## PDHonline Course E406 (3 PDH)

# Low Voltage Power Supplies I

*Instructor: Bart Greene, PE*

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5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

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# Low Voltage Power Supplies I

*Bart Greene, MSEE, P.E.*

## 1. Introduction

Low Voltage Power Supplies are a key component of electronics-based products such as televisions, radios, personal computers, smartphones, solar systems and almost all electronics systems. Power Supplies convert energy in one form to another form useful in providing power to a load for a particular application.

This course addresses fixed voltage power supplies where the input source to the supply is either an Alternating Current (AC) source such as the AC voltage from a wall outlet or a Direct Current (DC) voltage source such as a battery or solar panel. The output is a fixed DC voltage. The courses specifically targets techniques for designing power supplies where the output voltage of the supply is 24VDC or less and the output current that can be delivered to a load is less than 20A.

Section 2 defines measures of performance or figures of merit for power supplies that are the basis for comparing and specifying power supplies. Section 3 covers the unregulated AC-DC power supply. Section 4 covers Voltage Regulators and DC-DC Converters.

## 2. Performance Measures

In this section, four of the most important performance measures are defined. These measures can be considered figures of merit for a particular supply. When comparing commercial supplies, these performance measures are used to compare the relative quality of two or more supplies. When designing supplies, these terms are used to specify design requirements and their values are determined by the needs of the application in which it will be used.

## a. Power Rating

The **Power Rating** ($P_{MAX}$) is the maximum power a supply can deliver to a load and is expressed in Watts (W). There are a number of characteristics of a supply that can be derived from this rating that are useful in understanding a supply and its use.

The maximum output current ($I_{MAX}$) that can be supplied at the nominal DC output voltage ($V_{OUT}$) can be determined from the Power Rating. Using the DC power formula P = V x I;

$$I_{MAX} = P_{MAX} / V_{OUT}$$

Knowing the maximum output current, the minimum load resistance ($R_{LMIN}$) the supply can drive can be determined. Using Ohm's Law V = I x R;

$$R_{LMIN} = V_{OUT} / I_{MAX}$$

Power Rating and its derived current/resistance parameters are important in that they need to be adequate for the application in which they will be used. Knowledge of the characteristics of the load are required to design or select a supply. Often the first performance measure considered in selecting a supply is the Power Rating.

## b. Line Regulation

**Line Regulation** is a measure of the amount of change in the output voltage due to change in the input voltage and is expressed as a percentage. For an AC-DC power supply, the change in input voltage refers to the change in RMS Voltage at the input. For DC-DC power supplies, the input voltage refers to variations of the input DC voltage. The formula for calculating the line regulation is:

$$\text{Line Regulation} = 100 \times \frac{\left|V_{OUT\ MAX} - V_{OUT\ MIN}\right|}{\left|V_{IN\ MAX} - V_{IN\ MIN}\right|}$$

Line Regulation is usually defined for a fix load resistance. In most cases, $V_{OUT\ MAX}$ will be the output for an input of $V_{IN\ MAX}$ and $V_{OUT\ MIN}$ will be the output due to and an input of $V_{IN\ MIN}$. However, this does not have to be the case so the equation includes absolute values if the opposite is true.

While this equation is the most common definition of line regulation, it is worth noting that other components can affect the output voltage and strictly speaking could be included in a more complete definition of the term. Examples are variations in frequency of AC inputs, thermal characteristics of passive components in the system and variations in the load itself. However, for comparison purposes, this definition is the most useful. The main use of this performance measure is matching the input voltage characteristics to the input voltage sources that will be encountered by the supply.

Power supply line regulation is in the order of 0.01% for commercially available supplies.

## c. Load Regulation

**Load Regulation** is a measure of how much the output voltage will change due to changes in the output current drawn from the supply. This is equivalent to how much the output voltage will change due to changes in the load resistance. Load Regulation is expressed as a percentage also. There are two common definitions of Load Regulation. The first definition is Load Regulation is a comparison of output voltage changes to the output voltage at some nominal load resistance. The second is a comparison of the output voltage changes to the voltage at the minimum load resistance (hence the maximum current draw) of the power supply. The second is more common, however, when comparing power supplies it is important to know which definition is used in the specifications.

The formula below uses the second definition.

$$\text{Load Regulation} = 100 \times \frac{V_{OUT\ RLMIN} - V_{OUT\ RLMAX}}{V_{OUT\ RLMIN}}$$

$V_{OUT\ RLMIN}$ is the output voltage for the minimum load resistance. $V_{OUT\ RLMAX}$ is the output voltage for the maximum load resistance. The maximum load resistance may be infinite for many power supplies meaning that with no resistance on the output (i.e. open circuit) and no current being drawn from the supply. This is true of many supplies, however, the type of regulation used and protection circuitry can result in a large but not infinite maximum load resistance. Some supplies can provide a DC output voltage with no resistance on the output and some cannot.

Power supply load regulation is in the order of 0.01% for commercially available supplies.

## d. Efficiency

**Efficiency** is a measure of how much power is wasted in the process of generating the DC output voltages. Efficiency is the ratio of the power drawn from the input source ($P_{IN}$) to the power actually delivered to the load ($P_{OUT}$) and is expressed as a percentage. The formula for efficiency is

$$\text{Efficiency} = 100 \times \frac{P_{OUT}}{P_{IN}}$$

Note the power wasted ($P_{WASTE}$) can be derived from this equation.

$$P_{WASTE} = P_{IN} - P_{OUT} = P_{IN} - \frac{\text{Efficiency}}{100} \times P_{IN}$$

Power supply efficiency can be different for different load resistances so this figure is usually an average over the range of load resistances the supply will drive. Efficiencies for custom designed supplies embedded in products can be 85-90%. Lab grade power supplies have efficiencies that are typically in the 75-80% range.

## 3. AC-DC Unregulated Power Supplies

AC-DC Power Supplies are found in the majority of appliances and electronic devices used in home and business settings where the AC input is 120 VAC, 60Hz available at the wall outlet. They also are used in industrial applications where the input may be 120 VAC, 60 Hz or 240 VAC, 60 Hz. In electronic devices and industrial equipment it is common to need DC output voltages of less than 20 VDC. This section discusses the unregulated AC-DC supply. The unregulated supply has an average voltage of some DC value but may include a small, time varying ripple voltages "riding" on the DC voltage. The unregulated supply does not adjust the DC output voltage in reaction to a change in load current (or equivalently load resistance).

Unregulated supplies are used as voltage sources for many applications where the DC voltage does not have to be precise and has a relatively fixed current draw. They are also the front-end of regulated supplies that require more precision and need to operate in a less fixed environment.

Figure 1 shows a block diagram of the major components of an AC-DC unregulated power supply.

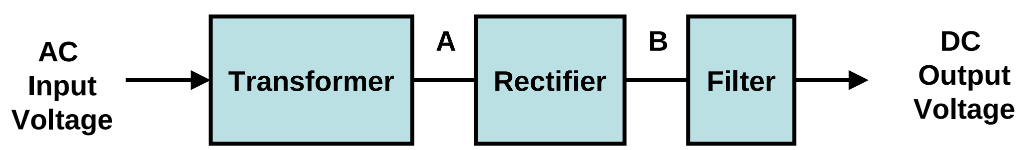



Figure 1 – Block Diagram, AC-DC Unregulated Power Supply

More detailed descriptions of each block will follow, however, as an overview of the operation, each block takes a step towards producing a DC output voltage. The Transformer block reduces the amplitude of the incoming AC waveform the general range of the DC output voltage at point A.

The rectifier turns a positive and negative going AC voltage into a single polarity signal. For a positive DC power supply, the Rectifier block "clips-off" the negative half-cycle of the waveform and produces a series of positive half-cycle waves at point B. For a negative DC power supply, the positive half-cycle is clipped. The characteristics of that waveform depend on the type of Rectifier; half-wave or full-wave.

The Filter block "smoothes" the half-cycle waveforms out of the rectifier to produce a DC output voltage that includes an AC ripple voltage "riding" on the nominal DC output.

## a. Transformer

The purpose of the **Transformer** is to reduce the peak AC voltage to a level in the general range of the DC output. A transformer is typically used in this input block because it has less power loss in reducing the AC voltage than other methods. The characteristics of a transformer ensure that output voltage does not change with changing current demands. The transformer should be selected such that it produces a peak voltage at point A that is "close" to the DC output voltage and large enough to allow for losses in following stages. Figure 2 shows the waveforms of a transformer with a 120 $V_{RMS}$, 60 Hz input and a 12 $V_{RMS}$, 60 Hz output from the transformer.

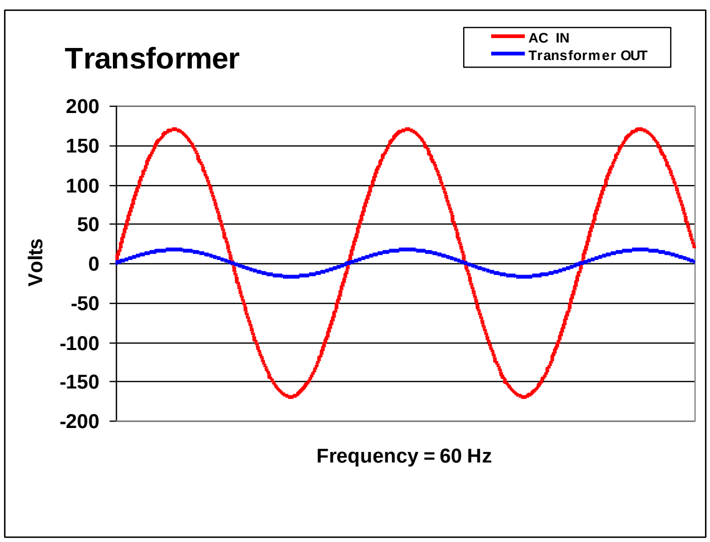



Figure 2 – Transformer Waveforms

Note that the amplitude, or peak, of the sine is $\sqrt{2}$ times $V_{RMS}$ for both waveforms. This is significant since rectifiers and filters respond to the peak voltage of an AC sine wave.

Figure 3 shows two types of transformers that could be used; non-center tapped (Figure 3a) and center tapped (Figure 3b). There is a design choice to be made with the architecture of a power supply and the architecture of its transformer / rectifier combination. Take the example of a power supply where 12 $V_{RMS}$ is desired as an input to the rectifier block. The non-center tapped transformer of Figure 3a would have a secondary voltage between pins 3 and 4 of 12 $V_{RMS}$. The center tapped transformer of Figure 3b would have a secondary voltage of 12 VRMS between CT and pin 3, and a 12 VRMS secondary of 12 V RMS between CT and pin 4 that is 180° out of phase with pin 4. To achieve this, the transformer of the center tapped transformer has twice as many windings in the secondary.

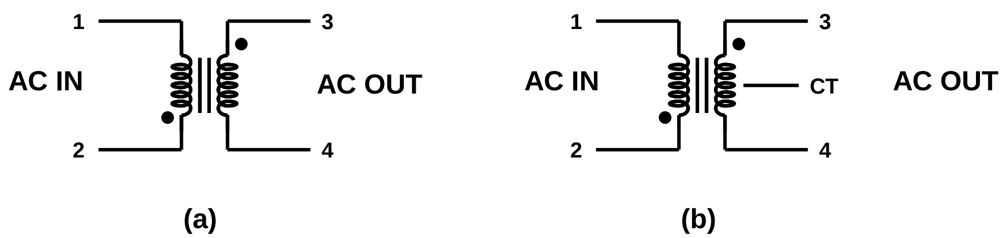


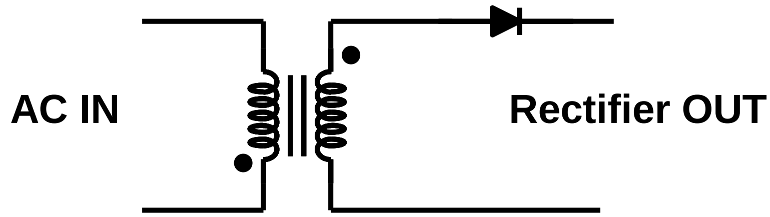

Figure 3 – Transformer Types

For this reason, the cost of the center tapped transformer is greater than the cost of a non-center tapped transformer. Architectures with non-center tapped transformers may require more components, however, the cost of the extra components is usually less so the non-center tapped architecture is the most common choice. Supplies with center tapped transformers will not be covered here.

## b. Rectifier

The purpose of the **Rectifier** block is to produce a modified AC waveform that is of the same polarity as the output of the supply; i.e. a supply with a positive DC output would use a rectifier that produces a modified AC wave form that is always positive and never negative. Two types of rectifiers are half wave and full wave.

Figure 4 shows a **half wave rectifier** composed of a single diode. The graph shows the output of a 12 $V_{RMS}$ (17.0 volts peak amplitude, $V_P$) transformer and the resulting output of single diode rectifier. The diode passes the AC waveform when it is positive and blocks the negative half cycle. Note that the amplitude the Rectifier OUT positive peak is one forward biased voltage diode drop, $V_{ON}$, (approximately 0.7 V) less than the positive peak of the 12 $V_{RMS}$ waveform.



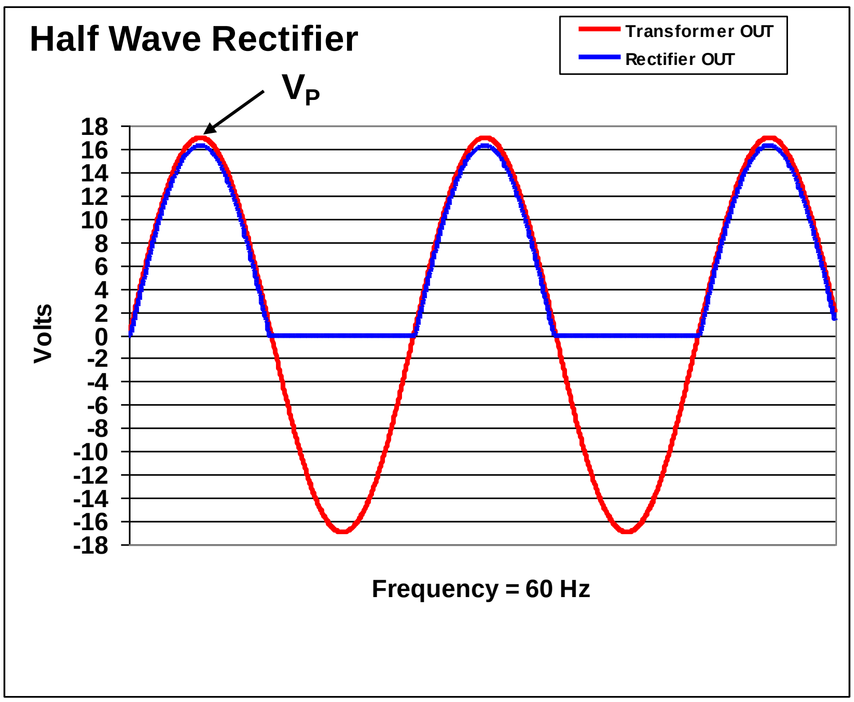
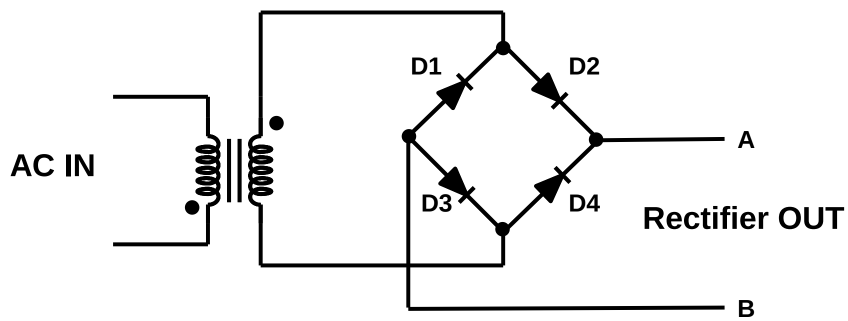




Figure 4 – Half Wave Rectifier

Figure 5 shows **full wave bridge rectifier** using four diodes in a bridge configuration. The graph shows the output of a 12 $V_{RMS}$ transformer and the resulting output of the bridge rectifier. During the half cycle when the "dotted" output of the transformer is positive in relation to the "undotted" side, only diodes D2 and D3 are "ON" and follow the AC waveform where A is positive with respect to B. During the half cycle when the "dotted" output is negative, diodes D4 and D1 are "ON" and follow the AC waveform where again A is positive with respect to B essentially "flipping" the negative half-cycle to become positive at the output of the rectifier.



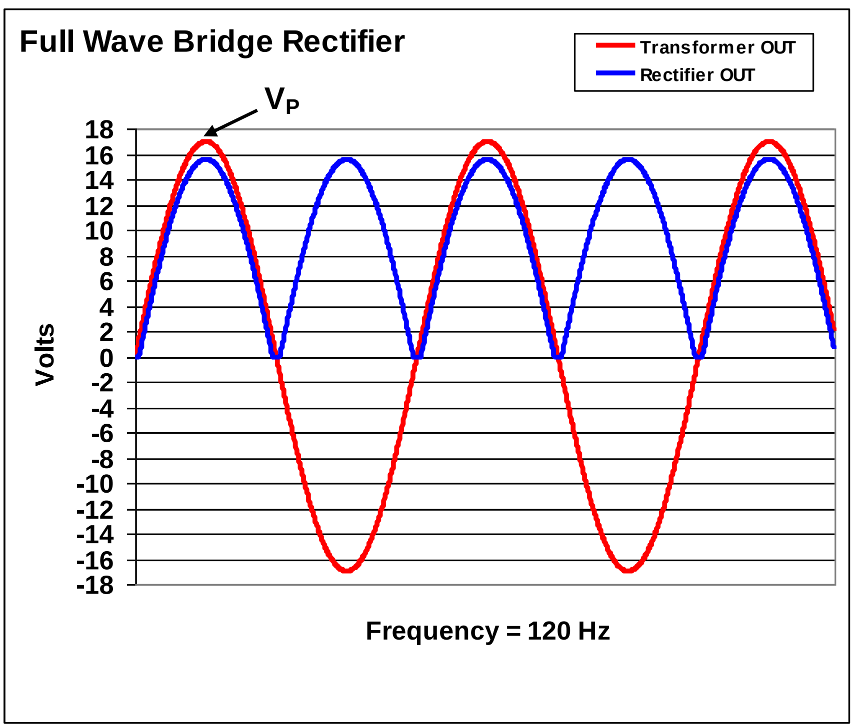




Figure 5 – Full Wave Rectifier

This “flipping of the negative half cycle effectively doubled the frequency of the waveform so that the output of the rectifier is a series of positive half cycle sine waves occurring at a 120 Hz frequency. Note that the peak of the rectified waveform is two diode drops, $2V_{ON}$ (1.4 V), below that of the transformer output.

The bridge rectifier is the more common rectifier used in low voltage power supplies because the over all cost of the supply is less. The trade off in cost between the one diode, half wave rectifier and the four diode, full wave rectifier is in the cost of filter in the following stage. The cost of the extra 3 diodes is less than the cost of the filter components for the same quality of DC voltage.

In selecting the diode, the first parameter to consider is the forward voltage drop, $V_{ON}$ (sometimes identified as $V_F$ in datasheets). The standard silicon switching diode will have a forward voltage drop of approximately 0.7V. In some cases the designer may find it advantageous or necessary to have a smaller $V_{ON}$ and select Schottky diodes where the forward voltage drop is in the 0.1-0.2 V range.

## c. Filter

The purpose of the **Filter** is to “smooth” out the peaks of the rectified waveform into as close to DC as desired. The most common form of filter is a simple RC circuit as shown in Figure 6. The resistor, R, in this circuit is the load resistance for an unregulated supply.

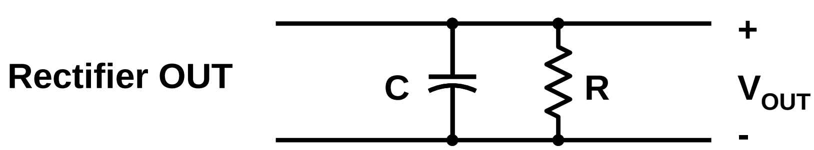
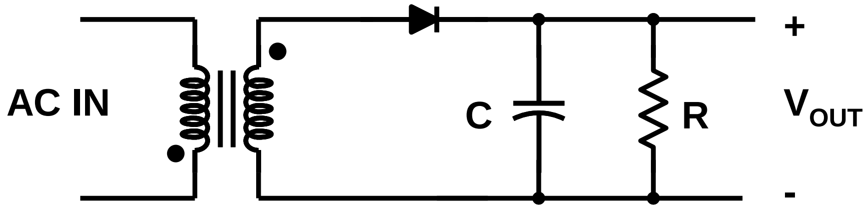



Figure 6 – Filter

Figure 7 shows the circuit and the waveform when the RC filter above is added to a half wave rectifier of Figure 4. An intuitive way to think of this circuit is that once C becomes charged to the peak level of the positive half-sine wave, C is the driving voltage source for R. C slowly discharges until the next positive half-sine wave from the rectifier equals the voltage of the discharging C. Then, during the conduction period, ΔT, the output of the rectifier is the driving voltage source for R and is recharging C. ΔT is called the conduction period because that is the time when the diode is forward biased and conducting current.



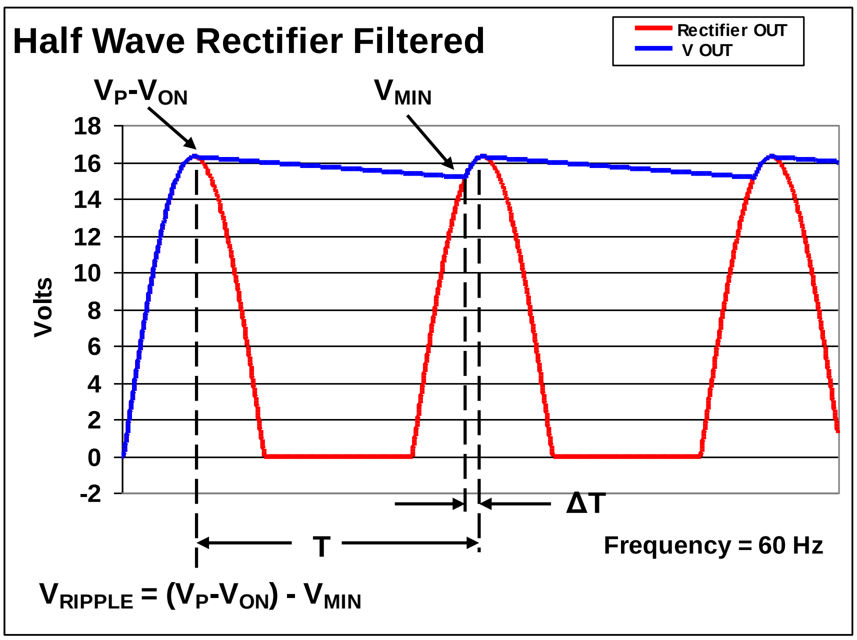




Figure 7 – Half Wave Rectifier with RC Filter

The value C and R determine the rate of discharge of the voltage on C. The period, T, and amplitude, $(V_P - V_{ON})$, of the Rectifier OUT waveform determine the point where Rectifier OUT and the discharge of C are equal, $V_{MIN}$. The result is a voltage at $V_{OUT}$ that has an average DC voltage, $V_{DC}$, with a ripple voltage, $V_{RIPPLE}$, riding on it.

$$V_{DC} = \frac{(V_P - V_{ON}) + V_{MIN}}{2}$$

$$V_{RIPPLE} = (V_P - V_{ON}) - V_{MIN}$$

The factors that determine the characteristics of the unregulated output voltage, $V_{OUT}$ are:

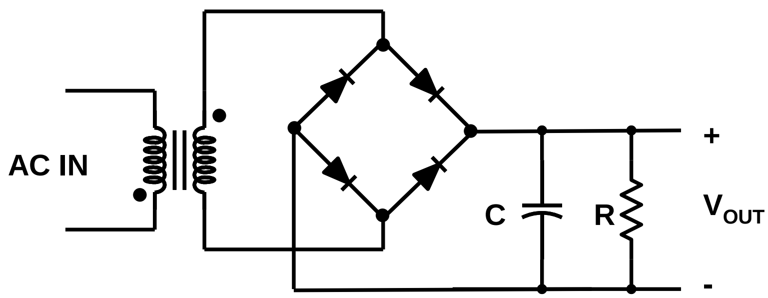
- $V_P$ - the peak voltage of the transformer secondary
- $T$ - the period of the AC voltage of the input sine wave
- $V_{ON}$ - the forward voltage drop of the diode
- $V_{MIN}$ - determined by the discharge rate from R and C

Looking at the graph in Figure 7, $V_{OUT}$ is approximately 15.6 V and $V_{RIPPLE}$ is approximately 0.8 V and has a frequency of 60 Hz.

Figure 8 shows the circuit and the waveform when an RC filter is added to a full wave bridge rectifier of Figure 5. Note that in this case, the period of the Rectifier OUT is half that of the AC IN frequency due to the configuration of the diodes and the "flipping" of the negative half-cycle. Since the period is half, the frequency is double. Again the capacitor, C, is holding up the DC voltage but in this case, the time for the Rectifier OUT signal to return to $V_{MIN}$ is half as long as in the half wave rectifier case. Therefore, the size of the capacitor, C, would be half that of the capacitor required with a half wave rectifier for the same $V_{RIPPLE}$.

Looking at the graph in Figure 8, $V_{OUT}$ is approximately 15.0 V and $V_{RIPPLE}$ is approximately 0.5 V and has a frequency of 120 Hz.

For either rectifier, selecting values for C for a given load resistance R is the main factor in determining $V_{RIPPLE}$. Table 1 gives the equations for selecting C.



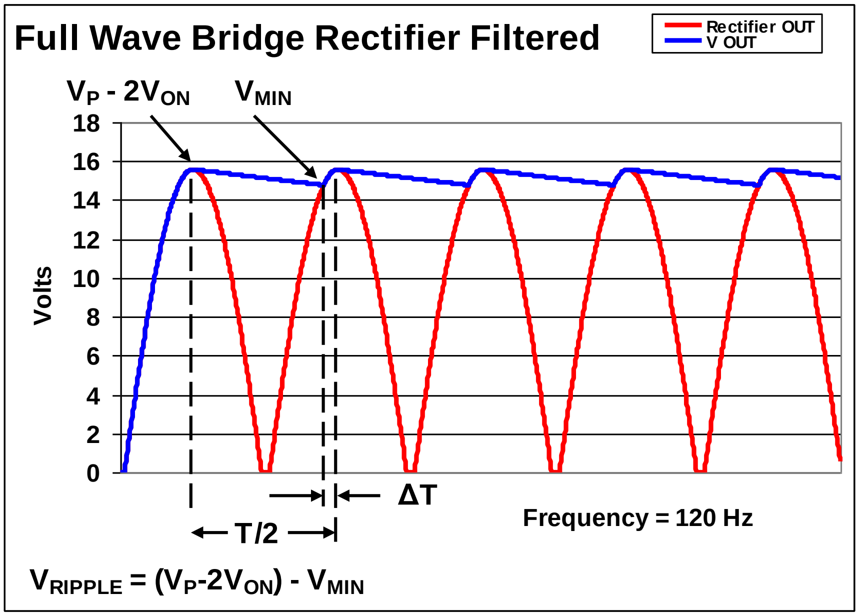




Figure 8 – Full Wave Rectifier with RC Filter

In selecting the diode, there are two considerations; 1) the maximum reverse voltage across the diode which is defined as the peak inverse voltage, PIV, in most diode datasheets, and 2) the maximum forward current, $I_{F\,MAX}$.

For the half wave rectifier, when the diode is OFF during the capacitive discharge the diode is reversed biased and sustaining almost twice $V_P$. So good rule of thumb is to select a diode with $V_{PIV} = 2\ V_P$. For the full wave rectifier, the diodes sustains $V_P$ when in the OFF state so $V_{PIV} = V_P$ in this case.

The maximum forward current, $I_{F\,MAX}$ can be large when the power supply is first turned on and the filter capacitor C is not yet charged. The magnitude of this charge is related to the choice of C which in turn determines the conduction period, ΔT. Equations for determining $V_{PIV}$ and $I_{F\,MAX}$ are given in Table 1.

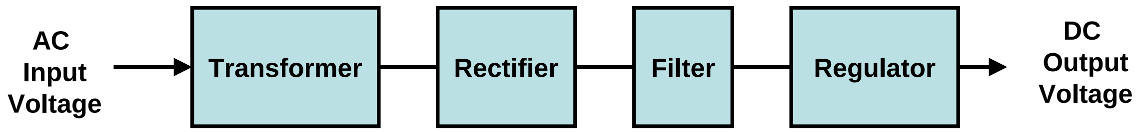
| | Half Wave | Full Wave Bridge |
|---|---|---|
| **Filter Capacitor** | $C = \frac{V_P - V_{ON}}{V_{RIPPLE}} \times \frac{T}{R}$ | $C = \frac{V_P - 2V_{ON}}{V_{RIPPLE}} \times \frac{T}{2R}$ |
| **Nominal DC Output Voltage** | $V_{OUT} = \frac{1}{2}(V_P - V_{ON})\left[1 + \frac{T}{RC}\right]$ | $V_{OUT} = \frac{1}{2}(V_P - 2V_{ON})\left[1 + \frac{T}{2RC}\right]$ |
| **PIV Rating** | $V_{PIV} = 2V_P$ | $V_{PIV} = V_P$ |
| **Peak Diode Current** | $I_{F\,MAX} = \frac{V_P - V_{ON}}{R} \times \frac{2T}{\Delta T}$ | $I_{F\,MAX} = \frac{V_P - V_{ON}}{R} \times \frac{T}{\Delta T}$ |

Table 1 – Component Selection Guidelines

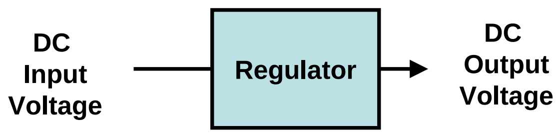
## 4. Voltage Regulators

Unregulated power supplies such as described in the previous section or a DC source whose output may change with time or environmental conditions can be used in many applications where the actual DC output voltage or the current demand on the supply (i.e. load resistance) does not vary greatly. However, in a large majority of applications, a more precise DC output voltage is required that can maintain that a constant DC voltage under widely varying conditions of input voltage and output current demand. In these cases, **Voltage Regulators** are added. A Voltage Regulator is added to an unregulated sources to maintain a DC output voltage that will vary only a small percentage (less than 0.1%) from the nominal value.

Figure 9(a) shows a block diagram of an AC-DC regulated power supply where a regulator has been added to the unregulated supply described in the previous section. Figure 9(b) shows a regulator added to a DC source such as a battery, solar panel or wind generator.




(a) AC-DC Regulated Power Supply




(b) DC-DC Regulated Power Supply

Figure 9 - Regulators

There are three main reasons to use a voltage regulator;

1. Set a DC Output Voltage that is different from the unregulated voltage source
2. Compensate for variations of the Input Voltage. In the case of AC-DC supplies this may be ripple voltage from an unregulated supply or changes to the AC Input Voltage to the supply. In the case of the DC-DC it may be a discharging battery, solar panel under varying light conditions, or a wind generator under varying wind conditions.
3. Maintain the rate DC Output Voltage over a wide range of current demands.

There are two main classifications of voltage regulators:

1. Linear Regulators
2. Switching Regulators

Linear regulators can be used in cases where the unregulated input voltage to the regulator is larger than the required DC Output Voltage. Switching Regulator techniques can be used in cases where the unregulated input voltage is either larger or smaller than the required DC Output Voltage.

Basic principles of each type regulator are discussed below. Details of their design and implementation are discussed in more detail in ***Low Voltage Power Supplies II – Linear Regulators*** and ***Low Voltage Power Supplies III – Switching Regulators***.

## a. Linear Regulators

Figure 10 shows the block diagram of a **Linear Regulator**. Linear regulators achieve regulation by comparing the DC Output Voltage ($V_{OUT}$), to a precise reference voltage ($V_{REF}$) and generating an error signal. That error signal adjusts the bias of a series pass device until the $V_{OUT} = V_{REF}$.

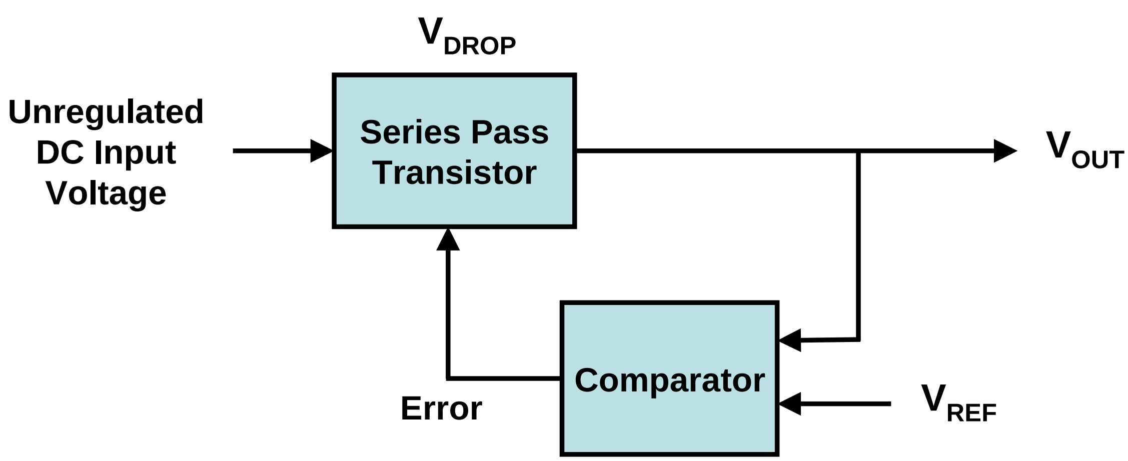



Figure 10 – Linear Regulator Block Diagram

The series pass transistor is commonly a bipolar junction transistor (BJT), Metal Oxide Silicon Field Effect Transistor (MOSFET) or Insulated Gate BJT (IGBJT).

In the steady state, where $V_{OUT} = V_{REF}$ and the current drawn by the load is $I_{OUT}$, there is a fixed voltage drop ($V_{DROP}$) across the series pass transistor. The transistor is operating at approximately the same current as $I_{OUT}$. If $V_{OUT}$ increases due to changes in the load, an Error signal to the series pass transistor causes $V_{DROP}$ to decrease and $V_{OUT}$ moves towards the value of $V_{REF}$. A decrease in $V_{OUT}$ causes an increase in $V_{DROP}$. Once the $V_{OUT} = V_{REF}$, a new steady state $V_{DROP}$ and $I_{OUT}$ are established for the new load conditions.

A similar change reaction takes place for to an increase or decrease in the Unregulated DC Input Voltage. The input change causes $V_{DROP}$ to change and in turn $V_{OUT}$ to change. The change in $V_{OUT}$ creates an Error signal to adjust the series pass transistor.

Note that this feedback control loop can be unstable if not properly designed. Stability will be discussed in ***Low Voltage Power Supplies II – Linear Regulators***.

One of the disadvantages of linear regulation is the series pass transistor consumes power that is approximately equal to $V_{DROP}$ times $I_{OUT}$. This is all unused power which reduces the Efficiency and increases $P_{WASTE}$ as defined in section 2d. In most supplies, $P_{WASTE}$ is almost entirely due to the series pass transistor.

***Low Voltage Power Supply II – Linear Regulations*** is a follow on course that covers the details of design and implementation of linear regulators.

## b. Switching Regulators

**Switching Regulators**, also known as Switch-Mode Regulators, rely on the ability of inductors to store energy in a magnetic field and release that energy into a load. The name comes from strategies of repeatedly charging and discharging the energy of an inductor to achieve the desired DC voltage. Switching regulators are also the underlying technique in DC-DC converters.

There are three types of switching regulators:

1. Buck Regulator – a step-down voltage regulator ($V_{OUT} < V_{IN}$)
2. Boost Regulator- a step-up voltage regulator ($V_{IN} > V_{OUT}$)
3. Buck / Boost Regulator – can step-up or step-down voltage

The following is a very high level description of each Regulator. Low Voltage Power Supply III – Switching Regulators is a follow on course that covers the details of design and implementation of switch regulators.

Figure 11 illustrates the principle of operation of a Buck Regulator. There are two modes of operation. In the first mode, S1 is closed and S2 is open. In this mode, $I_L$ and $V_L$ are positive with respect to the defined polarity. $V_L$ is initially large but decreases over time towards zero. $I_L$ is initially zero and increases causing the magnetic field in L to increase. In this mode, $V_{IN} – V_L = V_{OUT}$.
In the second mode, S1 is open and S2 is closed. The inductor is providing the voltage and current to the load and the polarity of both $V_L$ and $I_L$ are negative. So $V_{OUT}$ is positive. By continually switching the system between the two modes, the output voltage $V_{OUT}$ can be established. $V_{OUT}$ can be set at some value less than $V_{IN}$ based on the timing of the switching, the value of L and the load resistance $R_L$.

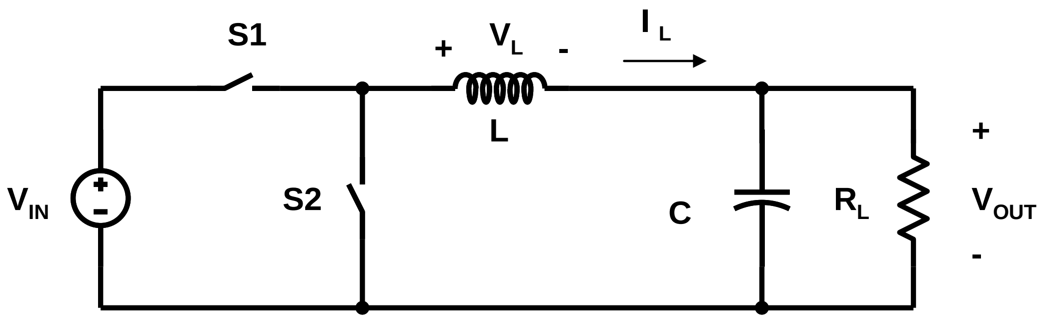



Figure 11 – Buck Regulator Principle of Operation

When implemented with real components, S2 is often replaced with a diode and S1 is replaced with a transistors. In addition, the output can be ripple voltage can be reduced with a capacitor as was done with the unregulated power supply of section 3. Figure 12 shows an example implementation. Switching between the two modes is accomplished with a Pulse Width Modulated (PWM) signal on the gate of the transistor, Q.

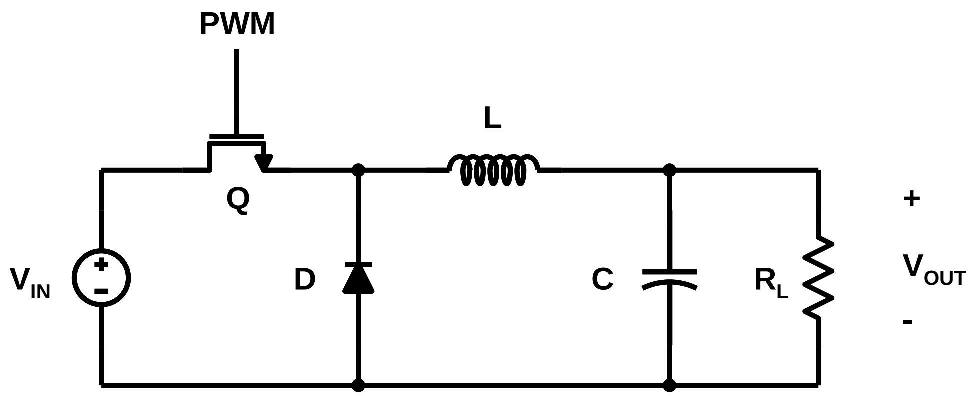



Figure 12 – Buck Switching Circuit

The PWM signal has a fixed frequency and the duty cycle determines when the circuit is operating in the first mode or the second mode.

When a feedback loop is added to the circuit of Figure 12, the regulator is completed. Figure 13 shows a block diagram of the feedback configuration. The PWM Generator produces a PWM signal whose duty cycle can be controlled by the Error input. $V_{OUT}$ is compared to a reference voltage, $V_{REF}$ to produce an Error signal. By changing the duty cycle of the PWM signal, the average output voltage, $V_{OUT}$, can be increased or decreased based on the amount of time the switching circuit is in each mode. As in the case of the linear regulator, this feedback control loop can be unstable if not properly designed.

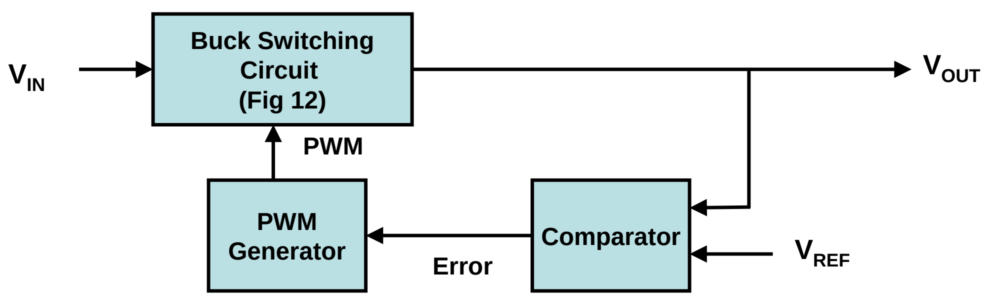



Figure 13 – Buck Regulator

With the Buck Regulator, the position of the inductor produced a net decrease in the voltage at $V_{OUT}$ as compared to the voltage at $V_{IN}$. By repositioning the inductor, a net increase in $V_{OUT}$ can be achieved. This is how the Boost Regulator works. Figure 14 illustrates the principle of operation of a Boost Regulator.

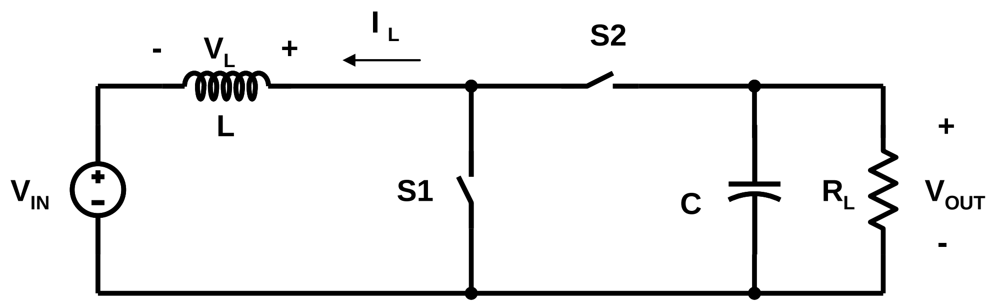



Figure 14 – Boost Regulator Principle of Operation

There are again two modes of operation. In the first, S1 is closed and S2 is open. In this mode the voltage on C is driving the load and the inductor is directly across the source $V_{IN}$ so L is being charged.

In the second mode, S1 is open and S2 is closed. Initially a large voltage that is opposite in polarity to the defined polarity of $V_L$ appears across L. The net output voltage, $V_{OUT} = V_{IN} – (-V_L)$. Therefore, $V_{OUT}$ is greater than $V_{IN}$ which provides the step up in voltage.

A practical implementation replaces S1 and S2 with a transistor and diode as in Figure 15.

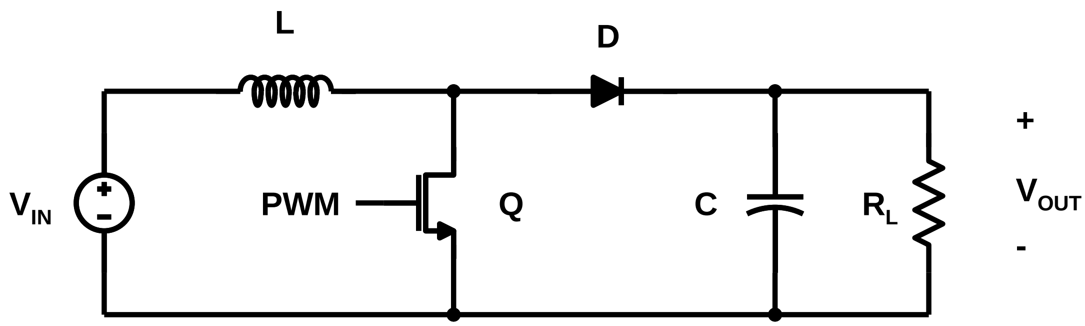



Figure 15 - Boost Switching Circuit

The timing of the two modes as established by the duty cycle of the PWM signal determines the average DC level at $V_{OUT}$. By adding a feedback loop similar to that of Figure 13, the Boost Regulator is complete.

The Buck / Boost converter positions the inductor in a parallel configuration as shown in Figure 16. Again there are two modes of operation; one for charging the inductor and the other for discharging. In this case, the timing can be such that $V_{OUT}$ is either greater or less than $V_{IN}$ depending on how long the inductor is in the charge and discharge modes.

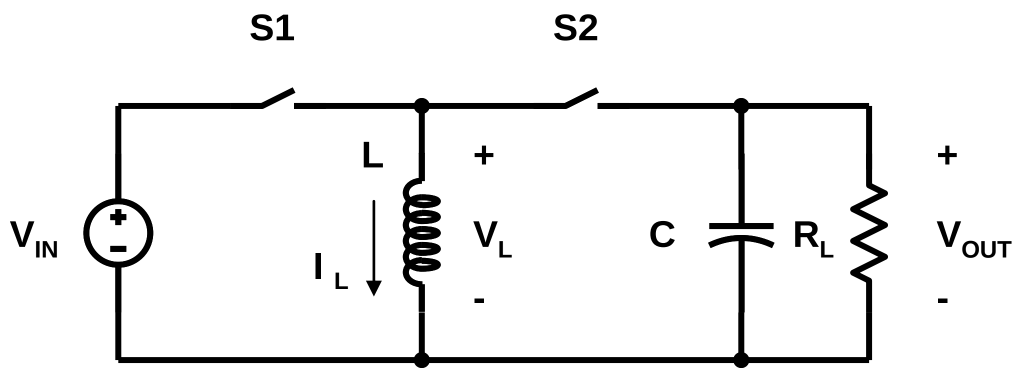



Figure 16 – Buck / Boost Regulator Principle of Operation

Figure 17 shows an implementation with transistor and diode replacing switches as in the cases of the Buck and Boost converter. Again a feedback loop similar to that of Figure 13 completes the Buck / Boost Regulator.

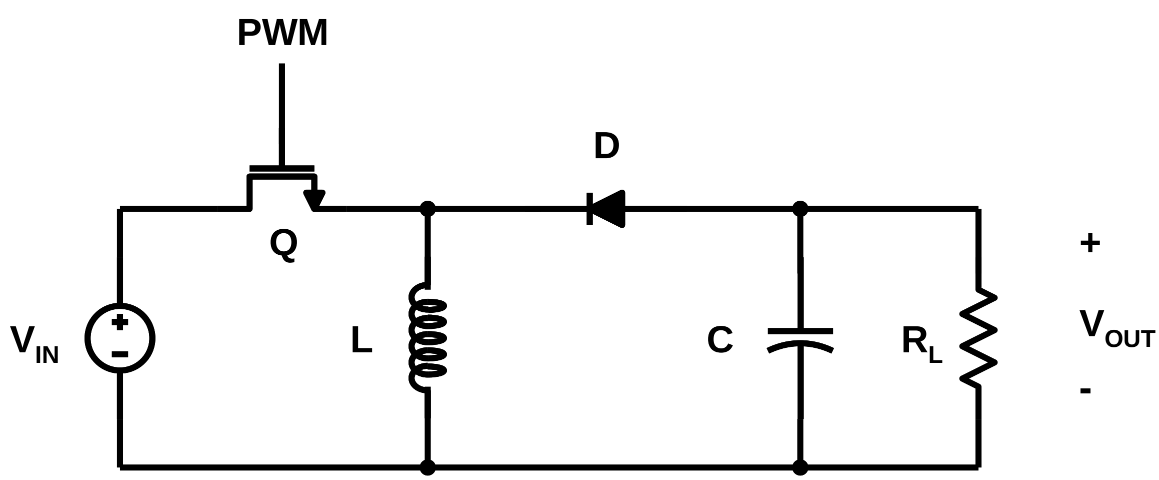



Figure 17 – Buck / Boost Switching Circuit

The biggest advantage of switching regulators is in the efficiency. If ideal components were available, all of the energy being put into the inductor or delivered from the source is being delivered to the load. Inductors and capacitors have internal resistance, wires have IR loss, and the DC source has some series resistance that limit the efficiency that can be obtained. However, 85% efficiencies are common and 95% efficiencies are achievable.

One disadvantage of switching regulators is the Electromagnetic Interference (EMI) caused by the switching of the PWM Generator. The PWM generator operates at a frequency in the tens of kilo-Hertz range and has a measurable contribution to conducted and radiated EMI of the system in which it is used.

## 5. Conclusion

Low voltage power supplies are an integral part of modern electronics. This course covered the major issues in understanding the operation of low voltage power supplies and some of the important considerations in designing and selecting power supplies for a particular application.

Follow on courses ***Low Voltage Power Supply II – Linear Regulators*** and ***Low Voltage Power Supply III – Switching Regulators*** give more detailed discussion of linear and switching power supplies.

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