Agenda

- Voltage Regulation
- Basic Linear Series Regulators
- Basic Linear Shunt Regulators
- Intro. to Switching Regulators
- **IC Voltage Regulator**

Intro.

- **Two** basic **categories** of voltage regulation are:
  - Line regulation
  - Load regulation

- The **purpose** of **line regulation** is to maintain a nearly **constant output** voltage **when** the **input** voltage **varies.**
- The **purpose** of **load regulation** is to maintain a nearly **constant output** voltage **when** the **load varies.**

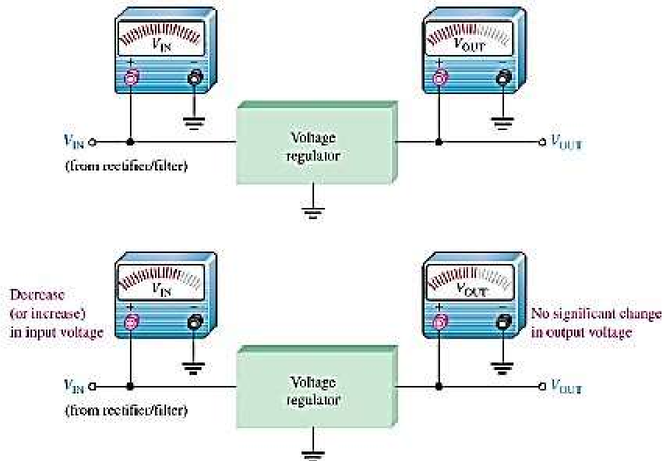
Line Regulation

- When the ac input (line) voltage of a power supply changes, an electronic circuit called a **regulator** maintains a nearly constant output voltage.
- **Line regulation** can be defined as the percentage change in the output voltage for a given change in the input voltage

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

- Line regulation can also be expressed in units of **%/V**

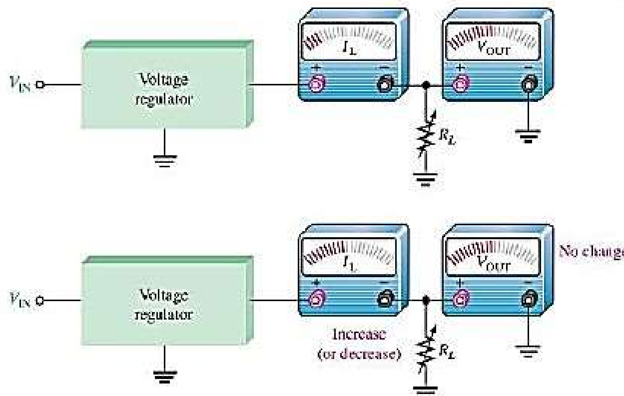
$$\text{Line regulation} = \frac{(\Delta V_{OUT}/V_{OUT})100\%}{\Delta V_{IN}}$$



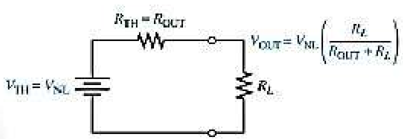
Load Regulation

- Load regulation can be defined as the percentage change in output voltage for a given change in load current.
- One way to express load regulation is as a percentage change in output voltage from no-load (NL) to full-load (FL).

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



- The load regulation can be expressed as a percentage change in output voltage for each mA change in load current.
- Using R_{OUT}, Thevenin equivalent circuit for a power supply with a load resistor.

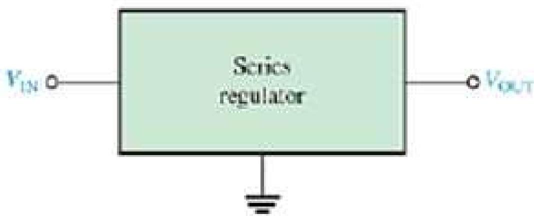


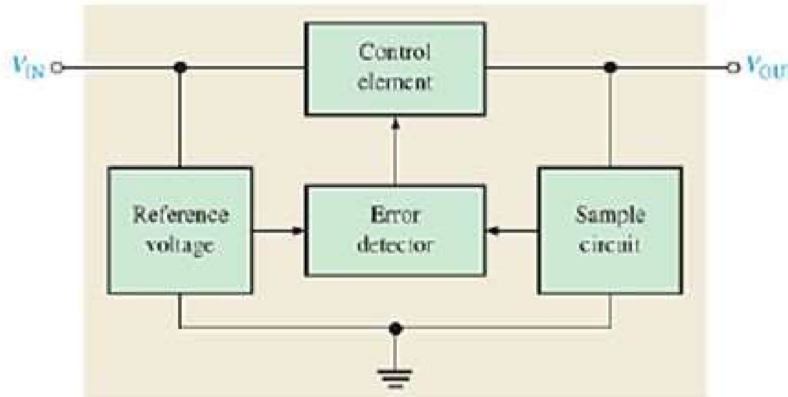
$$\text{Load regulation} = \left(\frac{R_{OUT}}{R_{FL}}\right)100\%$$

Types of Voltage Regulators:

- ❑ Series Voltage Regulator
- ❑ Shunt Voltage Regulator
    - ❑ Switching Regulator

1. Series Voltage Regulator



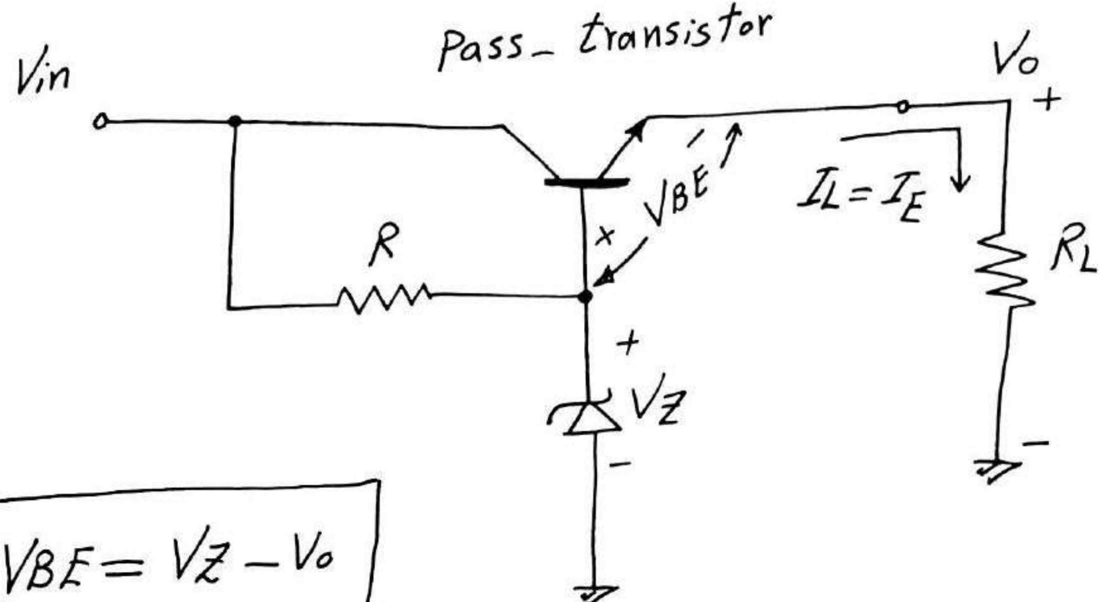


Block Diagram of Series Regulator

- **As Vo increased, the comparator circuit compares Vo with a reference voltage and since there a deference , generates a control signal to the control element to reduce Vo till Vo reaches the reference voltage and vice-versa.**
- **Series regulator**

  The control element is connected in series between Vo and Vin.

(a) Transistor Voltage Regulator:



$$\boxed{V_{BE} = V_Z - V_o}$$

* As V_o decreased, VBE increased so, I_B increased and I_E Also increased but $V_o = I_L . R_L$
so, V_o increased again.

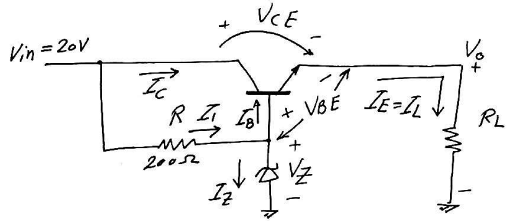
* As V_o increased, VBE decreased so, I_B decreased and Also I_E decreased, $I_E = I_L$
and $V_o = I_L . R_L$ decreased again.

$$I_B = I_S \, e^{\frac{VBE}{V_T}}$$

$VBE \uparrow \longrightarrow \therefore I_B \uparrow$

$VBE \downarrow \longrightarrow \therefore I_B \downarrow$

Example:



* $V_Z = 12V$, $V_{BE} = 0.65V$

Find :- [1] V_o [2] Collector to Emitter Voltage (V_{CE})

[3] The current in R. (I_1)

Solution

[1] K.V.L $-V_Z + V_{BE} + V_o = 0$

$V_o = V_Z - V_{BE} = 12 - 0.65$

$V_o = 11.35V$

[2] $V_{in} = V_{CE} + V_o$

$\therefore V_{CE} = V_{in} - V_o = V_C - V_E$

$= 20 - 11.35$

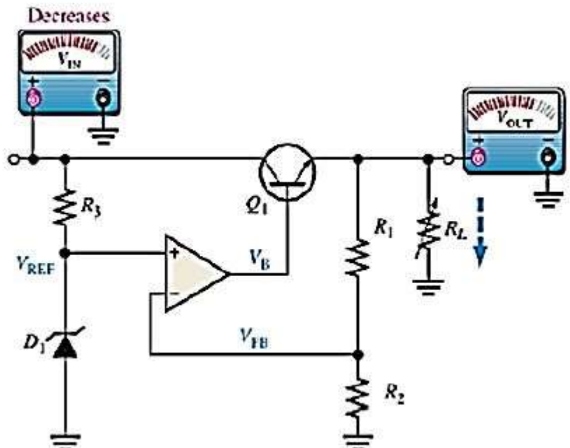
$V_{CE} = 8.65V$ (Not $V_{CE} > 0.7V$ ∴ Active mode)

[3] $I_1 = \dfrac{V_{in} - V_Z}{R} = \dfrac{20 - 12}{0.2\,k\Omega} = 40\,mA$

(c) Op-Amp series Regulator

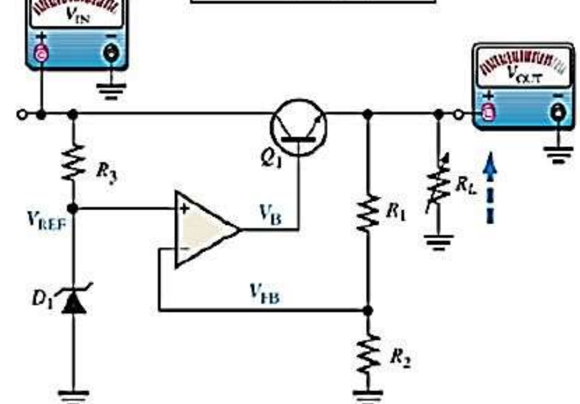
- Illustration of series regulator action that keeps V_{OUT} constant when V_{IN} or R_L changes.

$$V_{OUT} \cong \left(1 + \frac{R1}{R2}\right)V_{REF}$$



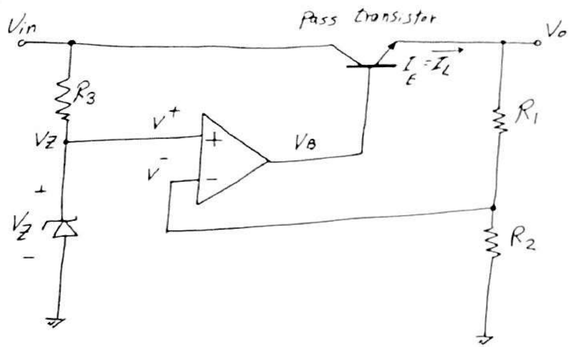
(a) When V_{IN} or R_L decreases, V_{OUT} attempts to decrease. The feedback voltage, V_{FB}, also attempts to decrease, and as a result, the op-amp's output voltage V_B attempts to increase, thus compensating for the attempted decrease in V_{OUT} by increasing the Q_1 emitter voltage. Changes in V_{OUT} are exaggerated for illustration.

When V_{IN} (or R_L) stabilizes at its new lower value, the voltages return to their original values, thus keeping V_{OUT} constant as a result of the negative feedback.



(b) When V_{IN} or R_L increases, V_{OUT} attempts to increase. The feedback voltage, V_{FB}, also attempts to increase, and as a result, V_B, applied to the base of the control transistor, attempts to decrease, thus compensating for the attempted increase in V_{OUT} by decreasing the Q_1 emitter voltage.

When V_{IN} (or R_L) stabilizes at its new higher value, the voltages return to their original values, thus keeping V_{OUT} constant as a result of the negative feedback.



* $\boxed{V^+ = V_Z}$

* $\boxed{V^- = \frac{R_2}{R_1+R_2} V_o}$

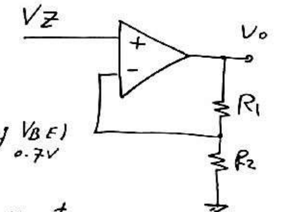
* V_B is proportional to $(V_Z - V^-)$
* As V_o decreased ↦ ∴ V^- decreased
  ∴ $(V_Z - V^-)$ Increased ↦ ∴ V_B Increased
  so, $I_E (I_L)$ is Increased ∴ V_o Increased.

* As V_o Increased ↦ ∴ V^- increased and
  then, $(V_Z - V^-)$ ↦ decreased ∴ V_B decreased
  ∴ $I_E (I_L)$ decreased
  ∴ V_o decreased.

op-amp acting as
Non-inverting amplifier
For V_Z so,

$$V_o = \left(1 + \frac{R_1}{R_2}\right) V_Z$$

(neglecting V_{BE} 0.7V)



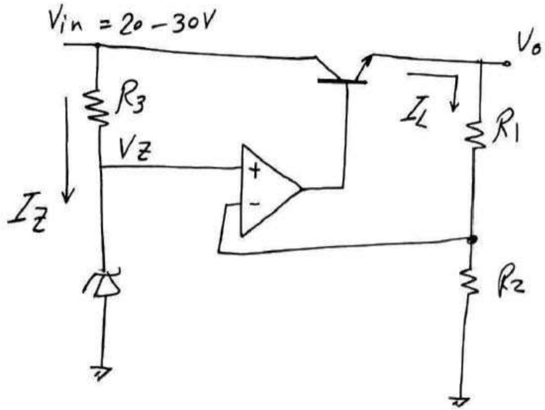
* R_3 is used to limit the current in Zener diode, and designed such that (I_Z) does not exceeds (I_{Zmax}) to prevent damage of Zener diode, and does not drop below (I_{Zmin}) to keep Zener diode operating in breakdown region.

Example:

Design a series Regulator using op-amp and a 6-V Zener diode to maintain a regulated output of 18V.

Assuming that the unregulated input varies between 20V and 30V and the current through the Zener diode must be at least 20mA to keep it in its breakdown region.

Solution:



$$* \quad V_o \cong \left(1+\frac{R_1}{R_2}\right)V_Z$$

$$18 = \left(1+\frac{R_1}{R_2}\right)6$$

$$1+\frac{R_1}{R_2} = 3 \Rightarrow \frac{R_1}{R_2} = 2$$

Let $\boxed{\begin{array}{l} R_2 = 10\,K\Omega \\ \therefore R_1 = 20\,K\Omega \end{array}}$

$$* \quad I_Z = \frac{V_{in} - V_Z}{R_3} \quad , \quad I_{Z_{min}} = \frac{V_{in(min)} - V_Z}{R_3}$$

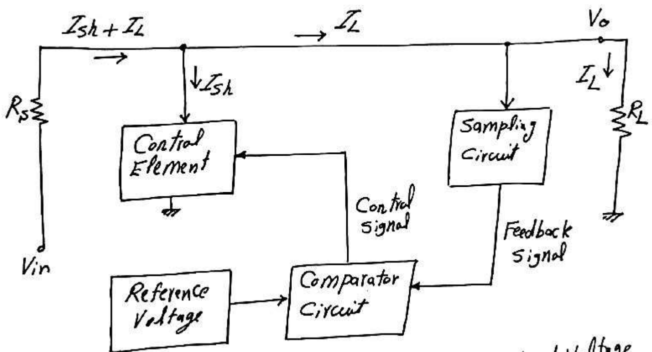
$$\therefore 20\,mA = \frac{20-6}{R_3}$$

$$R_3 = \frac{20-6}{20\,mA} = 0.7\,K\Omega$$

$$R_3 = 0.7\,K\Omega = 700\,\Omega$$

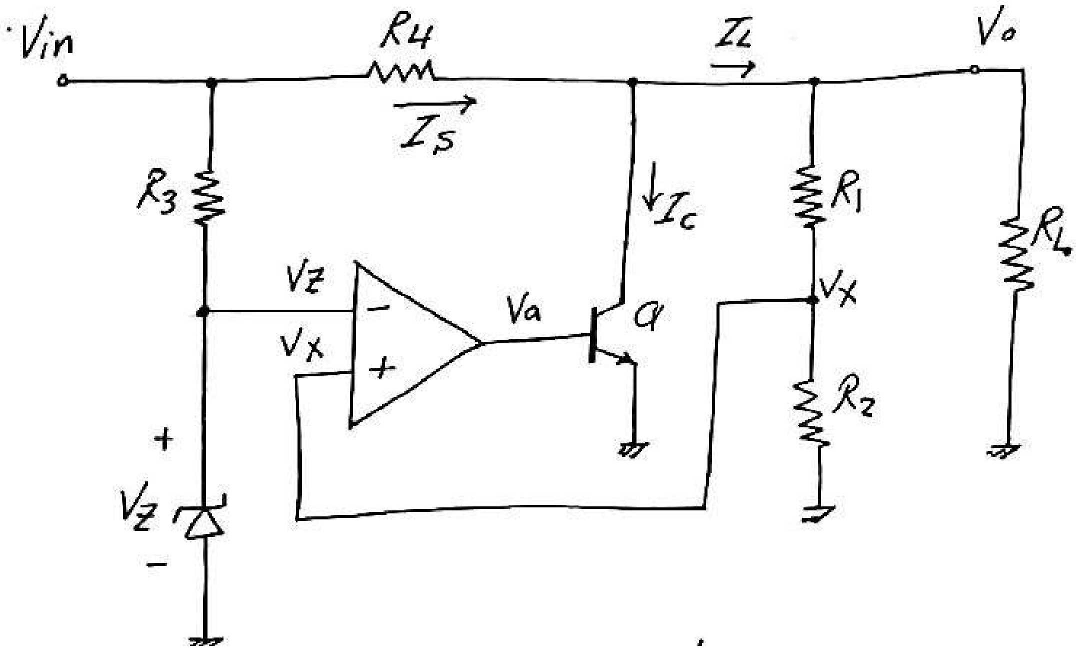
2. Shunt Voltage Regulator

Block-diagram



* The Control element maintains a Constant Load Voltage by shunting more or less current from the Load.
* Control element acts as a Variable resistance. When the Load Voltage decreases, resistance of Control element increases so that less current is diverted from the Load so, I_L increased, increasing V_o again and Vice-versa.

Op-Amp Shunt Regulator



* R_1 and R_2 acts as a voltage divider

$$V_X = \frac{R_2}{R_1+R_2} V_o$$

* $V_a = A(V_X - V_Z)$, A = op-amp gain

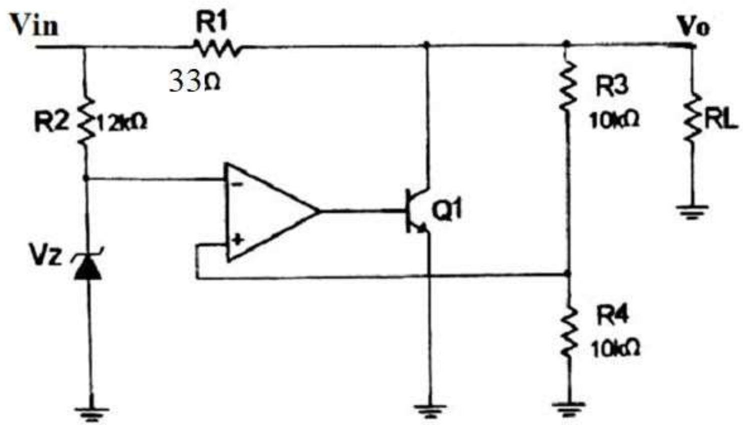
* As V_o increased → ∴ V_X increased
∴ V_a increased ∴ BJT (Q) conduct heavily and draws much current from I_S
so, I_L decreased ∴ V_o decreased.

* As V_o decreased (Lower than V_Z), V_a = -ve value
∴ BJT will be oFF ($I_C = 0$)
so, more current is driven into the Load increasing V_o.

* Short circuit current $\boxed{I_{S.C} = \frac{V_{in}}{R_4}}$ as $V_o = 0$

Example:

- The circuit shown in Figure represents a voltage regulator.



1. What is the type of this regulator?
2. What is the power rating must R_1 have if the maximum input voltage is 18V?

Solution:

1. What is the type of this regulator?

   Shunt Regulator

2. What is the power rating must R_1 have if the maximum input voltage is 12.5 V?

worst case $\rightarrow$ $R_L = 0$ (short)

$$\therefore V_o = 0$$

$$\therefore I_L = I_{S.C} = \frac{V_{in} - 0}{R_1} = \frac{18}{33} = 0.54545\text{A}$$

$$\therefore P_{R_1} = I_{SC}^2 R_1$$

$$\boxed{P_{R_1} = 9.82 \text{ watts}}$$

$\therefore$ A resistor with at least 10 watts should be used.

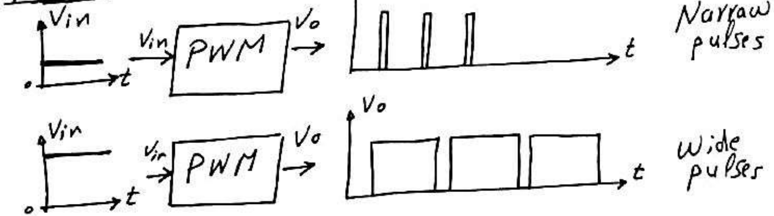
3. Switching Regulator

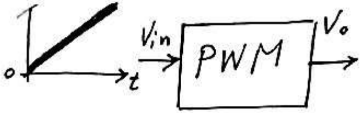
* The main disadvantage of series and shunt Regulators :-
  * The Control element must dissipate Large amount of power in order for the transistor to operate in its active region (Low power efficiency).

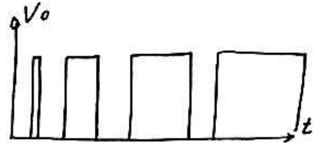
* Switching Regulators
  * The Control element is switched on and off at a rapid rate and is therefore either in saturation or cut-off modes most of time.
  So, very Low power Consumption is obtained.

* The Fundamental Component in switching Regulators is the pulse width modulator [PWM] that produces a train of pulses having widths that are proportional to the device input.

PWM :-

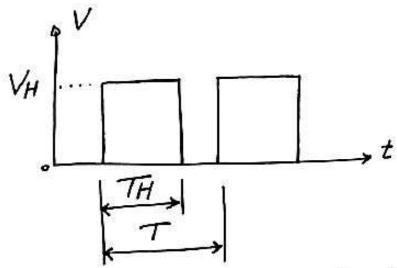






* Duty-cycle (D)

$$D = \frac{T_H}{T}$$



$$V_{d.c} = V_H\left(\frac{T_H}{T}\right)$$ Average (d.c) value of pulse train

* The switching Regulator uses a pulse-width modulator (PWM) to produce a pulse train whose duty cycle is automatically adjusted as ~~ness~~ necessary to increase or decrease the d.c value of the train

Note:-

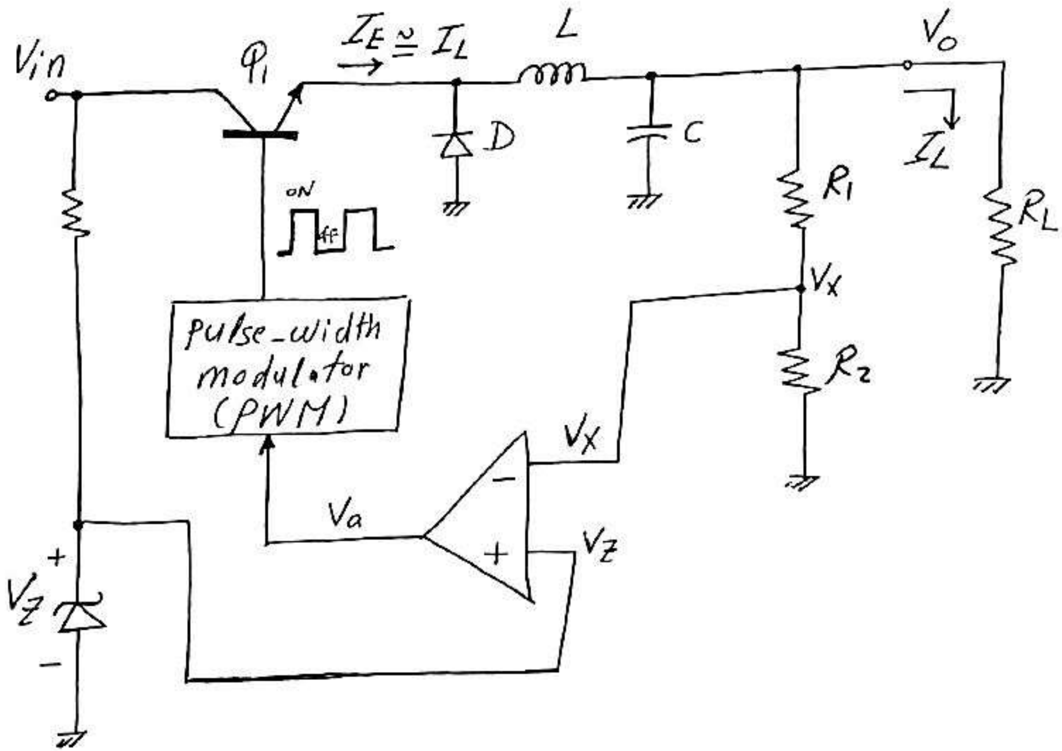
$$V_{d.c} = \frac{1}{T}\int_0^{T_H} V_H \, dt$$

$$= \frac{V_H}{T}\left[t\right]_0^{T_H}$$

$$= \frac{V_H}{T}\left(T_H - 0\right)$$

$$\boxed{V_{d.c} = V_H \cdot \frac{T_H}{T}}$$

Switching Regulator Circuit:



* The Zener diode provides the reference voltage (V_Z) to the op-amp that compared with (V_X) obtained from the voltage divider R_1 and R_2.

* As V_o decreases, V_X decreases
  ∴ ($V_Z - V_X$) increased
  ∴ V_a increased ↦ pulse-width increased
  (T_H increased) ↦ ∴ $V_{d.c}$ increased
  ∴ Q_1 conduct more current and increasing $I_E (\cong I_L)$ ∴ V_o increased.

* As V_o increased ↦ V_X increased ↦ ∴($V_Z - V_X$) decreased
  ∴ V_a decreased ↦ $V_{d.c}$ decreased
  ∴ Q_1 conducts less current ↦ $I_E (I_L) \downarrow$
  ∴ V_o decreased.

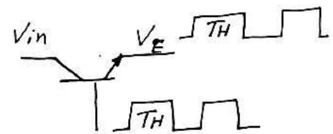
~~I~~nductor (L) and Capacitor (C) acting as Low pass Filter (LPF) that recovers the d.c value of the pulse waveform supplied by Q_1. (removing Harmonics).

*
↳ Diode (catcher diode) ↦ supress the negative voltage transient generated by the inductor when Q_1 OFF

Example:

A switching Regulator is designed to maintain 12 V d.c output when the unregulated input voltage Varies from 15V to 24V. VCE(saturation) of Q_1 is 0.5V Assuming that the Load is constant, Find the minimum and maximum duty cycle of PWM.

Sol.



* $V_{in} = 15V$ (minimum)

$V_o(d.c) = 12\ V$

$V_{E(H)} = V_{in} - V_{CE(sat.)} = 15 - 0.5$

$V_{E(H)} = 14.5V \quad (V_H)$

$$V_{d.c} = V_H \cdot \frac{T_H}{T} \rightarrow \frac{T_H}{T} = \frac{V_{d.c}}{V_H} = \frac{12}{14.5}$$

$$\therefore \frac{T_H}{T} \cong 0.828 = 82.8\ \%$$ max. duty cycle

* $V_{in} = 24V$ (maximum)

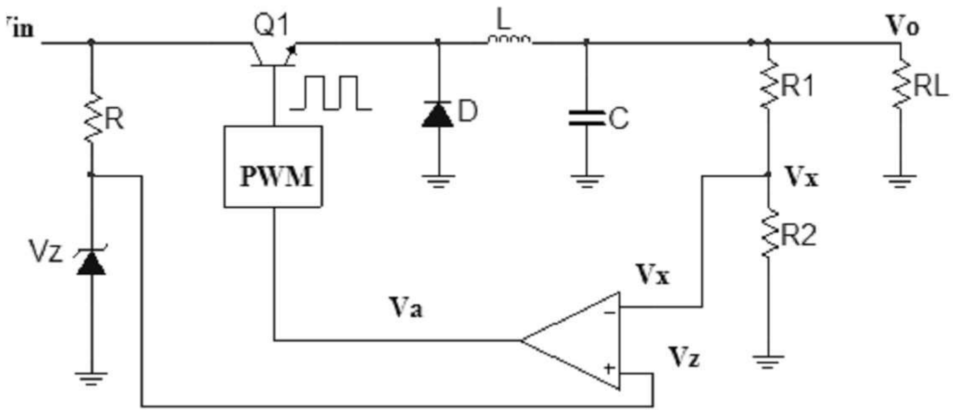
$V_{E(H)} = 24 - 0.5 = 23.5V$

$V_{d.c} = 12V$

$$\therefore \frac{T_H}{T} = \frac{12}{23.5} \cong 0.51 = 51\ \%$$ Max. duty cycle

Example:

A regulator circuit is shown in Figure :



1. What is the type of this regulator?
2. What are the functions of Diode (D), inductor (L) and capacitor (C)?
3. If this regulator is designed to maintain 12 V-DC output when the unregulated input voltage varies from 15V to 24V, V_{CE}(saturation) of Q1 is 0.2V and assuming that the load is constant, **Calculate the Minimum and Maximum Duty cycle of the PWM.**

Solution:

1. What is the type of this regulator?

switching Regulator.

2. What are the functions of Diode (D), inductor (L) and capacitor (C)?

Diode → supress negative Voltage Transient generated by inductor when Q_1 OFF.

(L, C) → Low pass Filter to recover the d.c value of the pulse waveform supplied by Q_1 (remove Harmonics).

3. If this regulator is designed to maintain 12 V-DC output when the unregulated input voltage varies from 15V to 24V, V_{CE}(saturation) of Q1 is 0.2V and assuming that the load is constant, **Calculate the Minimum and Maximum Duty cycle of the PWM.**

* $V_{in} = 15V$ (minimum)

$V_o(d.c) = 12V$

$V_E(H) = V_{in} - V_{CE(sat.)}$

$V_E(H) = 15 - 0.2 = 14.8V$

$V_{d.c} = V_H \cdot \frac{T_H}{T}$

$\therefore \frac{T_H}{T} = D = \frac{V_{d.c}}{V_H}$

$D(max) = \frac{V_{d.c}}{V_{H min}} = \frac{12}{14.8}$

$D(max) = 0.8108$

$= 81.08\%$

$V_{in} = 24V$ (maximum)

$V_E(H) = 24 - 0.2 = 23.8V$

$V_{d.c} = 12V$

$D(min) = \frac{V_{d.c}}{V_{E H max}} = \frac{12}{23.8}$

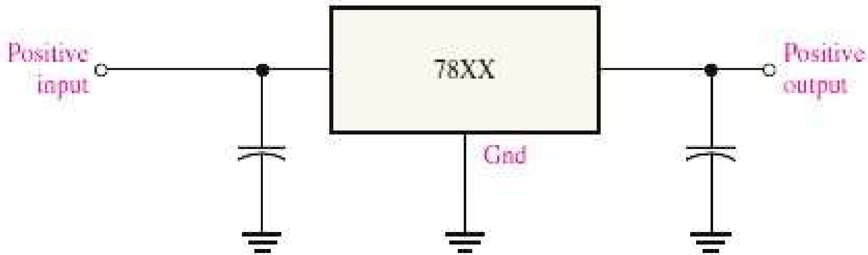
$D(min) = 0.5042$

$= 50.42\%$

4. Integrated Circuit Voltage Regulator

Fixed Positive Linear Voltage Regulators

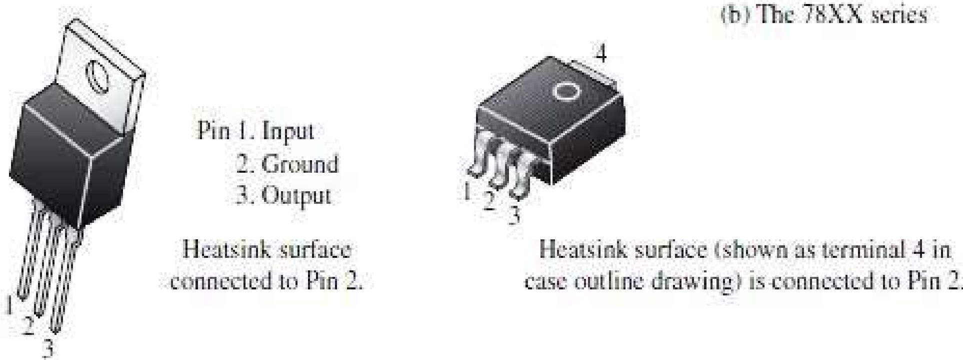
Although many types of IC regulators are available, the 78XX series of IC regulators is representative of three-terminal devices that provide a fixed positive output voltage. The three terminals are input, output, and ground as indicated in the standard fixed voltage configuration in Figure 17–26(a). The last two digits in the part number designate the output voltage. For example, the 7805 is a +5.0 V regulator. For any given regulator, the output voltage can be as much as ±4% of the nominal output. Thus, a 7805 may have an output from 4.8 V to 5.2 V but will remain constant in that range. Other available output voltages are given in Figure 17–26(b) and common packages are shown in part (c).



(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 17–26

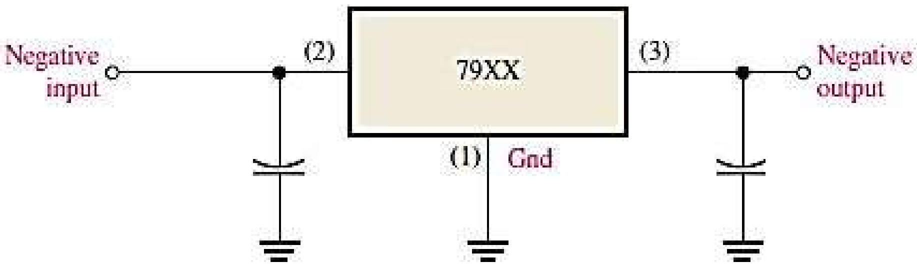
The 78XX series three-terminal fixed positive voltage regulators.

Capacitors, although not always necessary, are sometimes used on the input and output as indicated in Figure 17–26(a). The output capacitor acts basically as a line filter to improve transient response. The input capacitor filters the input and prevents unwanted oscillations when the regulator is some distance from the power supply filter such that the line has a significant inductance.

The 78XX series can produce output currents up to in excess of 1 A when used with an adequate heat sink. The input voltage must be approximately 2.5 V above the output voltage in order to maintain regulation. The circuits have internal thermal overload protection and short-circuit current-limiting features. **Thermal overload** occurs when the internal power dissipation becomes excessive and the temperature of the device exceeds a certain value. Almost all applications of regulators require that the device be secured to a heat sink to prevent thermal overload.

Fixed Negative Linear Voltage Regulators

The 79XX series is typical of three-terminal IC regulators that provide a fixed negative output voltage. This series is the negative-voltage counterpart of the 78XX series and shares most of the same features and characteristics except the pin numbers are different than the positive regulators. Figure 17–27 indicates the standard configuration and part numbers with corresponding output voltages that are available.



(a) Standard configuration

Type number	Output voltage
7905	–5.0 V
7905.2	–5.2 V
7906	–6.0 V
7908	–8.0 V
7912	–12.0 V
7915	–15.0 V
7918	–18.0 V
7924	–24.0 V

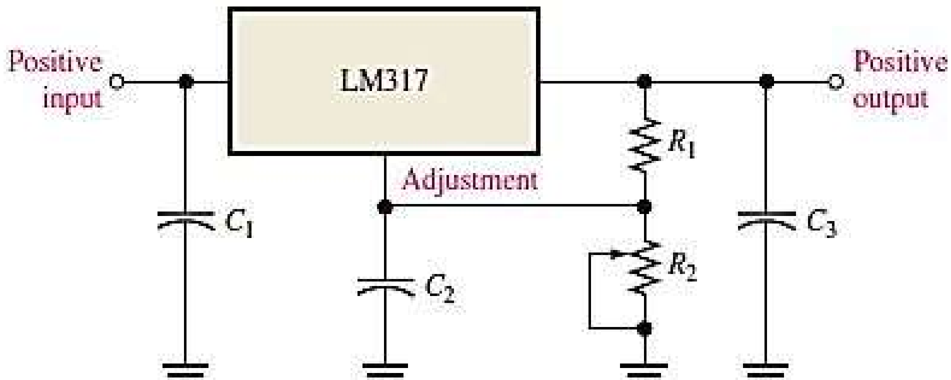
(b) The 79XX series

FIGURE 17–27

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

Adjustable Positive Linear Voltage Regulators

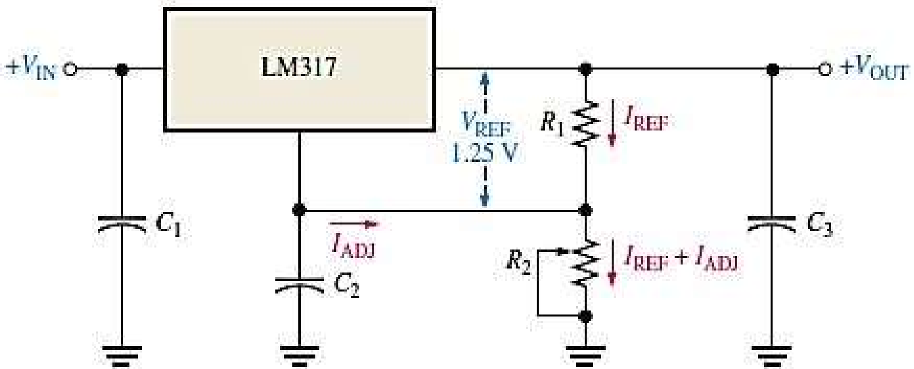
The LM317 is an example of a three-terminal positive regulator with an adjustable output voltage. The standard configuration is shown in Figure 17–28. The capacitors are for decoupling and do not affect the dc operation. Notice that there is an input, an output, and an adjustment terminal. The external fixed resistor R_1 and the external variable resistor R_2 provide the output voltage adjustment. V_{OUT} can be varied from 1.2 V to 37 V depending on the resistor values. The LM317 can provide over 1.5 A of output current to a load.



The LM317 is operated as a “floating” regulator because the adjustment terminal is not connected to ground, but floats to whatever voltage is across R_2. This allows the output voltage to be much higher than that of a fixed-voltage regulator.

Basic Operation As indicated in Figure 17–29, a constant 1.25 V reference voltage (V_{REF}) is maintained by the regulator between the output terminal and the adjustment terminal. This constant reference voltage produces a constant current (I_{REF}) through R_1, regardless of the value of R_2. I_{REF} is also through R_2.

$$I_{REF} = \frac{V_{REF}}{R_1} = \frac{1.25\ \text{V}}{R_1}$$



There is a very small constant current at the adjustment terminal of approximately 50 μA called I_{ADJ}, which is through R_2. A formula for the output voltage is developed as follows.

$$V_{OUT} = V_{R1} + V_{R2} = I_{REF}R_1 + I_{REF}R_2 + I_{ADJ}R_2$$
$$= I_{REF}(R_1 + R_2) + I_{ADJ}R_2 = \frac{V_{REF}}{R_1}(R_1 + R_2) + I_{ADJ}R_2$$

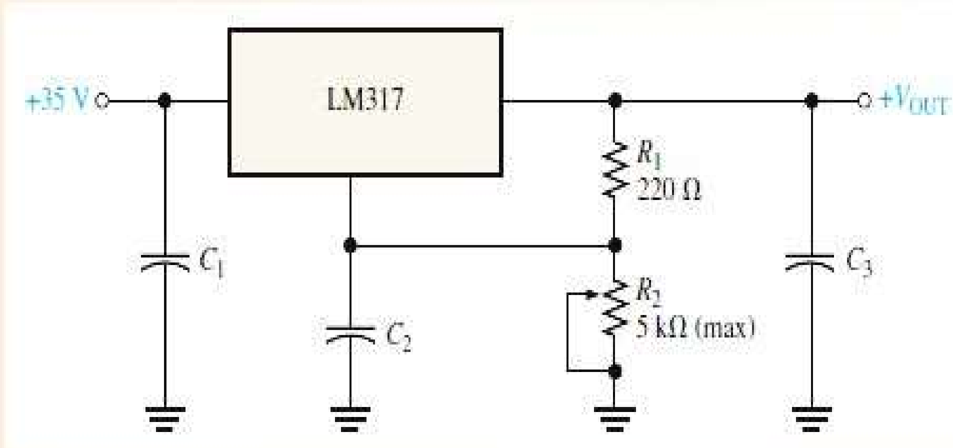
$$V_{OUT} = V_{REF}\left(1 + \frac{R_2}{R_1}\right) + I_{ADJ}R_2$$

As you can see, the output voltage is a function of both R_1 and R_2. Once the value of R_1 is set, the output voltage is adjusted by varying R_2.

EXAMPLE 17–6

Determine the minimum and maximum output voltages for the voltage regulator in Figure 17–30. Assume $I_{ADJ} = 50\ \mu A$.

FIGURE 17–30



Solution

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

When R_2 is set at its minimum of $0\ \Omega$,

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

When R_2 is set at its maximum of $5\text{ k}\Omega$,

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

$$= 29.66\text{ V} + 0.25\text{ V} = 29.9\text{ V}$$