ELEN-325. Part IV.

Diode's Applications

1.- The PN junction (diode).

The diode is a unidirectional device with two modes of operation: Forward bias when current can flow through the device and its intrinsic resistance is small and the second mode of operation is reverse biased. In the second mode of operation, the current flowing through the device is extremely small (less than 0.1 nA for most of the diodes used in micro-electronics applications), and the diode can be considered as an open circuit.

In forward bias region, the current flowing through the device is determined by the voltage applied to the diode; both parameters are approximately related as follows:

$$i_d = I_S\left(e^{\frac{v_d}{V_{th}}} - 1\right) \tag{4.1}$$

where I_S is the saturation current and V_{th} is the thermal voltage. The saturation current is function of the diode dimensions and other physical parameters, and its value is strongly affected by temperature variations; typical values are in the order of 10^{-10}-10^{-15} A. Usually its value increases by factor of two when the temperature increases by 10 degrees. The thermal voltage V_{th} is temperature dependent as well, and it can be computed by using the following expression

$$V_{th} = \frac{kT}{q} \tag{4.2}$$

where k is the Boltzmann constant (=); T is the temperature in kelvin degrees (300° K = 27° centigrade), and q is the fundamental charge of the electron (=1.6×10^{-19} C). At room temperature (300° K), the thermal voltage is roughly 26 mV. The symbol and typical i-v diode's curve are shown in figure 4.1

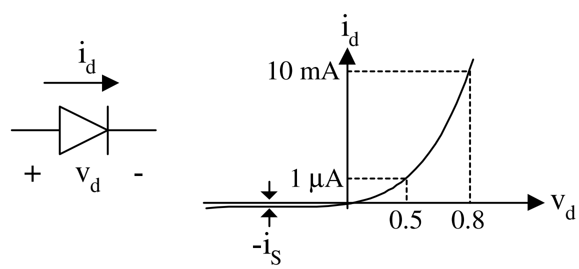

Fig. 4.1. Diode symbol and typical id-vd curve.

Since the I-v curve is obtained by sweeping the dc voltage across the diode at very low frequencies, none of the high frequency diode's limitations are then considered in this plot; the i-v plot is known as the DC diode's characteristics. For negative voltages, the diode operates as a very large resistor; the output current is around $-I_S$ (less than -0.1 pA) and in most of the practical cases it is negligible. For instance if -1 volt is applied to the diode's terminals the current flowing through it is around $-I_S$; if I_S=0.1 pA, the equivalent diode's resistance is in the order of r_{diode}=1V/0.1 pA=$10^{13}\Omega$.

The diode can be used for the processing of AC signals. The circuit shown in figure 4.2 for instance operates as an AC rectifier if the amplitude of the input signal is larger than 0.7V. The circuit can be described by the following equations:

$$\begin{cases} v_0 = i_d R_L = I_S R_L \left(e^{\frac{v_i - v_0}{V_{TH}}} - 1 \right) & \text{if} \quad v_i > 0 \\ v_0 = -I_S R_L \cong 0 & \text{if} \quad v_i < 0 \end{cases} \tag{4.3}$$

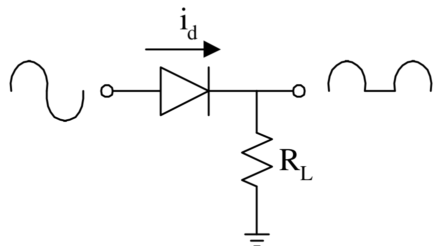

Fig. 4.2. A signal rectifier using a diode

Notice in equation 4.3 that the resulting circuit equation is non-linear and there is not a closed form solution. Usually computer based methods are used for plotting the output voltage as function of the input voltage. Even if the solution can be found for this case, practical cases might use more diodes, and the solution of the set of equations is quite complex. Thus, a simpler model must be found to be able to design more complex systems.

4.2 Simple switch model. In a first approximation, the diode can be considered as a switch: if current is flowing from anode to cathode, then it can be considered as a short circuit (v_d=0), otherwise it is considered as an open circuit (i_d=0) and current can not flow through it. A simple but approximated model is shown in Fig. 4.3.

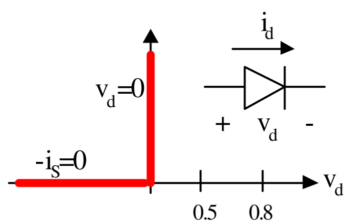

Fig. 4.3. Switch model for a diode

Although the model is very simple and inaccurate, especially when dealing with small signals, this model is very useful to understand the operation of the circuit. The results can be easily extrapolated if more elaborated models are used. To get some insight on the use of this model, let us re-consider the circuit shown in figure 4.2. For positive input signals, the current flows from anode to cathode, hence the diode operates in "on" condition, leading to the equivalent circuit shown in Fig. 4.3; this operation is illustrated in Fig. 4.4a. The output voltage is then $v_{out}=v_i$. The current flowing through the diode and resistor is then given by v_i/R_L.

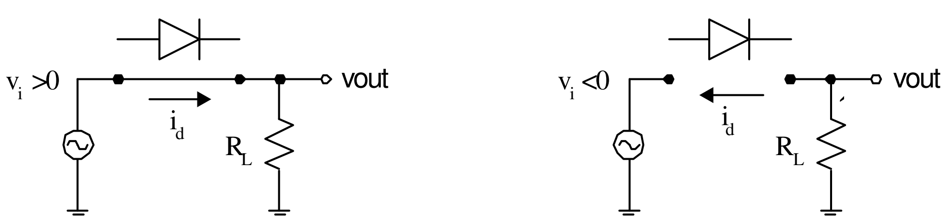

Figure 4.4. a) Equivalent circuit for vi>0 and b) equivalent circuit for the case vi<0.

For the case v_i <0, the current, if any, should flow from ground to v_i, that is in the diode's reverse direction. Due to the diode's characteristic, the reverse current is quite small and for this model it can be considered zero. The diode is represented as an open circuit as shown in Fig. 4.4. Since i_d=0, the resistor voltage drop is zero and consequently the

output voltage is zero, as depicted in Fig. 4.4b. Since only the positive output voltage appears at the output of the circuit, and output is zero during the negative half of the input signal this circuit is known as a half rectifier circuit.
The negative half rectifier circuit can be obtained if the diode is flipped, as shown in figure 4.5. When the input signal is negative, the current flow from ground to the input voltage, hence the diode operates in forward direction. The diode behaves as a short circuit, leading to and output voltage vout=vin. During the positive input cycle, the current should flow from input to output, which is in the diode's reverse direction. This current is quite small due to diode's operation, leading to zero output voltage since id is forced to be zero.

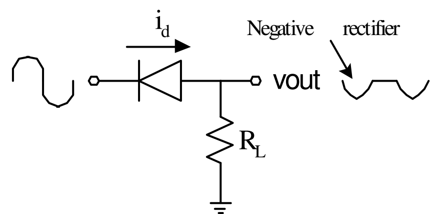

Figure 4.5. Half rectifier for the negative cycle.

Let us consider some other examples to get more intuition on the use of diodes in other applications, such as the topologies shown in Figure 4.6. The circuit shown in Fig. 4.6a is feed with a DC current source of 10 mA; two resistors and a diode are connected at the circuit's output. Since the current flows through the combination of resistors and diode, the current should flow in the diode's forward direction, and it can be considered as a short circuit. The load consists of two resistors of 1kΩ connected in parallel, leading to an equivalent load resistor of 500Ω; the output voltage is then approximately equal to vout=0.01x500=5V.
If the diode is reversed as shown in Figure 4.6b, the diode is off, and the load consists of a simple resistor of 1kΩ, leading to an output voltage of 10V.

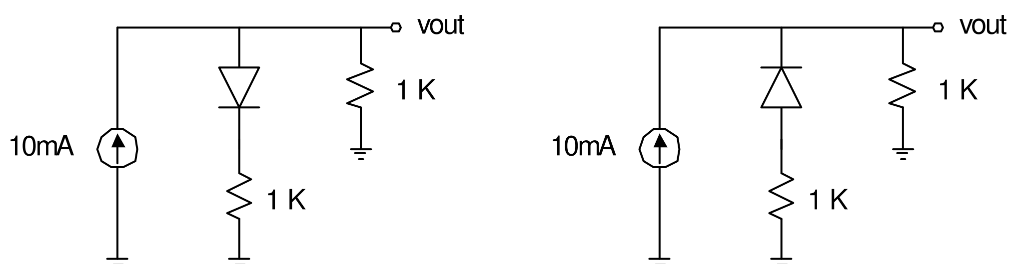

Figure 4.6. Current driven circuit with a) forward biased diode and b) same circuit with reverse biased diode.

The circuits shown in Fig. 4.7 are two examples of a voltage driven circuit. Notice that the current flows from the positive 10V voltage source down to the ground terminal. For figure 4.7a, the current flows through the diode in the forward direction, hence diode's voltage drop is zero limiting the output current iout =0 because the voltage-drop at the resistor in parallel with the diode is zero. The voltage drop and current flowing through the upper resistor of 1kΩ are 10V and 10 mA, respectively.
The diode used in the circuit shown in Fig. 4.7b is connected in reverse direction. Current can not flow through the diode, hence it can be considered as an open circuit. Therefore, the current flowing through both resistors is the same, and can be computed as iout=10V/2kΩ=5mA. The voltage measure at diode's terminals is 5V, with its anode being at 0V and its cathode at +5V.

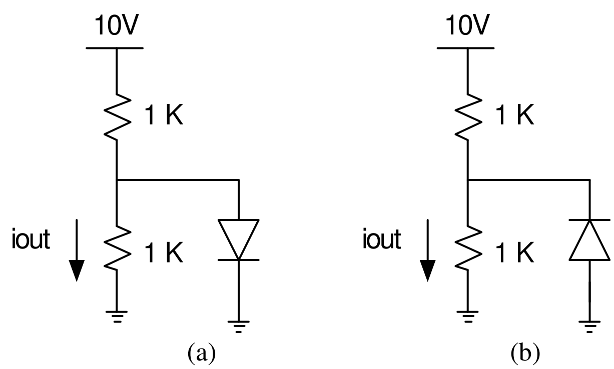

Figure 4.7. Voltage driven circuit with a) forward biased diode and b) same circuit with reverse biased diode.

4.3 More accurate diode's model. A rudimentary but more accurate model takes into account the voltage drop across diode's terminals, as shown in Figure 4.8; that diode's voltage drop is current dependent and has to be computed using diode's equation. The forward diode's voltage is usually in the range of 0.5-0.8 volts. Although not accurate, the results are closer to the actual values if a voltage drop of 0.7 V is used when the diode is forward bias; this model is depicted in figure 4.8. If diode's current is positive, then the diode is modeled by a fixed DC voltage source of 0.7 Volts; be aware that some textbooks and data sheets use a voltage drop of 0.65V. Although it is arbitrary, as a rule of thumb the diode's voltage drop can be approximated as 0.65V if small DC currents are used (< 1mA), 0.7V if 1mA<id<10mA and 0.8 if 10mA<id.

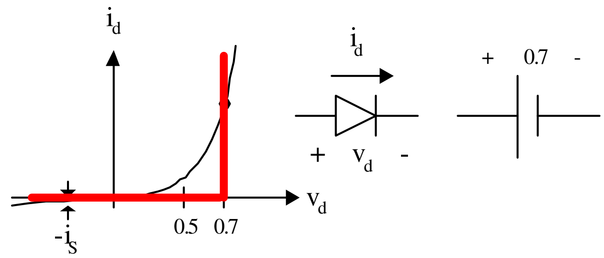

Figure 4.8. Diode's model using a constant DC voltage.

The numerical results obtained from this model are certainly more accurate than those obtained with the switch model. As an example, let us consider the circuit shown in Figure 4.7a in which the diode's voltage drop is approximated by a 0.7V battery; the equivalent circuit using this model is shown in Figure 4.9. In this case, iout=0.7V/1kΩ=0.7 mA while ix=4.3V/1kΩ=4.3 mA. Notice that these values are very different, especially iout, than the ones obtained from the switch model: iout=0 mA and ix=5 mA.

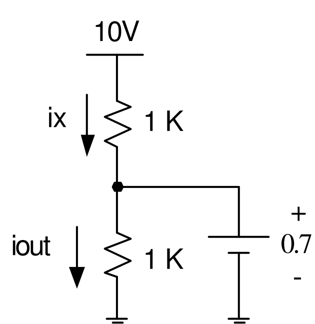

Figure 4.9. Equivalent circuit using the 0.7V diode's model.

Although useful, the previous models do not consider the fact that diode's voltage is a function of diode's current; a more accurate model should consider this fact. The simplest model that is used in most of today's applications is based on the combination of the DC battery plus a series resistor, as shown in figure 4.10. The question that arises now is how to compute resistance value.

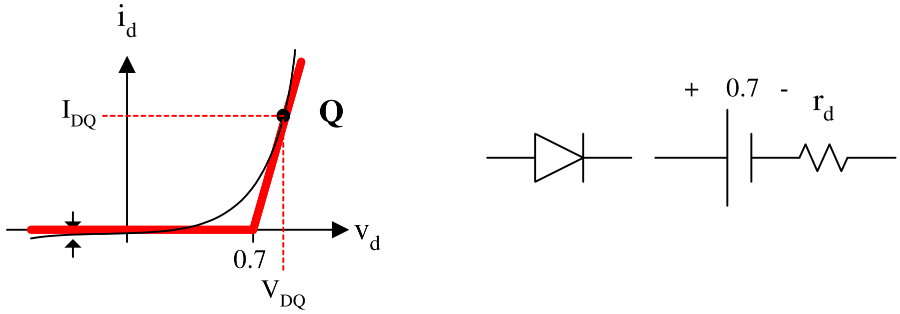

Figure 4.10. More accurate diode's model using a battery and a series resistor

To solve this issue, let us consider the diode's equation (1), repeated here for convenience.

$$i_d = I_S\left(e^{\frac{v_d}{V_{th}}} - 1\right) \tag{4.4}$$

What is done in Figure 4.10, is to approximate the non-liner diode's equation by a piece wise linear function composed by two straight lines such that

i) i_d=0 if the diode's voltage $v_d \le 0.7$V
ii) i_d= (v_d-0.7)/rd if v_d>0.7V.

Notice in Figure 4.10 that the actual value of the current (equation 4.4) and the one resulting from the piecewise linear model are the same at point Q, which is usually termed as the operating point. Q, defined by I_{DQ} and V_{DQ} (current and diode's voltage evaluated at the operating point), is selected based on the application and the characterization conditions of your device. At this point and for best curve fitting, the slope of the two curves should be the same, leading to the following condition

$$\left.\frac{\partial i_d}{\partial v_d}\right|_Q = \left.\frac{\partial I_S\left(e^{\frac{v_d}{V_{th}}} - 1\right)}{\partial v_d}\right|_Q = \left.\frac{I_S e^{\frac{v_d}{V_{th}}}}{V_{th}}\right|_Q = \frac{\left.I_S\left(e^{\frac{v_d}{V_{th}}} - 1\right)\right|_Q + I_S}{V_{th}} = \frac{I_{DQ} + I_S}{V_{th}} \cong \frac{I_{DQ}}{V_{th}} = \frac{1}{r_d} \tag{4.5}$$

In the previous equation, it is assumed that the diodes's current at Q I_{DQ} is much larger than I_S, this approximation is reasonable since I_S<1nA for most of the diodes. Manipulating equation 4.5 it leads to the following formula for the computation of diode's resistance

$$r_d \cong \frac{V_{th}}{I_{DQ}} \tag{4.6}$$

Usually the solution of circuits involving diodes involve two or three iterations before we endup with reasonable results. For instance, let us consider again the half-wave rectifier discussed in the previous section. Assuming that the a sinusoidal input signal with a peak value of 10 volts and a load resistor RL=10 kΩ are used, the output signal output for the three diode's models previously discussed can be computed as follows.

i) If the ideal switch model is used, during the positive cycle the diode is ON, and the output voltage follows the input; the output's peak value in this case is 10 V, as depicted in one of the traces shown in 4.11. The peak diode's current is then equal to 1 mA.

ii) If the constant voltage drop model is used, when the input signal is greater than 0.7V, the diode is ON, and the voltage drop through it is approximately 0.7 Volts. The output peak value is then equal to 9.3 Volts. Under these conditions, the diode's peak current is computed as 0.93 mA.

iii) If the diode's resistance is used, then the diode's current must be computed before the output voltage can be computed. Assuming that the diode's peak current is not affected by the series resistor (which is not correct!) from item ii), the diode's resistance is in the order of r_d=26 mV/0.93 mA=28Ω. With this first order approximation, a more accurate current value can be computed using I_{DQ}=9.3V/10.028kΩ=0.927 mA, which is relatively close to the previous value. The voltage drop through diode's resistor is only 28x0.927 mV=26mV. The output peak's value is then computed as V_{out-pk}=10-0.7-0.026V=9.274 V.

These three cases are plotted in Figure 4.11.

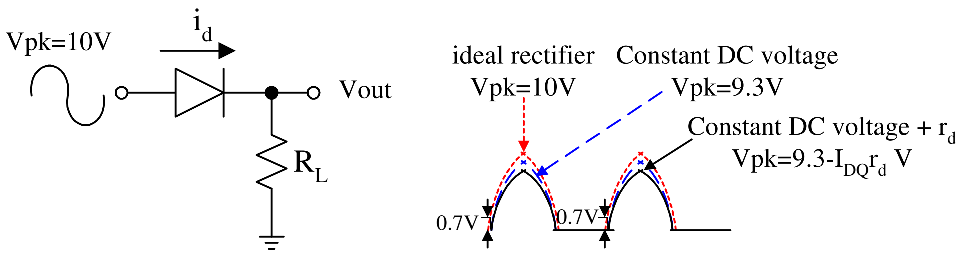

Figure 4.11. Half wave rectifier illustrating the differences between the three models.

2.4. Peak Detectors and AC-to-DC converters. The peak value of the input signal can be detected if the load resistor of the half-wave rectifier is replaced by a grounded capacitor; the resulting circuit shown in Figure 4.11 operates as a peak detector. To understand the operation of the peak detector, let us assume that the diode is ideal. If the initial condition of the capacitor is zero, as long as the input signal is greater than zero, the diode is on, and the output voltage follows the input signal, provided that the input signal increases. As long as the input signal decreases, the polarity of the voltage across the diode changes; notice that the output voltage is held by the capacitor. The only way the output voltage decreases is extracting current from the capacitor, but the diode is unable to do that since it can not handle negative current flowing through it. Therefore, the diode is off until the input voltage becomes greater than the voltage held by the capacitor. Theoretically, if the input signal does not exceed the voltage value stored in the capacitor CL, the capacitor should hold this value forever; in practice the diode has a negative leakage current I_S that will extract a small amount of negative current that eventually discharge the capacitor.

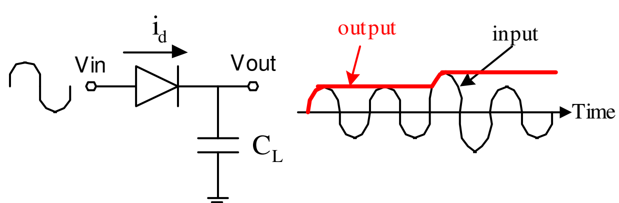

Fig. 4.12. Simple peak detector circuit.

Notice that the previous circuit is able to extract the peak value of the signal, however if glitches are present in the system, the peak value could not be the real information. Hence, some losses are included on purpose to partially discharge the capacitor to have a more robust solution at the expense of lower precision; the circuit is shown in the following figure. When the value of the input signal increases beyond the previously stored output voltage the diode is on, and the output follows the input. Assuming an ideal diode, the equation for the output voltage is

$$v_{out} = v_{in} \quad \text{for} \quad t_1 - T \le t \le t_0 \tag{4.7}$$

At the time t=t_0, v_{in}=V_{peak}, afte this time the input signal goes down; the output voltage is partially sustained by the capacitor, hence the diode is reverse biased operating as an open circuit. Since the diode is off when t_0<t<t_1, the capacitor is discharged through the load resistor R_L; during this time period, the output voltage is determined by the first order differential equation $i_{CL}+i_{RL}=C_L(dV_{out}/dt)+V_{out}/R_L=0$ whose solution is given by the following expression (check this result!)

$$v_{out} = V_{peak} e^{-\frac{t-t_0}{R_L C_L}} \quad \text{if} \quad t_0 \le t \le t_1 \tag{4.8}$$

The parameters to be determined are t_1-t_0 and the voltage ripple $V_{ripple}=(V_{peak}-V_{out}(t_1)$. The output voltage ripple determines the quality of the AC-to-DC converter; the smaller the ripple the better the converter is. To facilitate the computations, let us assume that our time reference is such that $t_0=0$. The output signal reaches the peak value at $t=t_0=0$ and decreases until the input signal increases such that the following condition is met

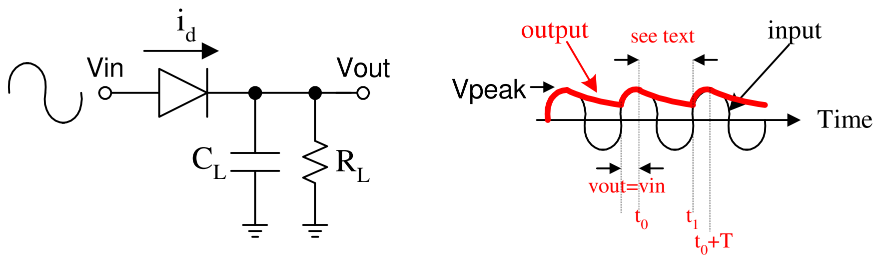

Figure 4.13. AC-to_DC converter using a half wave rectifier. This circuit is also known as Peak/envelope detector with resistive losses; frequently used in old FM radio demodulators.

$$V_{peak} \cos(\omega_0 t_1) = V_{peak} \cos\left(2\pi\left(\frac{t_1}{T}\right)\right) = V_{peak} e^{-\frac{t_1}{R_L C_L}} \tag{4.8}$$

The solution of the previous equation at $t=t_1$ is not trivial since it is non-linear and has to be solved using numerical methods. A simple and useful solution is obtained if we assume that the ripple is small, hence t_1~T. The easiest way to get an approximated solution is expanding the exponential function in a taylor series

$$e^{-\left(\frac{t_1}{R_L C_L}\right)} \cong 1 - \left(\frac{t_1}{R_L C_L}\right) - \frac{1}{2}\left(\frac{t_1}{R_L C_L}\right)^2 - .... \tag{4.9}$$

If the resistor and capacitor are selected such that t_1, T<<$1/R_LC_L$, the higher order terms can be neglected and the output voltage can then be approximated as follows

$$V_{out}(t) = V_{peak} e^{-\frac{t}{R_L C_L}} = \left(1 - \left(\frac{t}{R_L C_L}\right)\right) V_{peak} \tag{4.10}$$

If t_1~T, then the normalized ripple voltage $(V_{peak}-V_{out})/V_{peak}$ becomes

$$V_{ripple}(\%) \cong \frac{V_{peak} - V_{out}(t = t_1 \cong T)}{V_{peak}} \cong \frac{T}{R_L C_L} = \frac{T}{\tau} \tag{4.11}$$

Where T is the period of the input signal and $R_LC_L=\tau$ is the circuit's time constant. For smaller ripple, increases as much as possible τ. Equation (4.11) is very simple and give you a clear indication on how to design a small ripple AC-to-DC converter. Just make the ratio T/τ < ripple specification; 10% ripple means that $T/\tau<0.1$.

Full wave rectifiers. To reduce the ripple, a transformer is typically combined with diodes to get full-wave rectification; the classic full-wave rectifier with output filter is shown in figure 4.14 can be used. A center tapped transformer is employed to generate fully-differential output signals that are rectified by the diodes. To understand the operation of the circuit, let us assume that the voltage on the secondary of the transformer is such that the voltage in the upper terminal is positive while the voltage at the bottom terminal is negative. Under these conditions the upper diode is ON and the lower diode is OFF, as depicted in Figure 4.14. The positive signal is then transferred to the output leading to a peak output voltage equal to the peak value of the secondary of the transformer minus the 0.7 voltage drop due to diode's forward voltage. The operation repeats during the following half cycle but now the bottom diode is ON while the top diode is OFF. If the circuit is not capacitive loaded, the output will be a rectified version of the input signal. The ripple can be further minimized if a capacitor is connected in parallel with the load, as depicted in Figure 4.15.

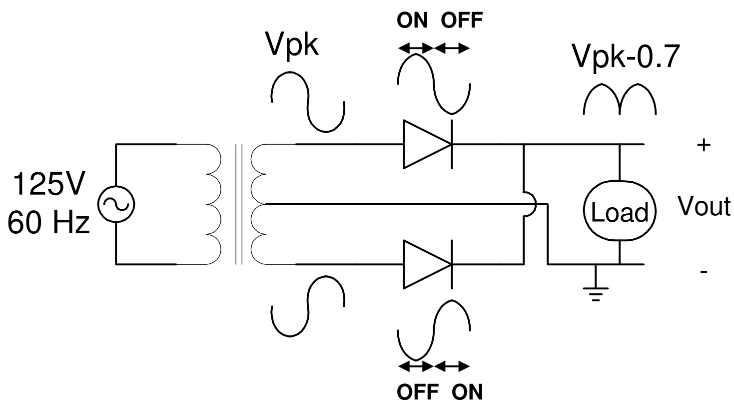

Figure 4.14. Typical full wave rectifier with a centered tap transformer available.

The circuit can be analyzed in a similar way as the one shown in Fig. 13; the main difference is that this topology is a full-wave rectified where the period of the rectified signal is T/2. As a result, the output ripple can be computed as follows:

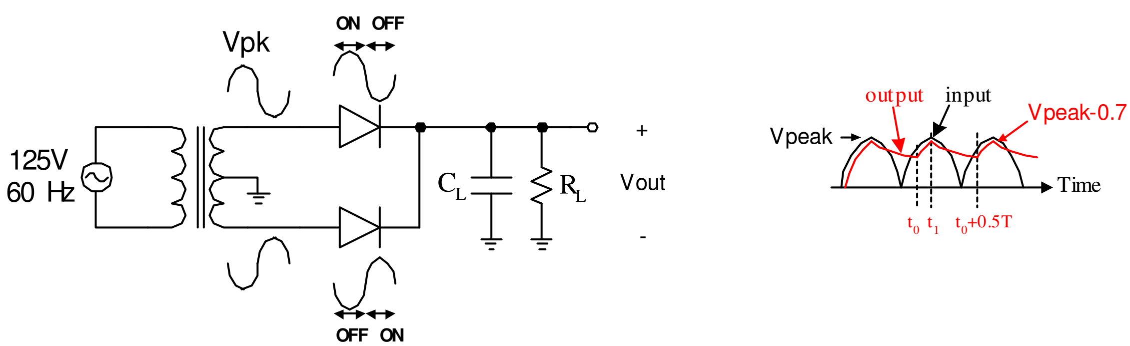

Figure 4.15. Full wave rectifier using a center-tapped transformer.

$$V_{ripple}(\%) \cong \frac{V_{peak} - V_{out}(t \cong T/2)}{V_{peak}} \cong \frac{T}{2R_L C_L} = \frac{T}{2\tau} \tag{4.12}$$

Evidently the ripple in a full-wave rectifier is half of that of the single rectifier. This is a major advantage in this circuit, and is the result of using the two transformer output phases and the diodes. If the transformer is not fully balanced, such that the peak output voltage in both outputs is the same, the output ripple will increase since it is affected by the peak value of the two outputs. It is however not easy to maintain a good output balance in center tapped transformers. The topology shown below in Figure 4.16 overcomes this drawback since it uses non-center tapped transformer.

This structure is a full-wave rectifier using an array of four diodes such that two diodes are ON and two are OFF depending on the polarity of the input signal. The capacitor CL is used to minimize the output ripple as discussed in the previous topologies; since this is a full-wave rectifier, ripple should be computed using equation 4.12.

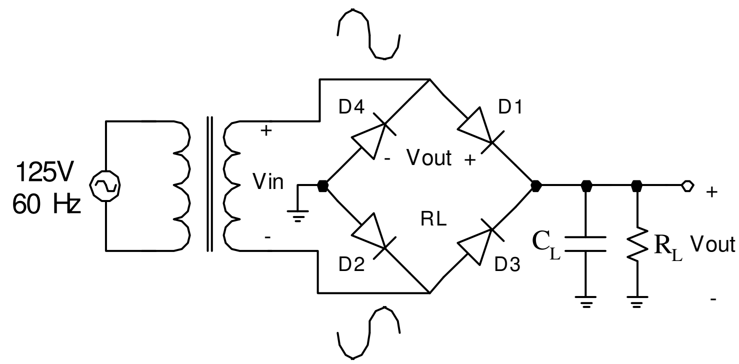

Figure 4.16. AC-to-DC converter using a full wave rectifier using a non center-tapped transformer.

To get some insight on the operation of the circuit, let us to remove the capacitor and analyze the simplified version of the rectifier depicted in Figure 4.17. During the positive cycle, the upper transform terminal is positive and diodes D1 and D4 are ON and OFF, respectively. Since the voltage at the transformer bottom terminal is negative, D2 and D3 are ON and OFF, respectively, leading to the equivalent circuit depicted in Fig. 4.18. This circuit will be fully explained in class

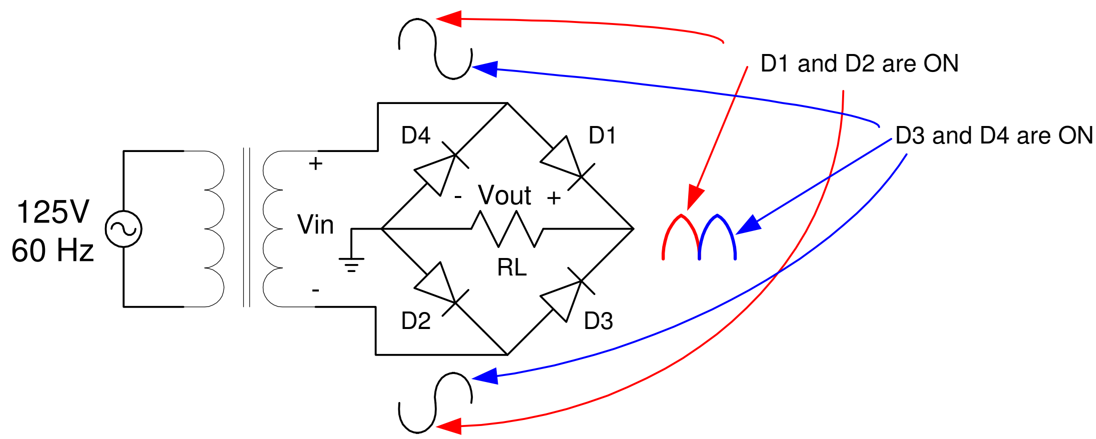

Figure 4.17. Full wave rectifier using a floating transformer.

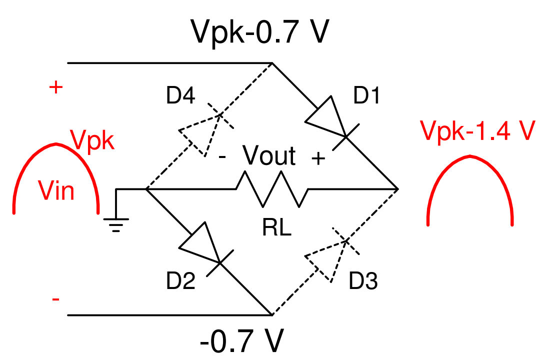

Figure 4.18. Equivalent circuit for the Full wave rectifier during the positive cycle.

The typical AC-to-DC converter is depicted in Figure 4.16. Due to time constraints we will not cover the entire system, but if you are going to work in power generation or power management you have to deal with this type of architectures.

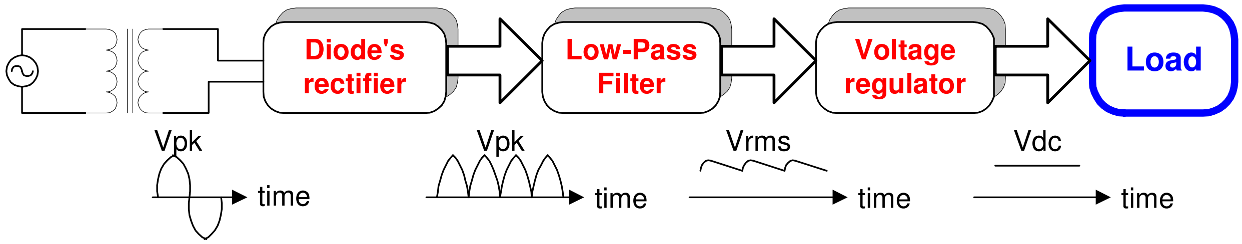

Figure 4.16. Typical architecture of a AC-DC converter.