CHAPTER 9

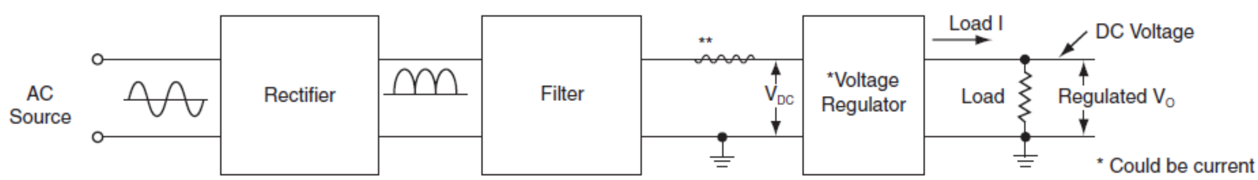
System Power and Control

Introduction

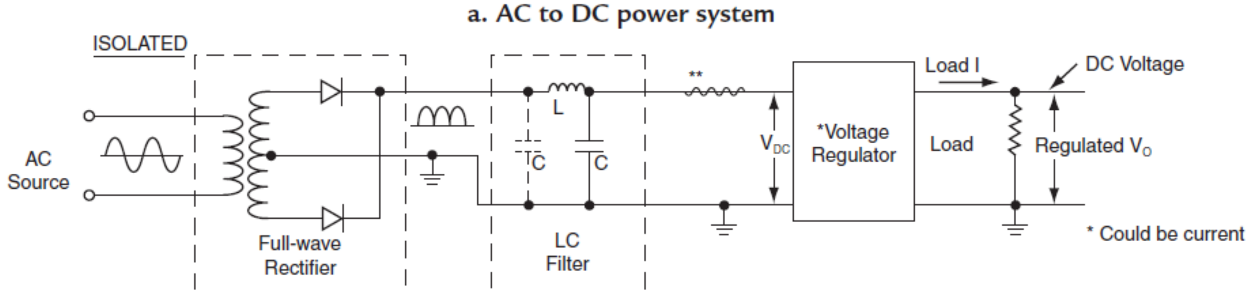
All electronic systems require a source of power. In almost all cases the voltage and current values are specified. The current value is in amperes as a load on the supply, and the voltage value is to be held within a specified tolerance (usually a percentage of the nominal value) as the current value varies within specified limits as the load changes. The nominal value of voltage times the nominal value of current determines the watts of power required of the supply. In this chapter, not only will the source of the voltages and their regulation be discussed, but the way the supply voltages are distributed throughout a system. In addition, the sophisticated circuits that are now available to monitor, detect and protect systems from damage, errors and failure will be discussed.

AC to DC Power Supplies

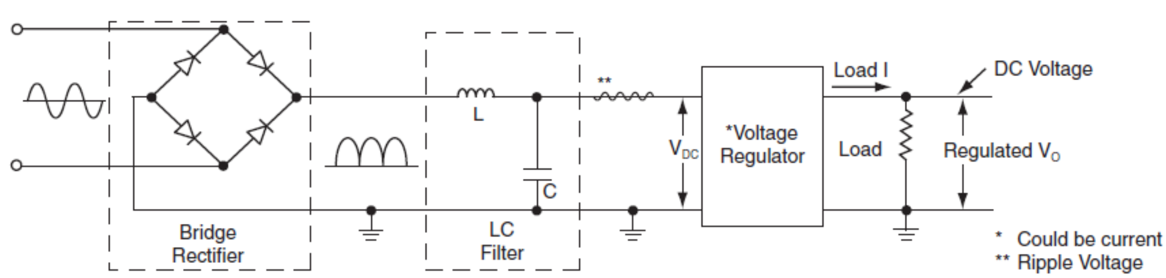
Figure 9-1a shows a general AC to DC power supply. Its source is the alternating current voltage of 120VAC or 250VAC, 60 Hz that is distributed commercially by the local power company. The alternating voltage varying plus and minus around zero is rectified into voltages that vary only above zero. The



a. AC to DC power system



b. AC to DC power system isolated from AC line



c. AC to DC power system not isolated from AC line

Figure 9-1: Examples of AC to DC power supplies half-alterations are passed through a filter that produces a DC voltage of designed amplitude. A small ripple voltage results from the amount of filtering compared to the input voltage variations. The ripple is superimposed on the DC voltage and represents a so-called noise. Because the output voltage must be controlled accurately within tight tolerances, a voltage regulator (or it could be a current regulator) is required. The voltage is held to within 1% to 10% of V_{OUT} over the specified load current and its changes depending on the application and type of regulator.

Many AC to DC power supplies must be isolated from the incoming AC line. *Figure 9-1b* shows such a design using a full-wave rectifier and transformer isolation. If the power supply need not be isolated, *Figure 9-1c* shows a design using a bridge rectifier supplied directly from the AC line.

Voltage Regulators

Zener Regulator

Figure 9-2 shows different versions of linear voltage regulators. The simplest of these is shown in *Figure 9-2a*. It consists of a zener diode and a resistor connected to a voltage V_{IN}. A zener diode is a semiconductor diode designed to operate in the reverse-biased avalanche region (similar to breakdown) that has the characteristic of maintaining a constant voltage across it as the current through it varies. It must have a minimum current, $I_{Z(min)}$, through it to operate properly, and because of a power dissipation temperature limit, it can

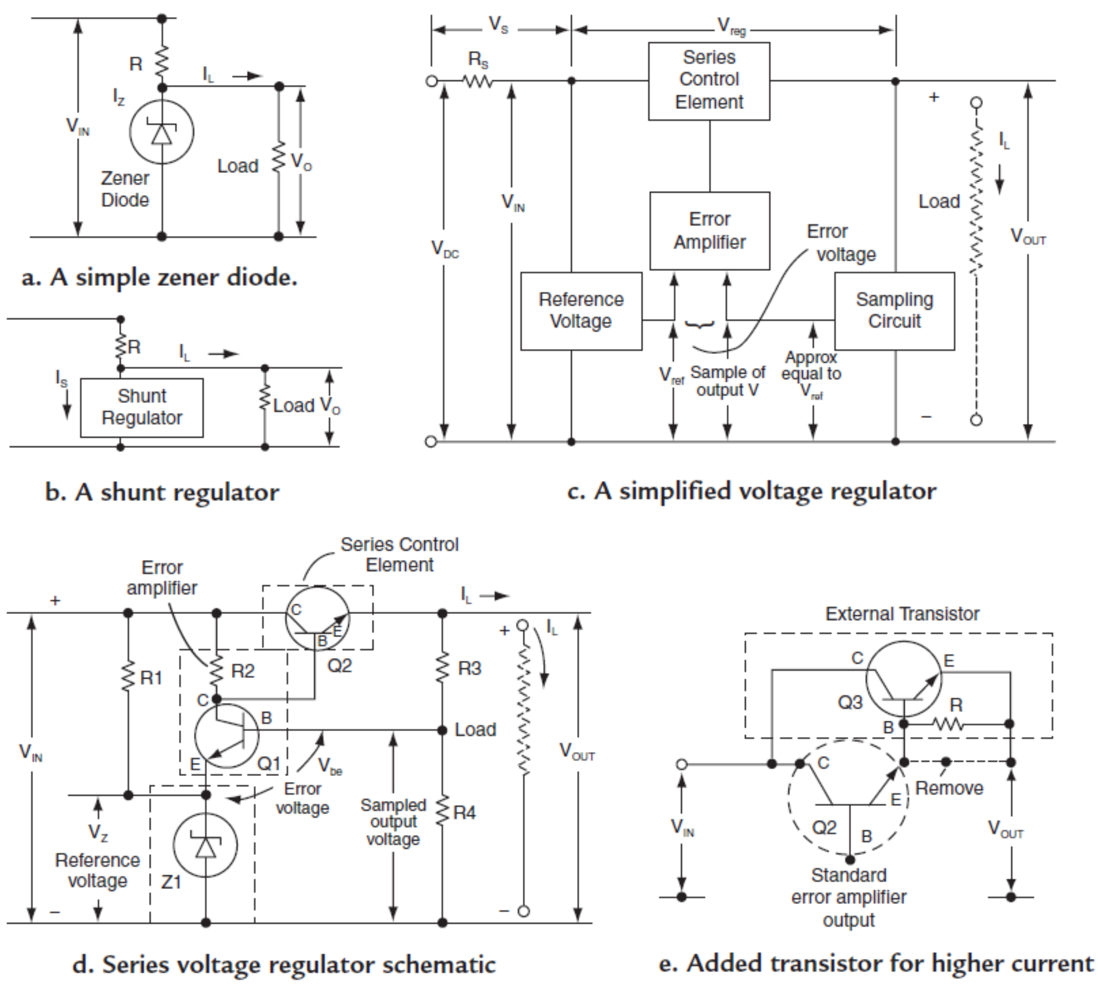


Figure 9-2: Linear voltage regulators

handle only up to a maximum current, $I_{Z(max)}$. Here is how it works as a regulator. I_Z can be any value from $I_{Z(min)}$ to $I_{Z(max)}$, and V_O will remain within a specified percentage of V_O. Initially with no-load, $I_L = 0$, the series resistor is set so that the current is $I_{Z(max)}$. When I_L is increased, I_Z decreases, but V_O will remain within specified limits until $I_Z = I_{Z(min)}$. Thus, I_L varies over its range but V_O remains within specified limits. The zener diode is not a regulator for wide variations in current; it is more a regulator for a constant load with little variations. Currents that it can handle are usually less than 100 milliamperes (100 mA).

Example 1. Zener Voltage Regulator

A Zener diode has the characteristics shown for points 1 and 2. What is the percent load regulation when the load changes between point 1 and point 2?

	V_Z	I_Z	
Point 1	6.0V	1 mA	(maximum current drawn by load)
Point 2	6.42V	100 mA	(minimum current drawn by load)

Solution:

% Load Regulation = $V_{NO\ LOAD} - V_{LOAD}/V_{LOAD} \times 100$

% Load Regulation = $6.42 - 6.0/6.0 \times 100 = 0.42/6 \times 100 = 0.07 \times 100$

% Load Regulation = 7%

Shunt Regulator

The shunt regulator shown in *Figure 9-2b* also shunts current from the load but is designed to handle much larger currents. It duplicates the zener diode regulator. Initially, I_S is a maximum through the shunt. As I_L increases to a maximum, I_S will decrease to a minimum. It is packaged to handle much greater power dissipation, since the device power dissipation is V_O times I_S.

Linear Series Voltage Regulators

A true feedback-type linear voltage regulator is shown in *Figure 9-2c*. All components operate in their linear mode. It is a simplified block diagram that does not have all the bells and whistles that are designed into IC regulators today, but the modern IC regulators are based on the same principles. The input voltage, a DC voltage, is separated from the load by a control element in series between V_{IN} and V_{OUT}. There is a voltage drop across the control element of V_{REG}. The series control element is controlled by an error amplifier. The error amplifier amplifies a voltage difference, called the error voltage, between a reference voltage and a sampled portion of the output voltage approximately equal to the reference voltage. Changes in the load current cause V_{OUT} to vary and the error voltage to change such that the series drop across the control element compensates for the change in V_{OUT}.

Load Variations

The regulation works as follows: If I_L increases it will tend to reduce V_{OUT}. The reduction in V_{OUT} is fed through the sampling circuit to an input of the error amplifier. The reference voltage is on the other input. Since the reference voltage is constant, the error voltage decreases and causes the voltage across the control element to decrease. As a result, V_{OUT} increases to compensate for the initial decrease.

Likewise, if I_L decreases, it tends to increase V_{OUT}. Increasing V_{OUT} increases the error voltage, which increases the control element voltage, V_{REG} and reduces V_{OUT} to compensate for the initial increase. The stable operating point of the system is such that with V_{IN} a particular value and V_{OUT} a specified value, the error voltage is tending toward zero.

Actual Linear Voltage Regulator Circuit

Figure 9-2d is a schematic of the interconnection of components for a linear series voltage regulator. The active devices shown are bipolar transistors, but MOS devices can (and are) used for the same design. NPN transistors and a positive output voltage are used in the design because the circuit is a bit easier to understand.

Note first that the series control element is just a NPN transistor. Note also that the reference voltage is really the zener voltage regulator that was discussed in *Figure 9-2a*. The only variations in the zener diode current will be those caused by variations in the input voltage, V_{IN}. Q_1 and R_2 form an inverting amplifier whose output drives the base of Q_2, the series control element. The input to the amplifier is the error voltage, V_{be} of Q_1. The sampled output voltage under the quiescent state is equal to a V_{be} voltage above V_Z, the reference voltage.

Load Variations

The regulation proceeds as follows: When I_L increases and V_{OUT} tends to reduce due to the increased drop across Q_2, the V_{be} error voltage on Q_1 reduces, reducing current through Q_1 and R_2. The rise in the collector voltage of Q_1 and base voltage of Q_2 raises the emitter voltage of Q_2, increasing V_{OUT} to compensate for the initial reduction.

Likewise, for a decrease in I_L, V_{OUT} tends to increase because of the decreased drop across Q_2. The V_{be} error voltage increases, which reduces the Q_1 collector voltage and base voltage of Q_2, which reduces the emitter voltage to compensate for the initial rise in V_{OUT}.

Line Variations

Similar regulation occurs for V_{IN} variations. If V_{IN} increases, V_{OUT} tends to increase, but the reference voltage, V_Z, changes very little. The error voltage increases because of an increase in V_{OUT}, which reduces the Q_1 collector voltage and base voltage of Q_2, which reduces the emitter voltage, V_{OUT}, to compensate for the increase. Similar to load variations, a decrease in V_{IN} will be met with a compensating increase in V_{OUT} to complete the regulation.

Higher-Current Regulators

In order to handle larger currents and, thus, more power dissipation for the regulator, external devices can be connected as shown in *Figure 9-2e*. Many IC regulators have the connections for the external devices provided in the design. Again, bipolar devices are used in the example, but MOS devices can be used just as well. Power devices with external heat sinks are usually required in order to satisfy the power dissipation requirements and keep the operating temperatures of the devices within specifications.

Voltage Regulation

Return now to *Figure 9-2c*. The input voltage V_{DC} is the voltage out of the rectifier and filter of *Figure 9-1*. There is an impedance associated with the rectifier and filter. It is R_S shown in *Figure 9-2c*. As a result, the output voltage, V_{OUT}, is equal to:

$$\begin{aligned} V_{OUT} &= V_{DC} - I_L R_S - V_{REG} \\ &= V_{DC} - V_S - V_{REG} \\ &= V_{DC} - (V_S + V_{REG}) \end{aligned}$$

Using this information, the regulation can be explained as follows: V_{DC} is always considered constant. The regulator varies V_{REG} to keep V_{OUT} constant as I_L and V_S change. With an increase in I_L and thus V_S, V_{OUT} would tend to decrease; however, V_{REG} is reduced to compensate and V_{OUT} remains constant.

A decrease in I_L causes a decrease in V_S, but regulation compensates by increasing V_{REG} so that V_{OUT} remains constant. V_{DC} was considered constant but if V_{DC} changes, either up or down, regulation follows to compensate by increasing or decreasing V_{REG} to keep V_{OUT} constant.

Percent Regulation

The load regulation of a voltage regulator can be expressed as follows (where the load is some specified current value):

$$\%\ \text{Load Regulation} = \frac{V_{NO\ LOAD} - V_{LOAD}}{V_{LOAD}} \times 100$$

If $V_{NO\ LOAD}$ = 11V and, at a specified current, V_{LOAD} = 10V then

$$\%\ \text{Load Regulation} = \frac{11 - 10}{10} \times 100$$

$$\%\ \text{Load Regulation} = 10\%$$

Common percent load regulation for IC voltage regulators is from 1% to 5%.

Example 2. Voltage Regulation

To have 1% load regulation for the above supply where $V_{NO\ LOAD}$ = 11V, at the specified load, what does the V_{LOAD} have to be?

$$1\% = \frac{11 - V_{LOAD}}{V_{LOAD}} \times 100$$

$$0.01 = \frac{11 - V_{LOAD}}{V_{LOAD}}$$

$$V_{LOAD}\,(1 + 0.01) = 11$$

$$V_{LOAD} = \frac{11}{1.01} = 10.89\text{V}$$

Power Dissipation

The power dissipation within an IC is a very important parameter because excessive temperature rise within a semiconductor junction can ruin the device. In linear series voltage regulators, the device that handles the most current is the series control element. The power dissipated in the control element is the product of the voltage across the unit times the current through the unit. The load is the current, I_{LOAD}, through the unit as shown in *Figure 9-2c and d*. The voltage across the series element is V_{REG}; therefore, the power dissipation in the series element is:

$$P_D = V_{REG} \times I_{LOAD}$$

V_{REG} is:

$$V_{REG} = V_{DC} - V_S - V_{OUT}$$

V_S is usually very small compared to V_{OUT}, therefore, the series element power dissipation can be expressed as:

$$P_D = (V_{DC} - V_{OUT})\, I_{LOAD}$$

> ***Example 3.* Power Dissipation**
>
> A voltage regulator has an input voltage of +12V and is regulating a +5V supply line. The load current is 100 mA. What is the power dissipation in the control element?
>
> **Solution:**
>
> $P_D = (V_{DC} - V_{OUT})I_{LOAD}$
>
> $P_D = (+12 - +5)V \times 0.1A$
>
> $P_D = 7 \times 0.1 = 0.7$ watts

In many IC voltage regulators, especially the low-drop-out regulators, the V_{DC} is restricted to specified values so that the V_{REG} is not too great across the series element at the rated load current. This prevents exceeding the rated power dissipation of the device.

Switching Voltage Regulators

A regulator that has gained prominence as the requirements for load current increased is the switching voltage regulator. Standard linear regulators only have conversion efficiencies of less than 50%. Switching regulators can have efficiencies of up to 85%. This results in lower power dissipation, much smaller size components for a given power output, and operation over a wide range of voltage and current.

Figure 9-3 details a switching voltage regulator. One notes that there are similarities to a linear voltage regulator. There is the sampling of the output, the error amplifier, and the error voltage resulting from a comparison of a sample of the output voltage and the reference voltage.

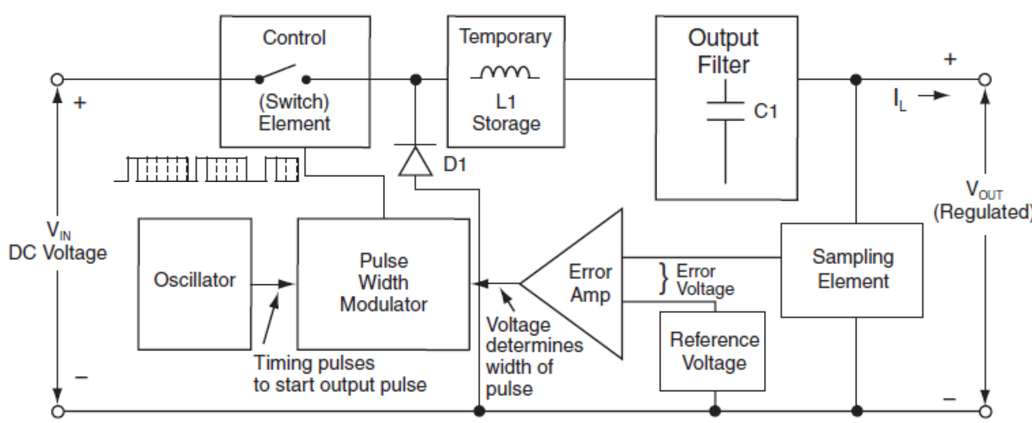


Figure 9-3: Switching voltage regulator (step-down)

Here are the differences between the two regulators:

1. The error amplifier output controls a switch whose ratio of open to closed is varied.
2. Since the control element is a switch rather than a linear element, there is considerable difference in the regulator action.

The Control Element

Instead of a series element operating in the linear mode, the control element is a switch that is in series with a temporary energy storage element, an inductor. The switch is opened and closed at a very rapid rate, and the ratio of the time it is closed to the time it is opened is varied to accomplish the regulation. There is no linear control element operation; it is all digital, either open or closed. When the switch is closed, it charges the inductor with energy by creating a field of magnetic flux around the inductor. When the switch is opened, the magnetic flux collapses across the inductor and returns the energy to the circuit. As the energy is returned, the inductor uses D1, shown in *Figure 9-3*, to complete the circuit and keep current, I_L, through the load.

Actual Regulation

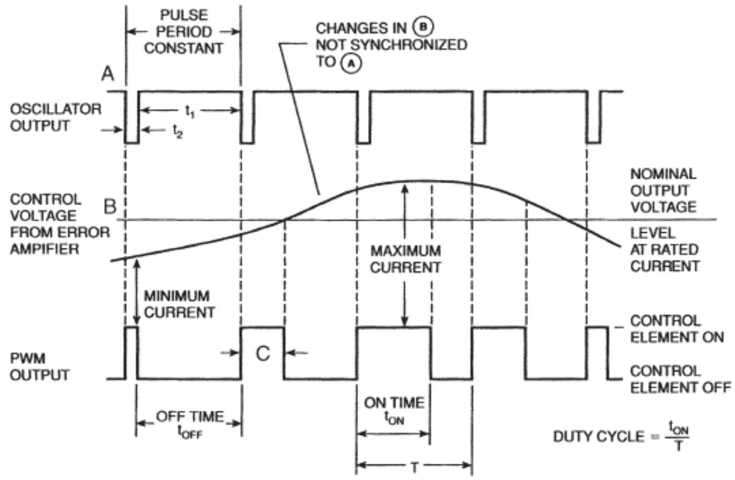


Figure 9-4: Switching regulator waveforms

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Producing more or less voltage across the load is based upon modulating the time that the control element is closed. This is accomplished by the pulse-width modulator (PWM) driven by the error amplifier. An oscillator produces the start of pulses at a constant rate, but the end of the pulse is determined by the voltage supplied by the error amplifier. The relationship of the control voltage from the error amplifier to the pulse width that turns on the switch is shown in *Figure 9-4*. Note the center of the figure has a line that represents a constant level of the control voltage B that is the nominal voltage level at the rated current output. The pulse width for this control voltage is shown as width C.

When the demand for current increases, the pulse width increases because the ON time of the pulse is increased. More energy is stored in the inductor so that the increased current can be supplied and the voltage maintained. The integration of the current pulses by the output filter establishes the output voltage level. More ON time in the pulses produces a higher voltage, less ON time in the pulses produces a lower voltage. As shown in *Figure 9-4*, when minimum current is required the pulse width is narrow with a short ON time. Likewise, when maximum current is required the pulse width is wide with a long ON time.

Here is a description of the regulation in simple terms. When the load demands more current the output voltage tends to decrease. This voltage decrease is sampled and converted to an error voltage that increases the control voltage B and increases the ON time of the pulses. The increase in ON time supplies the increased current and raises the output voltage to its required value.

A load that demands less current would tend to increase the output voltage. The voltage increase is sampled and converted to an error voltage that decreases the control voltage B and decreases the ON time of the pulse. The decrease in ON time of the pulses lowers the voltage and satisfies the demand for less current.

Switching regulators operate at frequencies from 100 kHz to several million cycles/sec. Because of the range of frequencies and the switching action, there is some concern about RFI energy; and attention must be paid to the shielding of sensitive circuits.

Step-Up and Inverting Switching Regulators

The switching regulator shown in *Figure 9-3* is a step-down regulator—V_O is smaller in value than V_{IN}. *Figure 9-5* shows two other types of regulators, a step-up and an inverting regulator. The step-up regulator produces a regulated voltage V_O that is greater in value than V_{IN}, while the inverting regulator produces a V_O that is inverted in polarity from V_{IN}. A positive V_{IN} produces a negative V_O.

Switching Regulator Design

The design of switching regulators can be accomplished in a number of ways, but they all include the inductor as the temporary energy storage element and large storage capacitors. The inductor and capacitor(s) cannot be integrated into ICs; therefore they are external to any ICs used. Any of the other components,

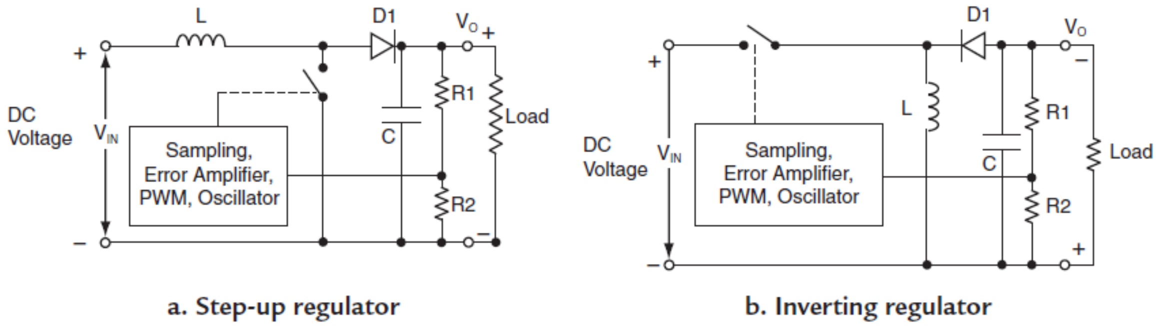

Figure 9-5: Different kinds of switching regulators

depending on the current and voltage requirements, can at least be partially integrated circuits. For example, if the current handling is within the range of 1–2 amperes, all of the error amplifier, PWM circuit, oscillator, and the control element can be one IC. With higher current requirements, external heat-sinked driver packages can be used for the control element. Resistor dividers are always used to sample the output voltage to feed back to the error amplifier.

Transformed PWM Regulators

In a different design than that shown in *Figure 9-3,* the PWM circuit, which contains the error amplifier, oscillator, voltage reference and some protection circuits, is used as an AC source. This AC source is transformed to the desired voltage, filtered, and fed back to the error amplifier to close the regulation loop. Such a regulator is similar to the ones described because it uses PWM pulses for regulation control, but it does not utilize the inductor as a temporary storage element. An increased pulse width (larger ON time) will increase the voltage out from the transformed source; while a decreased pulse width decreases the voltage output.

Summary of Regulators

Nothing has been said in the discussion on regulators about all of the protection techniques that can be used in the regulator circuit. For example, protection for maximum current, for short-circuits, for exceeding temperature limits, for over voltage, for under voltage, controlling the power-up or power-down sequence are all protection features that regulators may contain. Some of the features may be built into the IC regulator itself, while others may be separate ICs designed specifically to provide the protection function.

Many IC voltage regulators that handle low power requirements may have two separate individual regulators in a package, or the regulator may be one that has been designed to regulate two different voltages at the same time. As mentioned previously, many regulators have external connections provided so that higher current control elements can be driven as was shown in *Figure 9-2e.*

Switching regulators normally handle larger currents and voltage than fully-integrated regulators. Great care must be taken to keep regulators within temperature limits by the use of heat sinks and proper ventilation. The switching elements of switching regulators can be subjected to rather extreme current spikes and/or voltage spikes because of the nature of the operation; therefore, careful design is required to manage these concerns.

As mentioned previously, because switching is occurring at relatively high frequencies, and because the magnitude of currents switched are high, there is significant RF energy generated. Thus, a major concern is the circuit layouts and shielding of sensitive circuits due to the RF energy present.