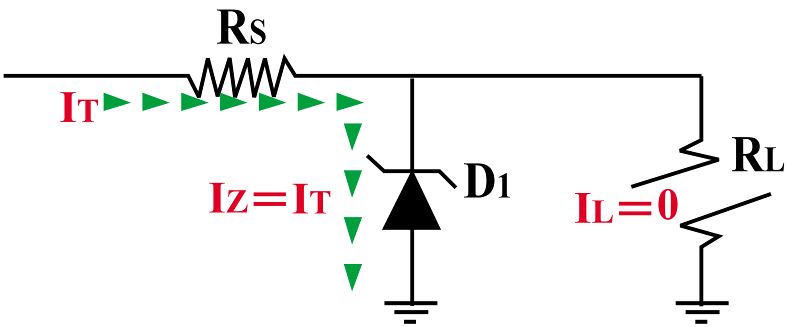


Fig 4 Load Open

The Minimum Value of R_L is determined by the zener voltage and the value of I_{ZK}. To maintain regulation, the minimum zener current is I_{ZK}. Then:

$$\boxed{I_{L(max)} = I_T - I_{ZK}}$$

Since $I_{L(max)}$ occurs when R_L is minimum, then:

$$\boxed{R_{L(min)} = \frac{V_Z}{I_{L(max)}}}$$

Example 3.20 page 123 finds the minimum allowable R_L

Zener Reduction in Ripple Voltage

The zener regulator, in addition to ***regulating the output***, also ***reduces the ripple voltage*** present at the output.

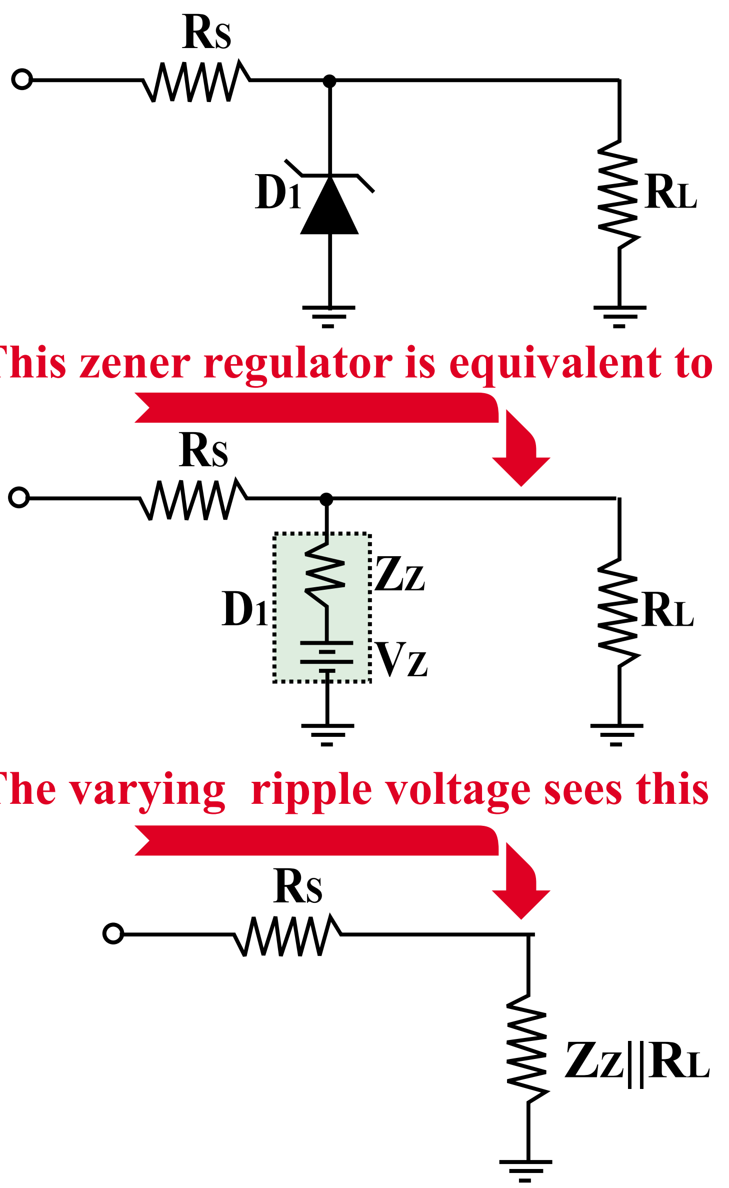
We know that Z_Z is an ac value called zener impedance. It must be considered in any analysis involving a change in current or voltage.

Since ripple voltage is a changing quantity , it is affected by Z_Z.

If we consider the circuits to the right, we can see that D_1 is really a series combination of V_Z and the zener impedance Z_Z.

The ripple voltage sees only R_S in series with the parallel combination of Z_Z and R_L.

This means that a voltage divider exists that affects the ripple voltage only.
Example 3.21 uses this equation.



This zener regulator is equivalent to

The varying ripple voltage sees this

This voltage divider circuit gives us this formula

$$\boxed{V_{r(out)} = \frac{(Z_Z \| R_L)}{(Z_Z \| R_L) + R_S} V_r}$$

Figure 6

The Final Analysis

Now we will put the four main parts of our power supply together into a complete basic power supply.

In Summary:

The Transformer	converts the incoming line voltage to a lower secondary voltage.
The Rectifier	converts the secondary ac voltage to pulsating dc voltage.
The Filter	reduces the variations in the rectifier dc output voltage.
The Zener Regulator	Performs two functions: 1) It reduces the ripple variations in the output voltage further than the filter can do alone. 2) It ensures that the dc output from the power supply will be relatively constant despite variations in load demand.

The following pages analyze a complete basic power supply to determine the values of dc output voltage, ripple , and load current

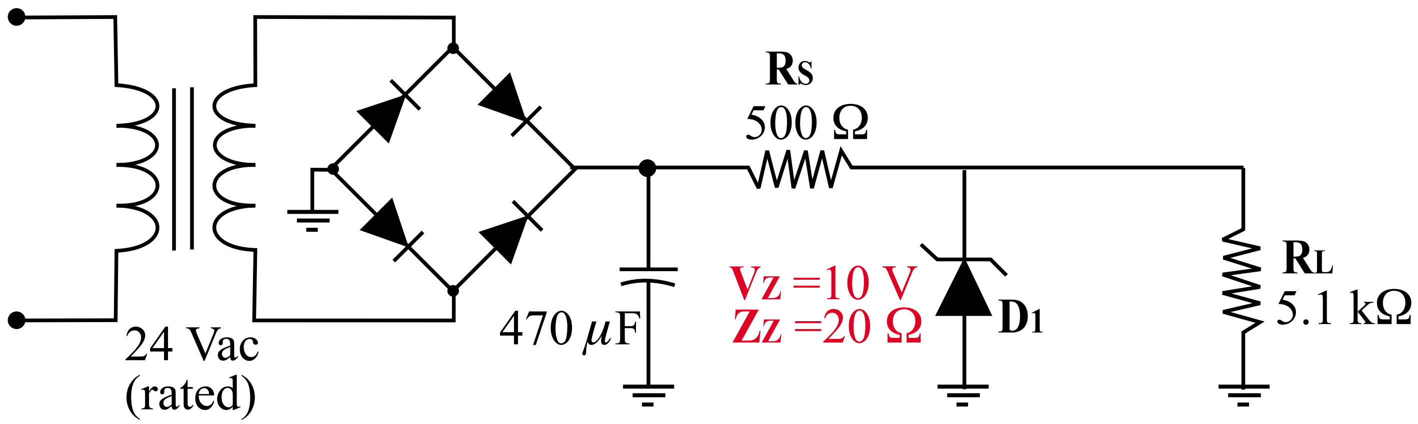
Analyzing the Basic Power Supply

Procedure for finding the values of V_{dc} , $V_{r(out)}$, and I_L

1/ Determine the *rms* value of the secondary voltage
2/ Determine the value of $V_{2(pk)}$
3/ Determine the value of $V_{(pk)}$ at the rectifier output.
4/ Determine the total current through the series resistor. (Call this current I_R)
5/ Determine the value of ripple voltage for the filter using the value of I_R determined above.
6/ Find V_{dc} at the output. (this value will be the V_Z rating of the zener diode in normal circumstances).
7/ Using the rated value of Z_Z, find the approximate final ripple voltage $V_{r(out)}$.
8/ Using V_z and R_L, determine the value of load current.

Example

Solve for the values of V_{dc}, $V_{r(out)}$, and I_L



1/ Determine the rms value of the secondary voltage.

The secondary “rated” value is given at 24 Vac. This is the rms value of the transformer secondary voltage.

2/ Determine the value of $V_{2(pk)}$.

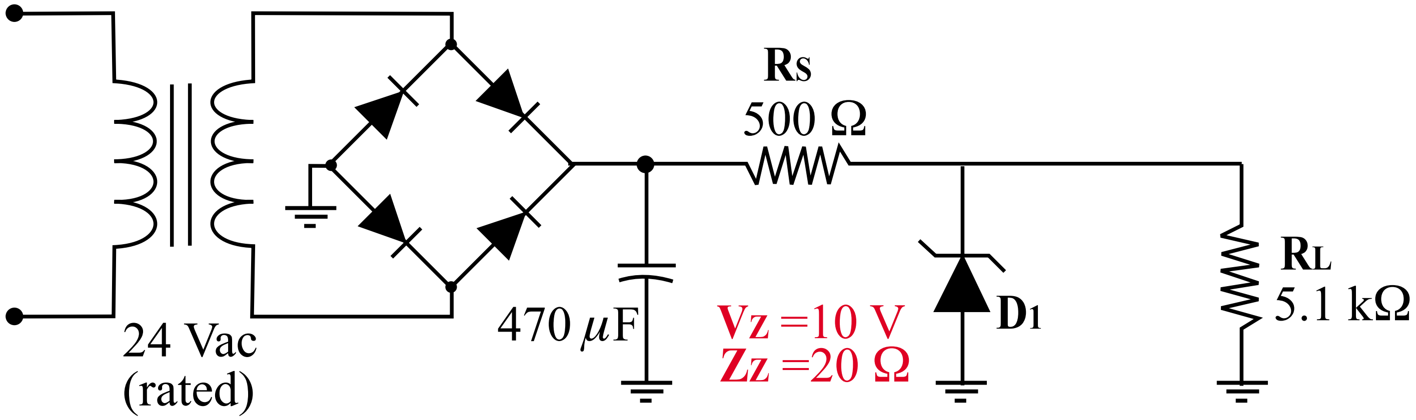
$$V_{2(pk)} = \frac{24\ \text{V}}{0.707} = 33.95\ V_{pk}$$

3/ Determine the value of $V_{(pk)}$ at the rectifier output.

$$\begin{aligned} V_{pk} &= V_{2(pk)} - 1.4\ \text{V} \\ &= 33.95\ V_{pk} - 1.4\ \text{V} \\ &= 32.55\ V_{pk} \end{aligned}$$

4/ Determine the current through the series resistor. Call this current I_R. Assume that V_{pk} found in step 3 is the dc source voltage V_S.

$$I_R = \frac{V_S - V_Z}{R_S} = \frac{32.55\ \text{V} - 10\ \text{V}}{500} = 45.1\ \text{mA}$$



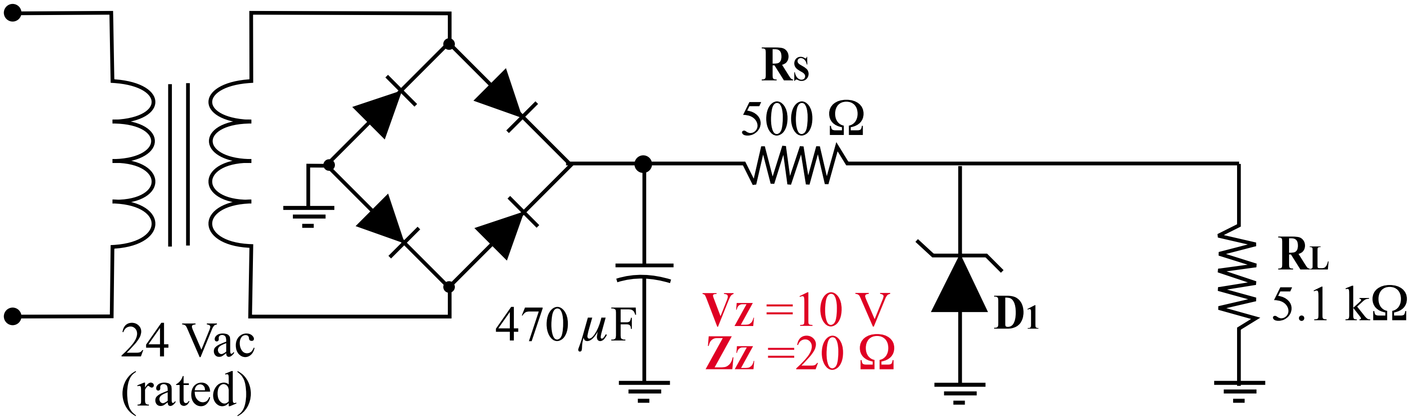
5/ Determine the value of ripple voltage from the filter using the value of I_R determined in step 4.

This is a full wave rectifier , therefore the frequency is 120 Hz and the period (T) is 8.33 ms.

$$V_r = \frac{I_{R(t)}}{C} = \frac{45.1\text{ mA}\,(8.33\text{ ms})}{470\,\mu\text{F}} = \frac{(45.1 \times 10^{-3})(8.33 \times 10^{-3})}{470 \times 10^{-6}} = 0.799\text{ V}_{p\text{-}p} \text{ or } 799\text{ mV}_{p\text{-}p}$$

Or

$$V_r = \frac{I_R}{fC} = \frac{45.1\text{ mA}}{120\text{ Hz}(470\,\mu\text{F})} = \frac{(45.1 \times 10^{-3})}{(120)(470 \times 10^{-6})} = 0.799\text{ V}_{p\text{-}p} \text{ or } 799\text{ mV}_{p\text{-}p}$$



6/ Find V_{dc} at the output. (this value will be the V_Z rating of the zener diode under normal circumstances.

$$\boxed{V_{dc} = V_Z = 10\text{ V}}$$

7/ Using the rated value of Z_Z, approximate the final output voltage

$Z_Z = 20\ \Omega$

$$V_{r(out)} = \frac{Z_Z \parallel R_L}{(Z_Z \parallel R_L) + R_S} V_r = \frac{19.92\ \Omega}{19.92\ \Omega + 500\ \Omega}\, 799\text{ mV}_{p\text{-}p}$$

$$\boxed{= 30.61\text{ mV}_{p\text{-}p}}$$

8/ Using V_Z and R_L, determine the value of load current.

$$I_L = \frac{V_Z}{R_L}$$

$$= \frac{10\ \text{V}}{5.1\ \text{k}\Omega}$$

$$\boxed{= 1.96\ \text{mA}}$$