Chapter 14: Voltage Regulation

Power Supply Regulation

An **ideal** power supply provides a constant dc voltage despite changes to the input voltage or load conditions. The output voltage of a real power supply changes under load as shown in the second plot. The output is also sensitive to input voltage changes.

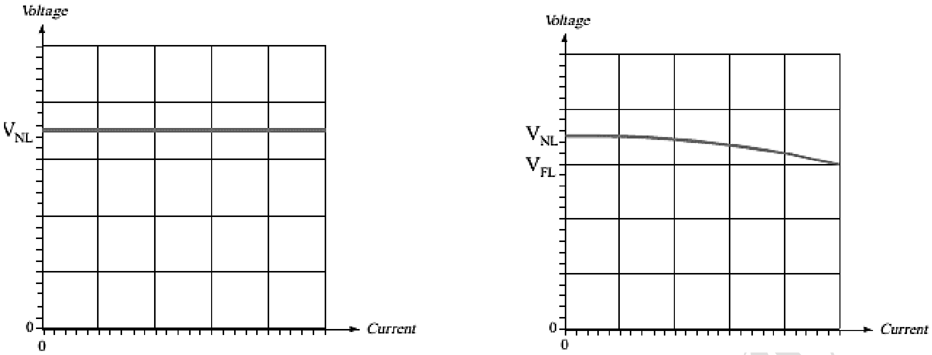


Figure 1: (a) Ideal power supply (b) Real power supply

Line Regulation

Line regulation is a measure of how well a power supply is able to maintain the dc output voltage for a change in the ac input line voltage. The formula for line regulation is

$$\text{Line regulartion} = \left(\frac{\Delta V_{OUT}}{\Delta V_{IN}}\right) 100\%$$

Line regulation can also be expressed in terms of percent change in V_{OUT} per volt change on the V_{IN} (%/V).

$$\text{Line regulartion} = \frac{(\Delta V_{OUT}/V_{OUT})100\%}{\Delta V_{IN}}$$

Load regulation

Load regulation is a measure of how well a power supply is able to maintain the dc output voltage between no load and full load with the input voltage constant. It can be expressed as a percentage change in load voltage:

$$\text{Line regulartion} = \left(\frac{V_{NL} - V_{FL}}{V_{FL}}\right) 100\%$$

Load regulation can also be expressed in terms of percent change in the output per mA change in load current (%/mA). Sometimes a maximum error voltage is given in the specification as illustrated in the next slide for a commercial power supply.

Commercial power supplies, such as you have in lab, have excellent line and load regulation specifications.

The *BK Precision* 1651A is an example of a triple output supply (two 0-24 V outputs and a fixed 5 V output). Voltage regulation specifications for this power supply are:

Line regulation: ≤0.01% +3 mV (Main supply)
≤5 mV (Fixed 5 V supply)
Load regulation: ≤0.01%+3 mV (Main supply)
≤5 mV (Fixed 5 V supply)

Sometimes the equivalent Thevenin resistance of a supply is specified in place of a load regulation specification. In this case, V_{OUT} can be found by the voltage divider rule:

$$V_{OUT} = V_{NL}\left(\frac{R_L}{R_{OUT} + R_L}\right)$$

In terms of resistances, load regulation can be expressed as:

$$\text{Load regulartion} = \left(\frac{R_{OUT}}{R_{FL}}\right)100\%$$

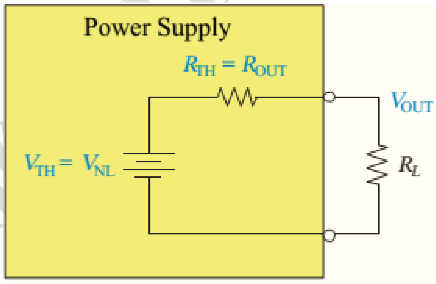


Figure 1

Example: A power supply has an output resistance of 25 mΩ and a full load current of 0.50 A to a 10.0 Ω load.
(a) What is the load regulation?
(b) What is the no load output voltage?

Solution:

(a) $$\text{Load regulation} = \left(\frac{R_{OUT}}{R_{FL}}\right)100\% = \left(\frac{0.025\ \Omega}{10.0\ \Omega}\right)100\% = 0.25\%$$

(b) By Ohm's law, $V_{OUT} = 5.0$ V.

$$V_{NL} = \frac{V_{OUT}}{\left(\frac{R_L}{R_{OUT} + R_L}\right)} = \frac{5.0\ \text{V}}{\left(\frac{10.0\ \Omega}{0.025\ \Omega + 10.0\ \Omega}\right)} = 5.013\ \text{V}$$

Series Regulators

The fundamental classes of voltage regulators are linear regulators and switching regulators. Both of these are available in integrated circuit form. Two basic types of linear regulator are the series regulator and the shunt regulator. A simple representation of a series type of linear regulator is shown in Figure 3(a), and the basic components are shown in the block diagram in Figure 3(b).

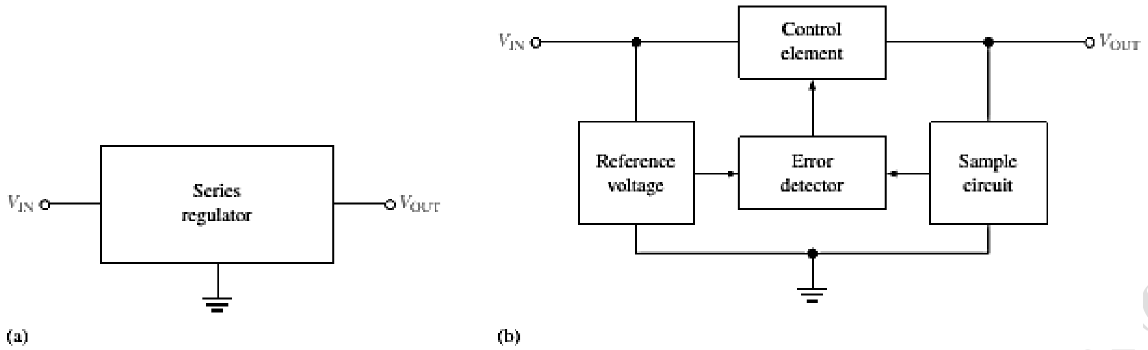


Figure 3

The control element maintains a constant output voltage by varying the collector-emitter voltage across the transistor. A basic op-amp series regulator is shown in Figure 4. The zener diode (D_1) holds the other op-amp input at a nearly constant reference voltage V_{REF}

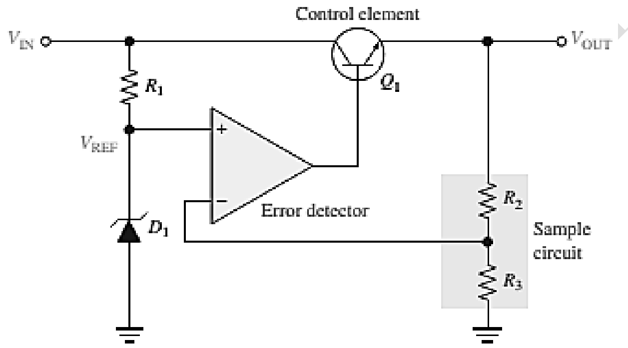
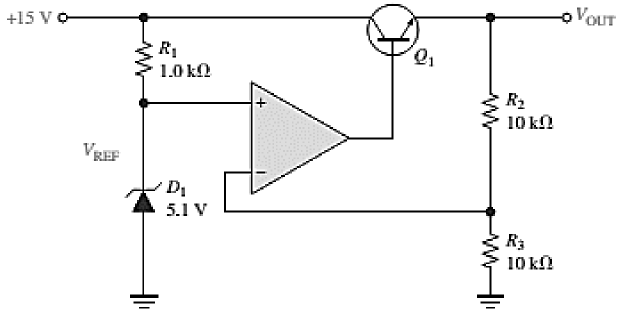


Figure 4

The output voltage for the series regulator circuit is:

$$V_{OUT} = \left(1 + \frac{R_2}{R_3}\right) V_{REF}$$

Example: Determine the output voltage for the regulator in the following Figure:



Solution:

$V_{REF} = 5.1$ V, the zener voltage. The regulated output voltage is therefore

$$V_{OUT} = \left(1 + \frac{R_2}{R_3}\right)V_{REF} = \left(1 + \frac{10\,\text{k}\Omega}{10\,\text{k}\Omega}\right)5.1\text{ V} = (2)5.1\text{ V} = \mathbf{10.2\ V}$$

Short-Circuit

Current limiting prevents excessive load current. Q_2 will conduct when the current through R_4 develops 0.7 V across Q_2's V_{BE}. This reduces base current to Q_1, limiting the load current. The current limit is:

$$I_{L(max)} = \frac{0.7V}{R_4}$$

For example, a 1.4 W resistor, limits current to about 0.5 A.

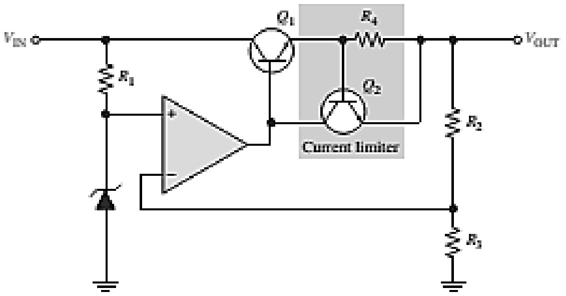


Figure 5: Series regulator with constant-current limiting.

Regulator with Fold-Back Current Limiting

Fold-back current limiting drops the load current well below the peak during overload conditions. Q_2 conducts when $V_{R5}+V_{BE}=V_{R4}$ and begins current limiting. V_{R5} is found by applying the voltage-divider rule:

$$V_{R5} = \left(\frac{R_5}{R_5 + R_6}\right) V_{OUT}$$

An overload causes V_{R5} to drop because V_{OUT} drops. This means that less current is needed to maintain conduction in Q_2 and the load current drops

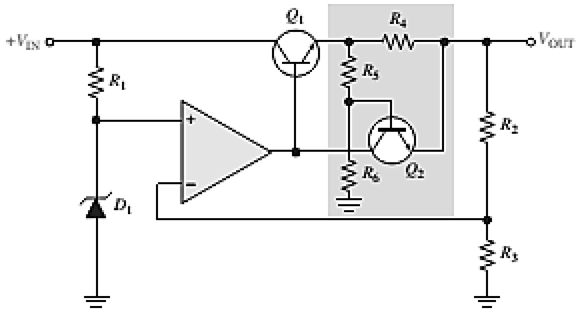


Figure 6: Series regulator with fold-back current limiting.

Basic Linear Shunt Regulators

The second basic type of linear voltage regulator is the shunt regulator, as shown in Figure 7. In the shunt regulator, the control element is a transistor in parallel (shunt) with the load, as shown in Figure 8. The control element maintains a constant output voltage by varying the collector current in the transistor.

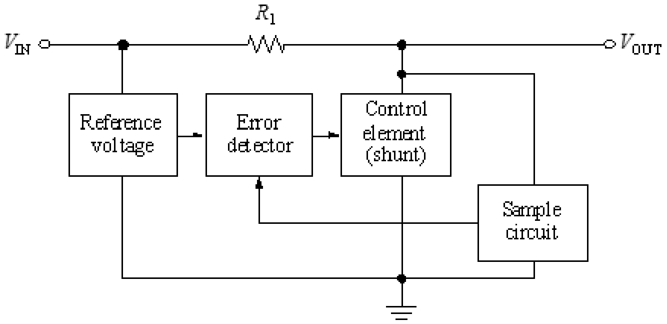


Figure 7

If the output voltage changes, the op-amp senses the change and corrects the bias on Q_1 to follow. e.g., a decrease in output voltage causes a decrease in V_B and an increase in V_C. Although it is less efficient than the series regulator, the shunt regulator has inherent short-circuit protection. The maximum current when the output is shorted is V_{IN}/R_1.

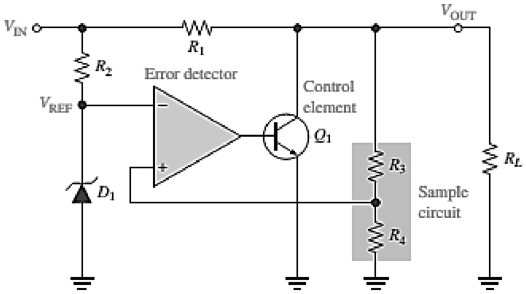
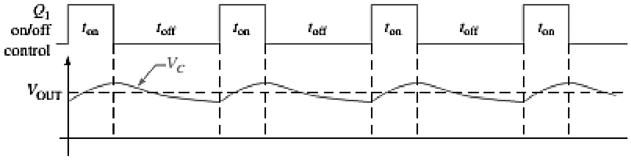


Figure 8

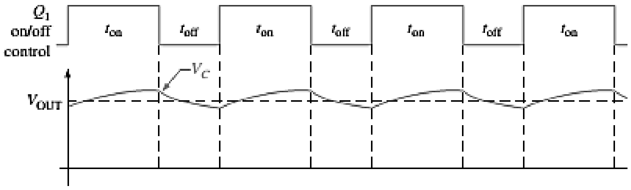
Switching Regulators

All **switching regulators** control the output voltage by rapidly switching the input voltage on and off with a duty cycle that depends on the load. Because they use high frequency switching, they tend to be electrically noisy.

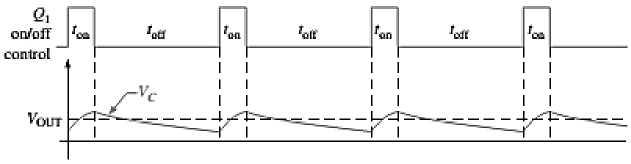
Figure 9



(a) V_{OUT} depends on the duty cycle.

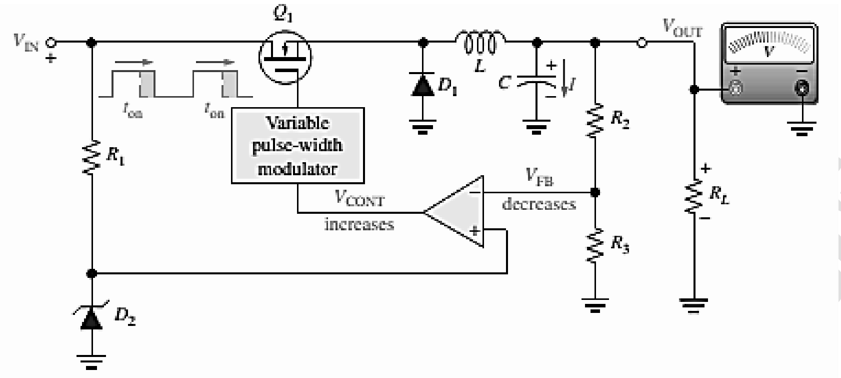


(b) Increase the duty cycle and V_{OUT} increases.

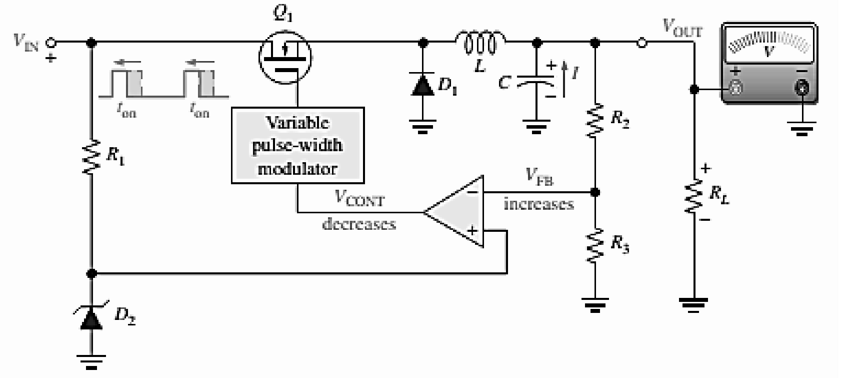


(c) Decrease the duty cycle and V_{OUT} decreases.

A **step-down switching regulator** controls the output voltage by controlling the duty cycle to a series transistor. The duty cycle changes depending on the load requirement. Because the transistor is either ON or OFF on all switching regulators, the power dissipated in the transistor is very small and the regulator is very efficient. The pulses are smoothed by an LC filter.



(a) When V_{OUT} attempts to decrease, the on-time of Q_1 increases.



(b) When V_{OUT} attempts to increase, the on-time of Q_1 decreases.

Figure 10: Basic regulating action of a step down switching regulator.

In a **step-up switching regulator**, the control element operates as a rapidly pulsing switch to ground. The switch on and off times are controlled by the output voltage. Step-up action is due to the fact the inductor changes polarity during switching and adds to V_{IN}. Thus, the output voltage is larger than the input voltage.

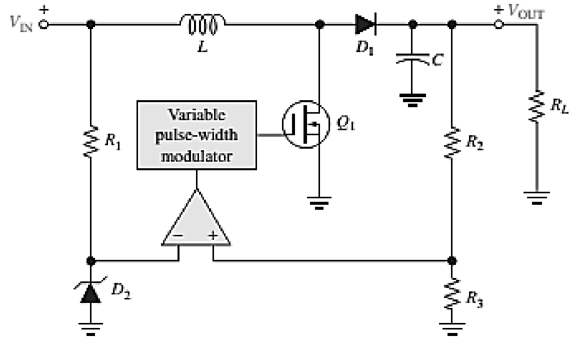


Figure 11: Basic step-up switching regulator.

Voltage-Inverter Configuration

In a voltage-inverter switching regulator, the output is the opposite polarity of the input. It can be used in conjunction with a positive regulator from the same input source. Inversion occurs because the inductor reverses polarity when the diode conducts, charging the capacitor with the opposite polarity of the input.

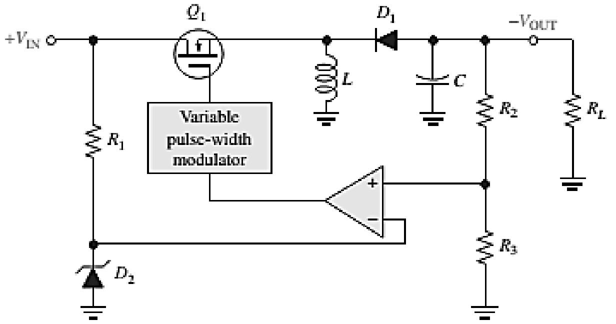
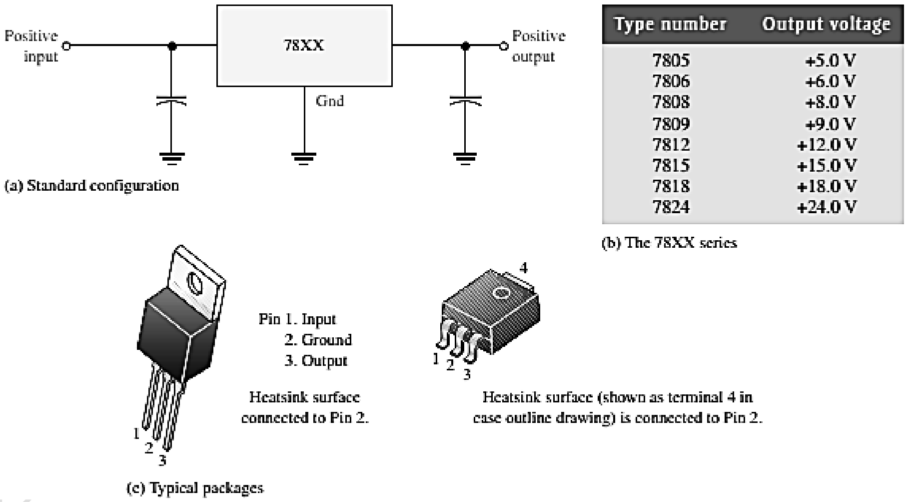


Figure 11: Basic inverting switching regulator.

Integrated circuit voltage regulators

Integrated circuit voltage regulators are available as series regulators or as switching regulators. The popular three-terminal regulators are often used on separate *pc* boards within a system because they are inexpensive and avoid problems associated with large power distribution systems (such as noise pickup).



(a) Standard configuration

Type number	Output voltage
7805	+5.0 V
7806	+6.0 V
7808	+8.0 V
7809	+9.0 V
7812	+12.0 V
7815	+15.0 V
7818	+18.0 V
7824	+24.0 V

(b) The 78XX series

(c) Typical packages

Figure 12: The 78XX series three-terminal fixed positive voltage regulators.

The 78XX series is a fixed positive output regulator available in various packages and with standard voltage outputs. The only external components required with the 78XX series are input and output capacitors and some form of heat sink. These IC's include thermal shutdown protection and internal current limiting. The 78XX series are primarily used for fixed output voltages, but with additional components, they can be set up for variable voltages or currents.

The 79XX series is the negative output counterpart to the 78XX series, however the pin assignments are different on this series. Other specifications are basically the same

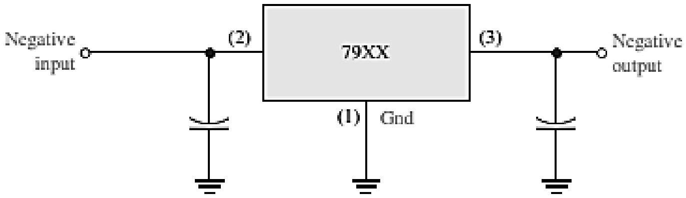


Figure 13: The 79XX series three-terminal fixed negative voltage regulators.

Adjustable Positive Linear Voltage Regulators

The LM317 is an example of a three-terminal positive regulator with an adjustable output IC regulator as shown in figure 14. There is a fixed reference voltage of +1.25 V between the output and adjustment terminals. There is no ground pin. The output voltage is calculated by:

$$V_{OUT} = V_{REF}\left(1 + \frac{R_2}{R_1}\right) + I_{ADJ}R_2$$

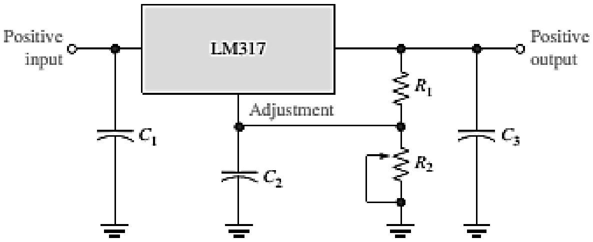
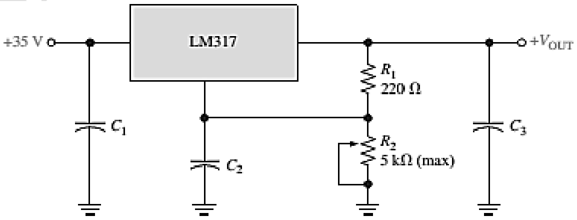


Figure 14: The LM317 three-terminal adjustable positive voltage regulator.

Example: Determine the minimum and maximum output voltages for the voltage regulator in the following Figure. Assume I_{ADJ} = 50 µA.



Solution:

$$V_{R1} = V_{REF} = 1.25\text{ V}$$

When R_2 is set at its minimum of 0 Ω,

$$V_{OUT(min)} = V_{REF}\left(1 + \frac{R_2}{R_1}\right) + I_{ADJ}R_2 = 1.25\text{ V}(1) = \mathbf{1.25\text{ V}}$$

When R_2 is set at its maximum of 5 kΩ,

$$V_{OUT(max)} = V_{REF}\left(1 + \frac{R_2}{R_1}\right) + I_{ADJ}R_2 = 1.25\text{ V}\left(1 + \frac{5\text{ k}\Omega}{220\ \Omega}\right) + (50\ \mu\text{A})\,5\text{ k}\Omega$$
$$= 29.66\text{ V} + 0.25\text{ V} = \mathbf{29.9\text{ V}}$$

The External Pass Transistor

IC regulators are limited to a maximum allowable current before shutting down. The circuit shown in Figure 15 is uses an external pass transistor to increase the maximum available load current.

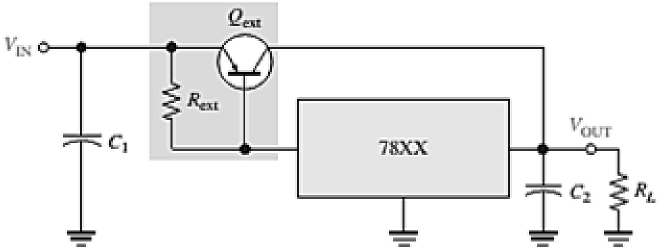


Figure 15

R_{ext} sets the point where Q_{ext} begins to conduct:

$$\mathrm{R_{ext}} = \frac{0.7\ \mathrm{V}}{\mathrm{I_{max}}}$$

The 78S40 is an IC containing all of the elements needed to configure a switching regulator, using a few external parts.

It is a **universal switching regulator subsystem** because it can be configured as a step-down, step-up, or inverting regulator by the user. The data sheet shows typical circuits for these configurations. In the figure 16 is the step-down configuration.

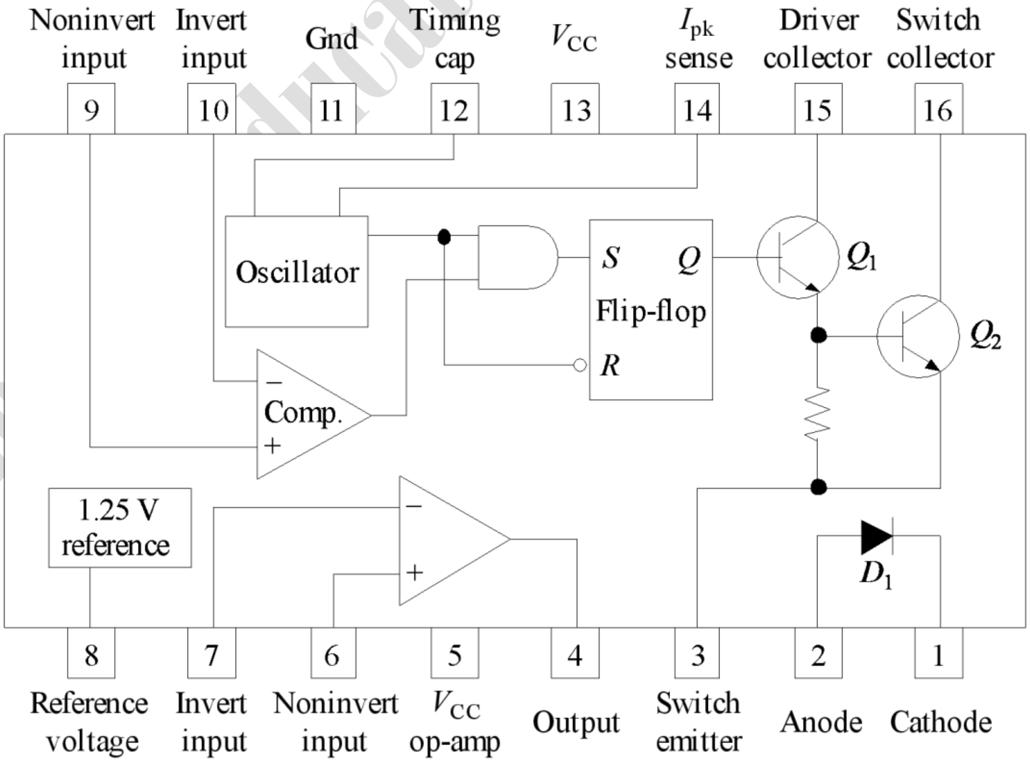


Figure 16