Chapter 6
POWER SUPPLIES, BREAKDOWN DIODES, AND VOLTAGE REGULATORS

KKJ

Unregulated power supply:

- The rectifier–filter combination constitutes an ordinary dc power supply whose dc output voltage remains constant so long as input ac mains voltage or load is unaltered. Such power supply is called unregulated power supply.
- Unregulated power supply has following drawbacks:
  - i. The dc output voltage changes directly with input as voltage.
  - ii. The dc output voltage decreases as the load current increases (by decreasing load impedance), because there is greater voltage drop in power supply & hence smaller dc output voltage occurs.

Voltage Regulation

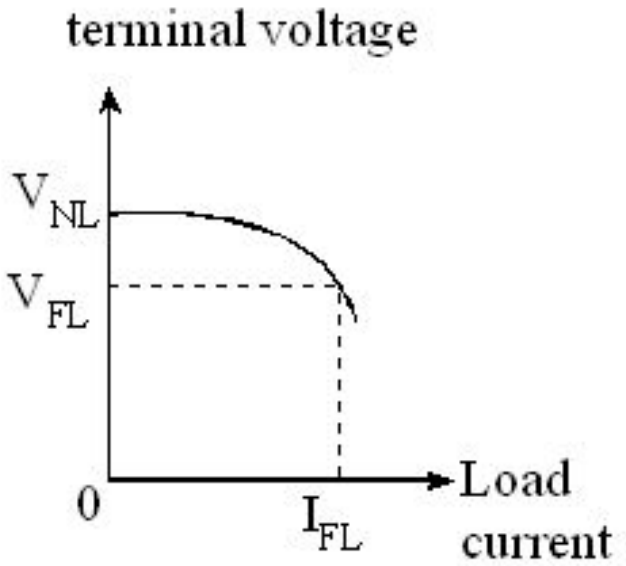


Fig. 6.1(a) No load and Full load condition in Power Supply

$$\left[\text{Voltage regulation} = \frac{\text{no-load voltage} - \text{full load voltage}}{\text{full load voltage}}\right]$$

$$\boxed{\%\ VR = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\ \%}$$

DC Voltage Regulators:

- **DC Voltage series regulator:**

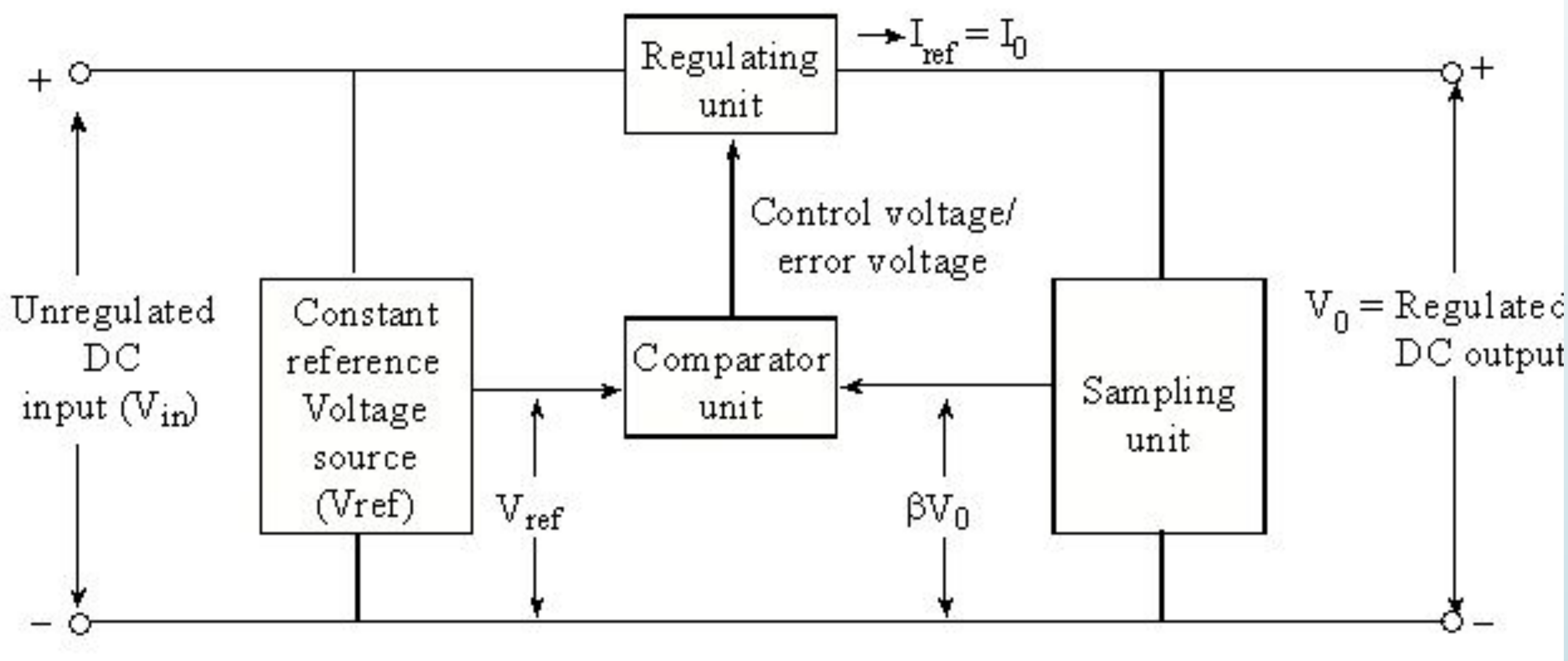


Fig.6.1(b) Block Diagram of DC Series Regulator

Series DC Voltage regulator using op-amp:

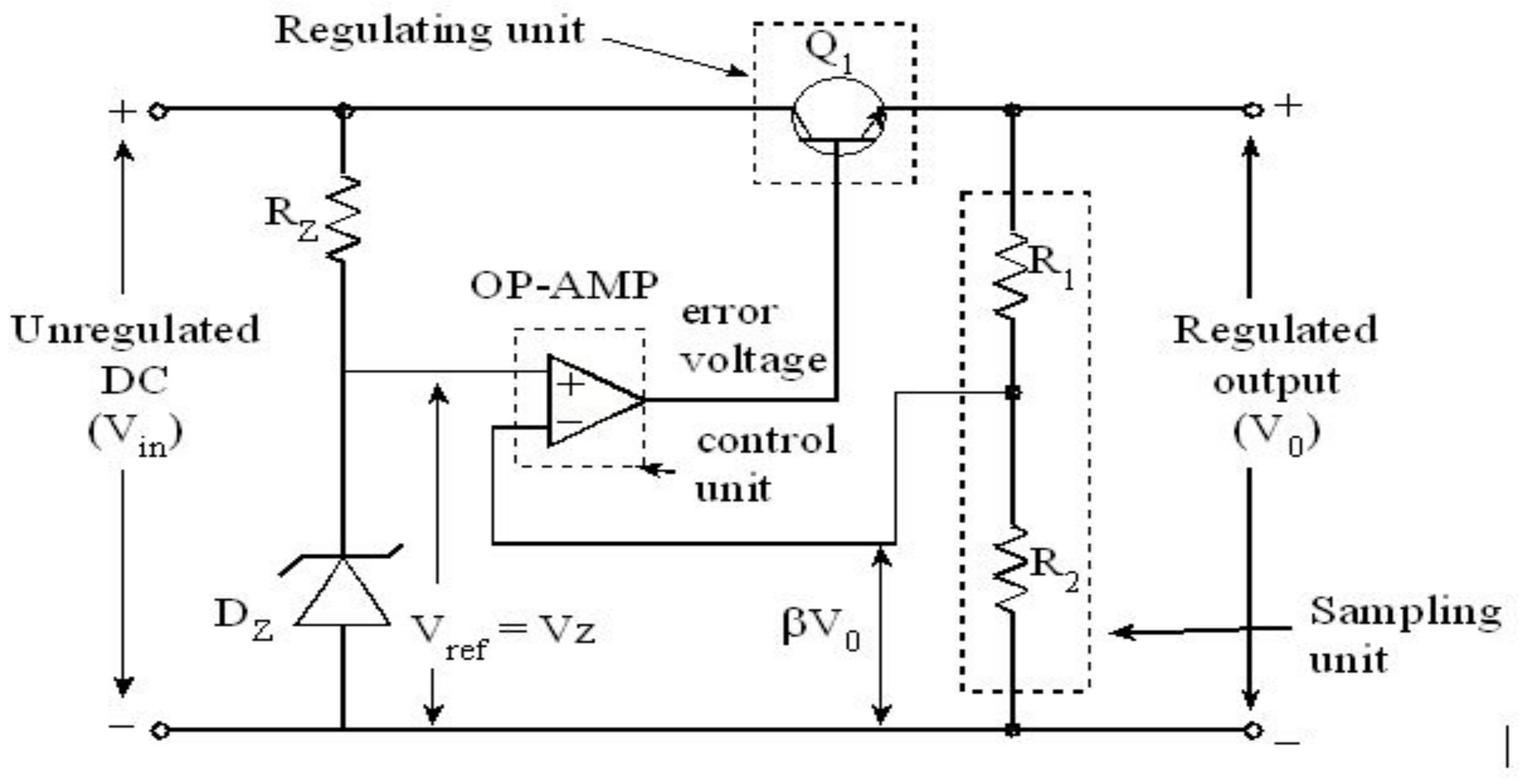


Fig.6.1(C) Series DCV Regulator using Op-amp

operation

- The feedback of output voltage applied to comparator which controls the conduction of transistor and thus maintains the output voltage constant.
- For zero error voltage, i.e. constant output;

  Input voltage to the op-amp:

  $$V_d = V^+ - V^- = 0$$

  $$\text{or,}\ \ V_Z - \beta V_o = 0$$

$$\text{or,}\quad V_o = \frac{1}{\beta}V_Z = \left(\frac{R_2 + R_1}{R_2}\right)V_Z$$

$$\boxed{\therefore V_o = V_Z\frac{(R_2 + R_1)}{R_2}} \Rightarrow \text{Regulated output voltage}$$

Series DC Voltage Regulator using Discrete Components:

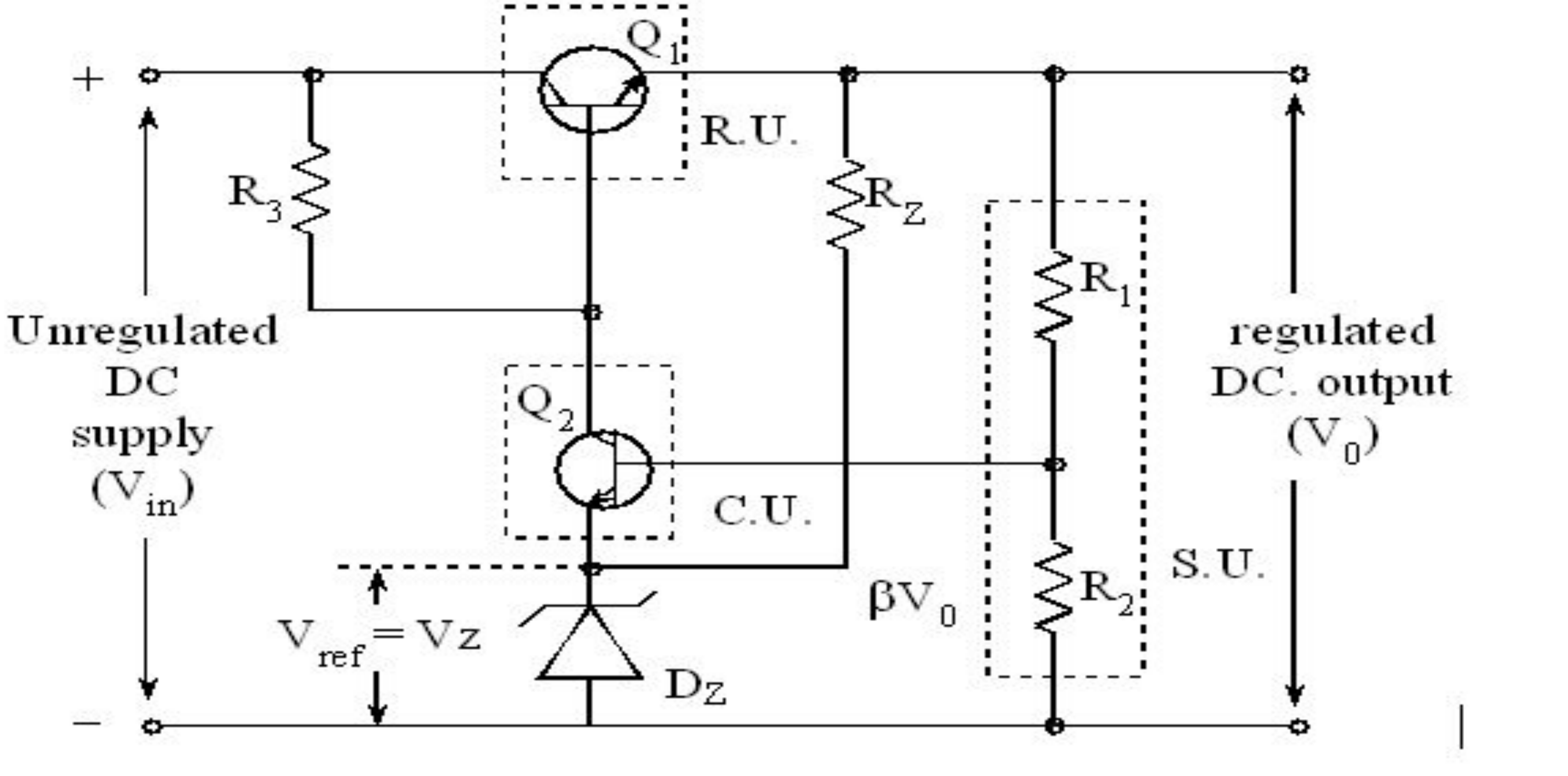


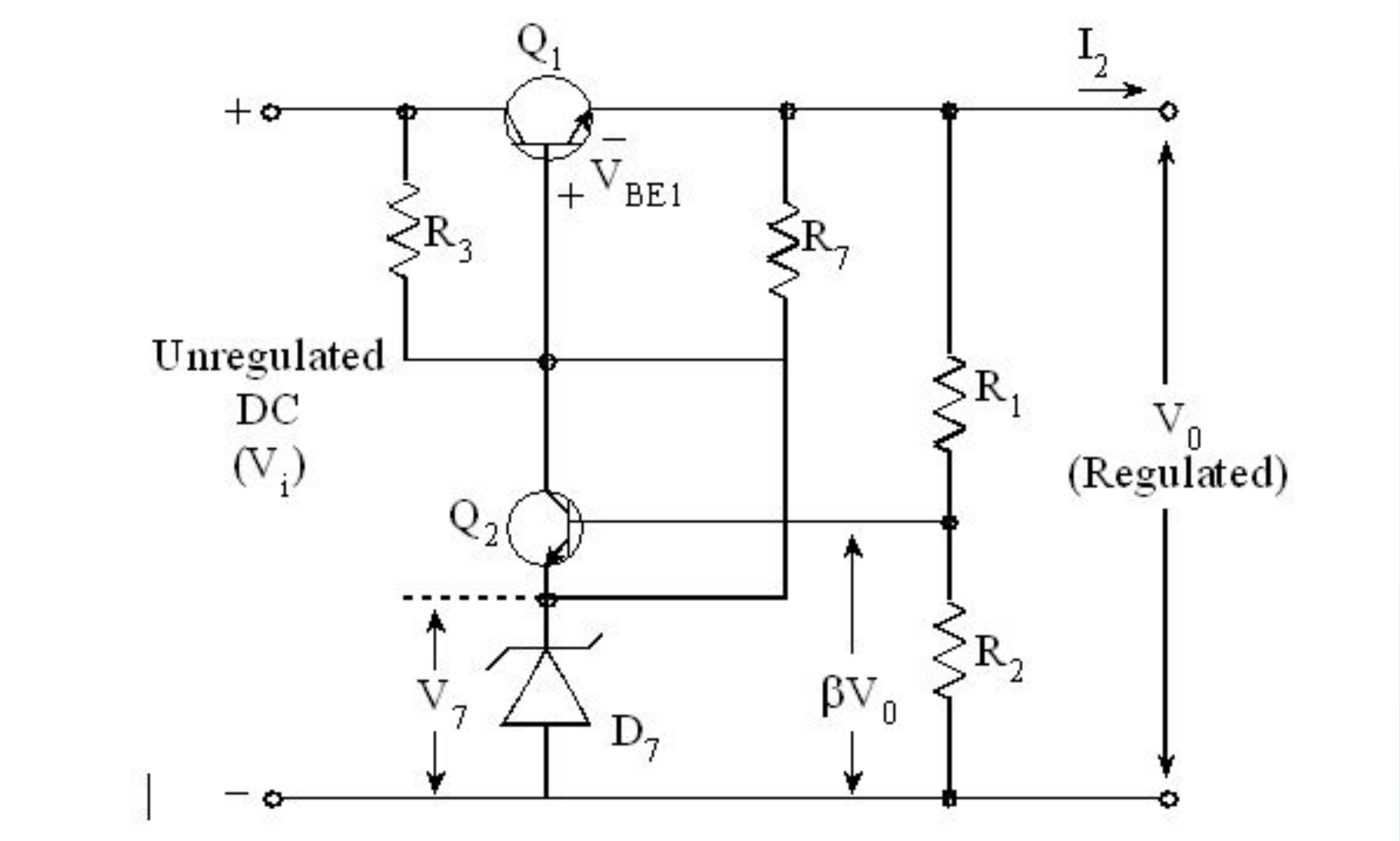
Fig. 6.1(d) Series DCV Regulator using Discrete Components

Operation

- Suppose the output voltage increases due to any reason. This causes an increase in voltage across R_2 as it is a part of the output circuit. This in turn means that more βVo is fed back to the base of transistor Q_2; producing larger collector current of Q_2. Most of this collector current flows through R_3 and causes the base voltage of Q_1 to decrease. This results in less output voltage i.e. increase in voltage is offset. Thus output voltage remains constant.
- (ii) Similarly, if output voltage tries to decrease, the feedback voltage βV_o also decreases. This reduces the current through Q_2 & R_3. This means more base voltage at Q_1 and more output voltage.

Consequently, the output voltage remains at the original level.

Estimation of stability factor (S_V) for the DC regulator:



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- The voltage gain of common emitter type transistor amplifier of Q_2 is expressed as;

$$A_V = \frac{\text{total resistance in collector section}}{\text{total resistance in emitter section}} = \frac{R_3}{r_e + r_Z}$$

Where,

$r_e \approx \frac{1}{g_m} = \frac{V_T}{I_{E2}}$ = emitter dynamic resistance

r_Z = dynamic resistance of zener diode

Input unregulated voltage; $Vi = V_{R3} + Vo + V_{BE1}$

Let $Vi = \Delta Vi$, $Vo = \Delta Vo$ be small changes in dc voltages. We assume $\Delta Vo = Vo$ = very small & can be ignored with respect to V_{R3}. Because by definition and by our requirement ΔVo should be zero for constant dc output voltage. Taking ac quantities only,

$v_i = v_{R3} + v_{be1} + v_o \approx V_{R3}$ [v_{be1} and v_o very small]

The output of the transistor Q_2

$v_{R3} = A_V \times$ (input to the base of Q_2)

$$= A_V.\ (\beta.Vo) = \frac{R_3}{r_e + r_Z} \times \beta v_o$$

$\approx v_i$

The stability factor of the regulator may be expressed as,

$$S_V = \frac{\Delta Vo}{\Delta Vi} \times 100\%$$

Contd..

$$= \frac{v_o}{v_i} \times 100\%$$

$$= \frac{v_o}{\left(\frac{R_3}{r_e + r_Z}\right) \beta v_o} \times 100\%$$

$$= \frac{r_e + r_Z}{R_3} \cdot \frac{R_1 + R_2}{R_2} \times 100\%$$

$$\text{Thus, } \boxed{S_V = \frac{r_e + r_Z}{R_3} \cdot \frac{R_1 + R_2}{R_2} \times 100} \approx 1.5\%$$

Best case

$S_V = 0$

Worst case

$S_V = 1$

Band gap Voltage Reference, a Constant Current Diodes:

- Fixed dc reference voltage that does not change with temperature
- Temperature independent voltage reference circuit widely used in IC circuits.

It is popular voltage reference method, also called as V_{BE} reference because it actually compensates negative temperature coefficient (NTC) characteristics of PN junction of V_{BE} with its PTC characteristics (thermal voltage) V_T, that means it involves generation of a voltage with PTC which is same as V_{BE} NTC. When added they yield zero temperature coefficient.

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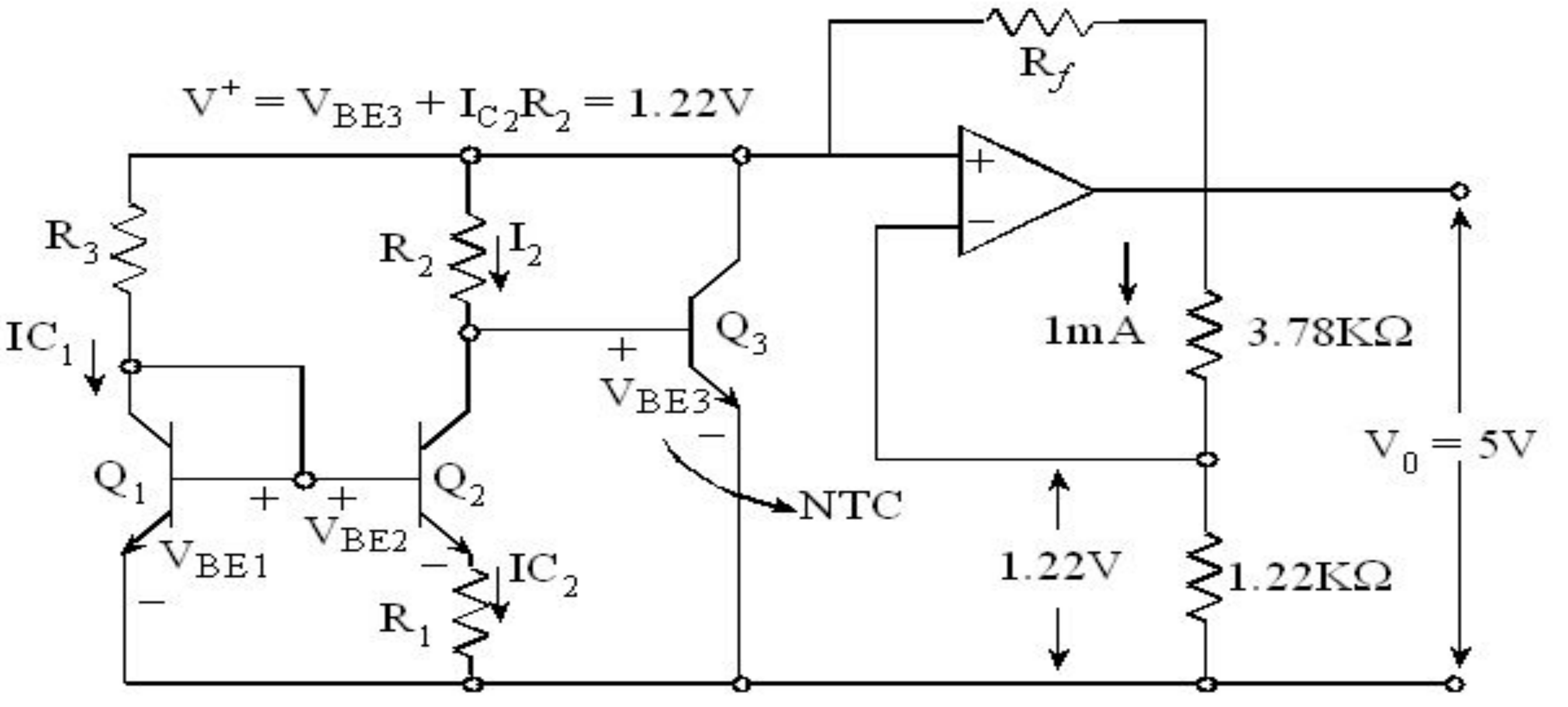

Fig.6.2 Typical5V regulator Circuit using Bandgap Reference

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- From figure, transistor Q_1 and Q_2 form a typical Widlar current source

Where;

$$I_{C2} R_1 = V_{BE1} - V_{BE2}$$

& $$I_{C1} = I_S e^{V_{BE1}/V_T}$$

$$I_{C2} = I_S e^{V_{BE2}/V_T}$$

So, $$\frac{I_{C1}}{I_{C2}} = \frac{e^{V_{BE1}/V_T}}{e^{V_{BE2}/V_T}} = e^{\frac{V_{BE1} - V_{BE2}}{V_T}}$$

Taking 'ln' on both sides,

or, $$\frac{V_{BE1} - V_{BE2}}{V_T} = \ln\left(\frac{I_{C1}}{I_{C2}}\right)$$

or, $$V_{BE1} - V_{BE2} = V_T \ln\left(\frac{I_{C1}}{I_{C2}}\right)$$

$$\boxed{\therefore R_1 I_{C2} = V_{BE1} - V_{BE2} = V_T \ln\left(\frac{I_{C1}}{I_{C2}}\right)}$$

To make PTC of voltage across R_2 equal to NTC of V_{BE3}, the current densities of Q_1 and Q_2 are chosen approx as 10:1.

Transistor Series Regulator

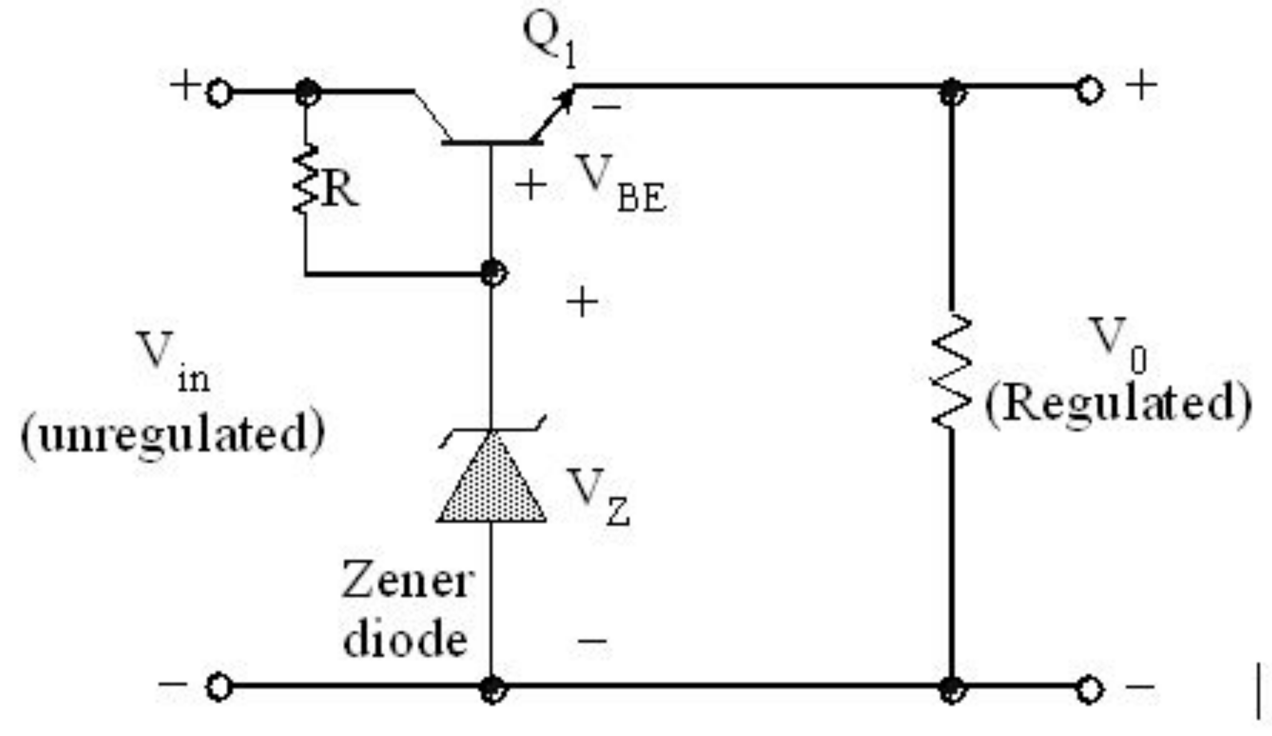

Fig.6.3 Transistor Series Regulator

Operation

The base voltage of transistor Q_1 is held to a relatively constant voltage across the zener diode in breakdown region.

Applying KVL we get

$V_Z = V_{BE} + V_O \Rightarrow V_{BE} = V_Z - V_O$.......... (1)

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- **Limitations:**
  - No provision to vary output voltage
  - Output will be affected by temperature variation
  - Regulator will perform only when zener diode is in breakdown region.

Improving Regulator Performance:

- By incorporating an additional transistor, we can improve performance of such regulator because it increases the gain. Here, R_1 and R_2 act as the voltage divider. Assuming, zener diode current doesn't load it appreciably.

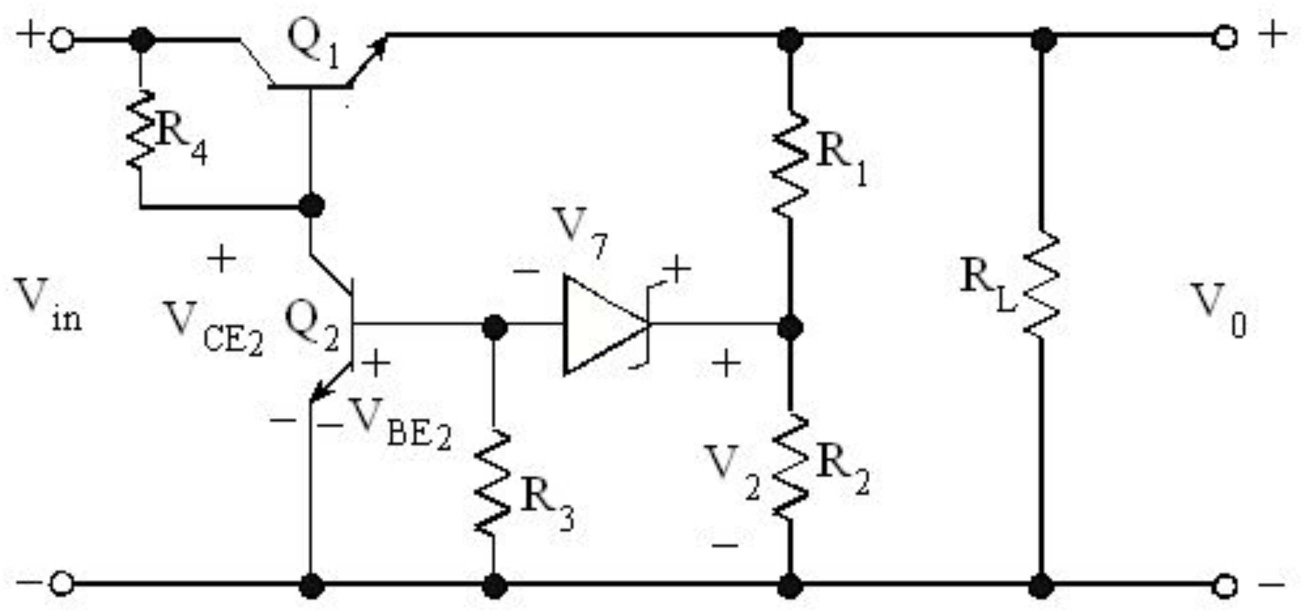

Fig.6.4 An Improved Transistor Series Regulator

$$V_2 = \frac{R_2}{R_1 + R_2} \cdot Vo \text{ .... } (2)$$

By Kirchhoff's voltage law,

$$V_{BE2} + V_Z = V_2$$

$$\therefore V_{BE2} = V_2 - V_Z \text{ .... } (3)$$

$$V_2 = \frac{R_2}{R_1 + R_2} V_O \Rightarrow V_O = \frac{R_1 + R_2}{R_2} V_2 = \frac{R_1 + R_2}{R_2} (V_Z + V_{BE2})$$

Current Limiting:

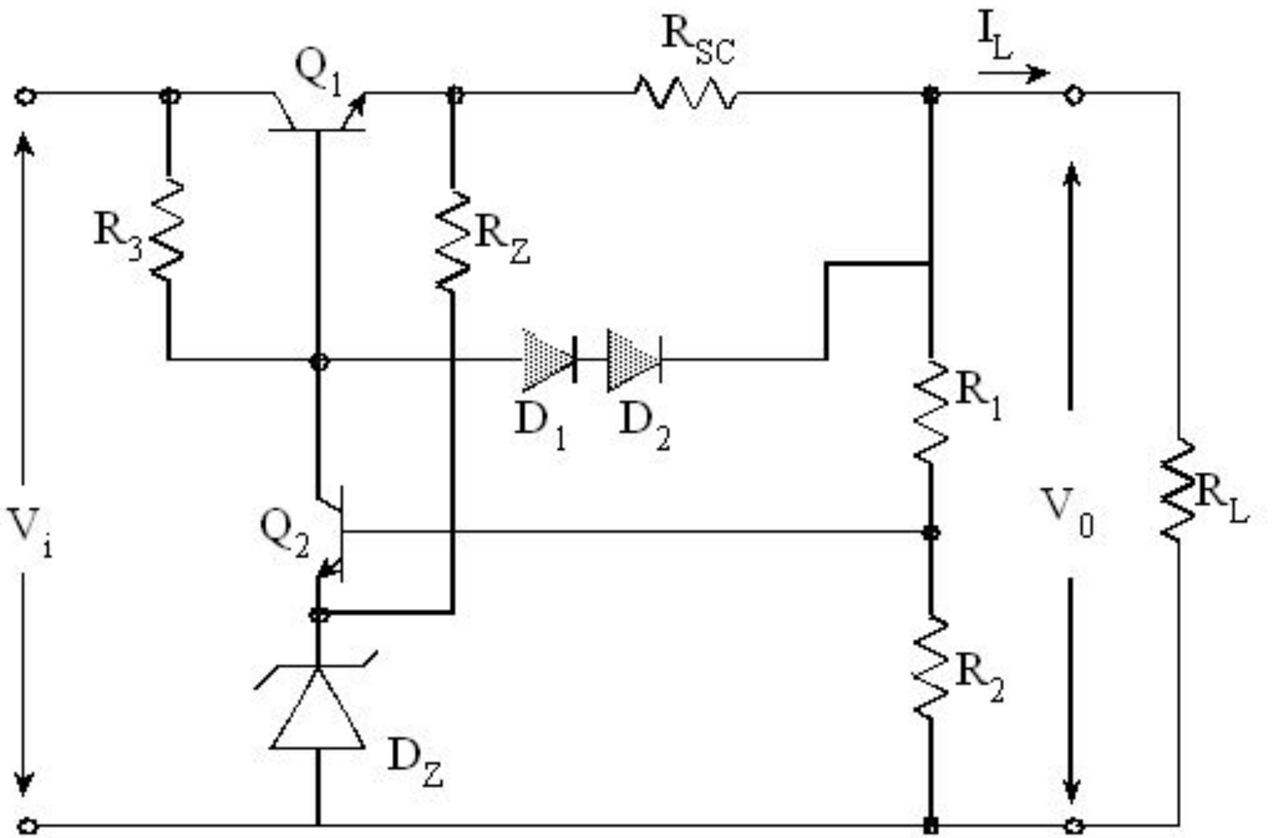

Fig.6.5 (a) Current Limiting Circuit using Diodes

- The above circuit uses a current limiting circuit to provide protection in case of overload or short circuit in a series regulator. As we know the main drawback of any series regulator is that the pass transistor (Q_1) can be destroyed by excessive load current if the load is accidently shorted. Here a current limiting circuit consists of two diodes (D_1 and D_2) and a series resistor R_{SC}.

- Here the diodes D_1 and D_2 are non-conducting until voltage drop across R_{SC} exceeds their forward threshold voltage, i.e. when $V_{RSC} = 0.7V$, diodes D_1 and D_2 conduct by passing the current through R_3 thereby decreasing the base voltage of Q_1. The decrease in base voltage of Q_1 reduces the conduction of Q_1, finally preventing any further increase in load current.

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$$V_{D1} + V_{D2} = V_{BE1} + V_{RSC}$$

or, $V_{RSC} = V_{D1} + V_{D2} - V_{BE1}$

or, $I_S R_{SC} = V_{D1} + V_{D2} - V_{BE1}$

$$\therefore \quad I_S = \frac{V_{D1} + V_{D2} - V_{BE1}}{R_{SC}} \quad \text{.........} \ (1)$$

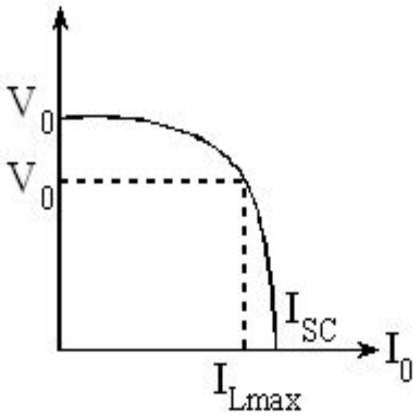


Fig.6.5 (b) Voltage-Current Relationship of Voltage Regulator

At limiting point;

$$0.7V = I_{L\,max} . R_{SC} = V_{RSC}$$

Current Limiting Circuit using Transistor

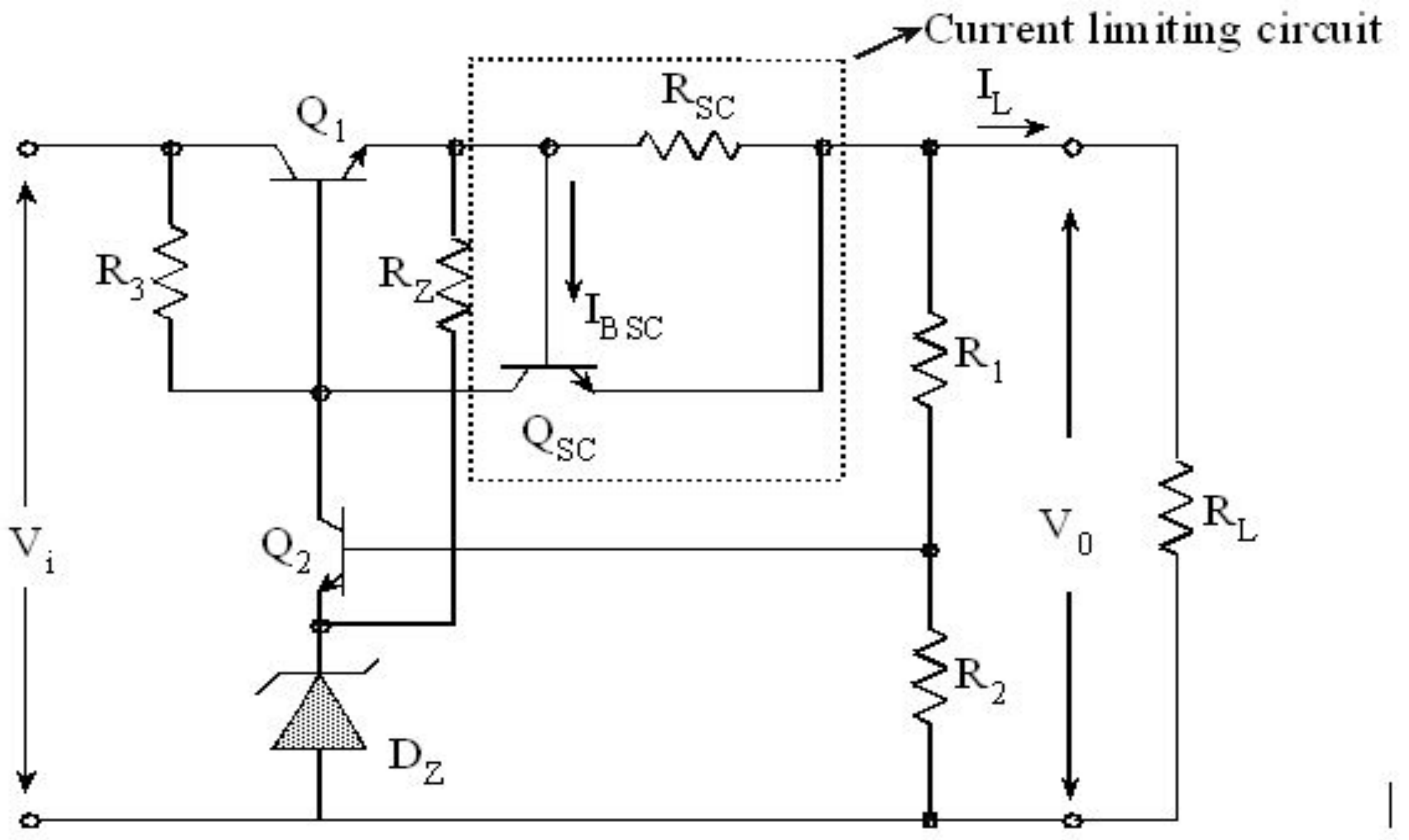


Fig.6.5 (c) Protection Circuit using Transistor

Operation

- When the load current is normal, the voltage across R_{SC} (i.e. voltage across base emitter of Q_{SC}) is small and Q_{SC} is off. Under this, circuit works as simple series regulator as discussed.
- If the load current becomes excessive (due to short circuit or overload), the voltage across R_{SC} becomes large enough to turn on Q_{SC}. The collector current of Q_{SC} flows through R_3, thereby decreasing the base voltage of Q_1. The decrease in base voltage of Q_1 reduces the conduction of pass transistor Q_1, preventing any further increase in load current.
- When Q_{SC} turned on, it diverts current from the base of transistor Q_1, thereby reducing load current through Q_1, preventing any additional current to load R_L. The action of components R_{SC} and Q_{SC} provides limiting of the maximum load current.

Shunt Voltage Regulaor

Shunt Regulators

Figure 13–13 is a functional block diagram of the shunt-type regulator. Each of the components shown in the figure performs the same function as its counterpart in the series regulator (Figure 13–5), but notice in this case that the control element is in parallel with the load. The control element maintains a constant load voltage by shunting more or less current from the load.

It is convenient to think of the control element in Figure 13–13 as a variable resistance. When the load voltage decreases, the resistance of the control element is made to increase, so less current is diverted from the load, and the load voltage rises. Conversely, when the load voltage increases, the resistance of the control element decreases, and more current is shunted away from the load. From another viewpoint, the source resistance R_S on the unregulated side of Figure 13–13 forms a voltage divider with the parallel combination of the control element and R_L. Thus, when the resistance of the control element increases, the resistance of the parallel combination increases, and, by voltage-divider action, the load voltage increases.

Figure 13–14 shows a discrete shunt regulator in which transistor Q_1 serves as the shunt control element. Since V_Z is constant, any change in output voltage creates a proportionate change in the voltage across R_1. Thus, if V_o decreases, the voltage across R_1 decreases, as does the base voltage of Q_2. Q_2 conducts less heavily and the current into the base of Q_1 is reduced. Q_1

FIGURE 13–13 Functional block diagram of a shunt-type voltage regulator

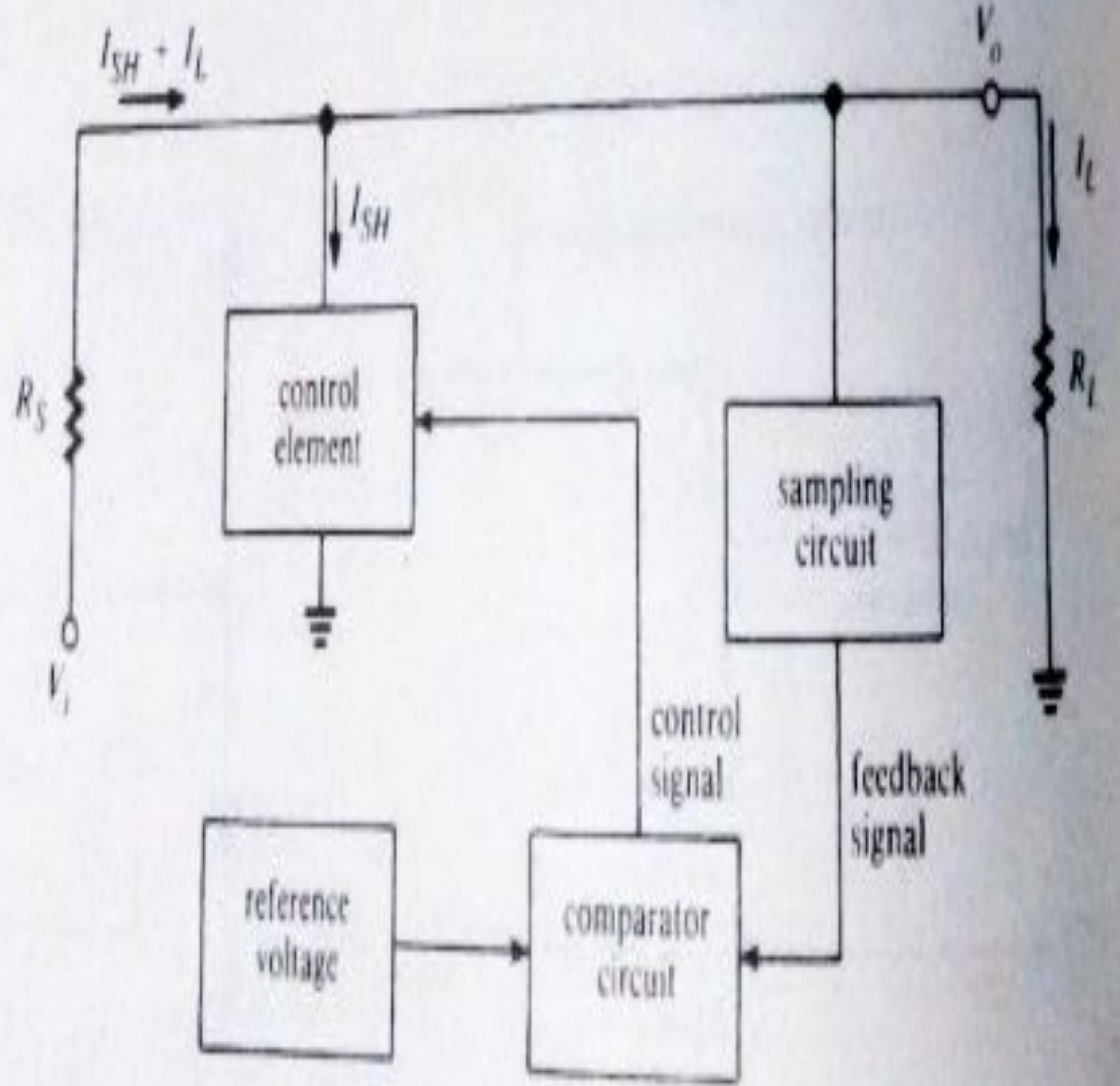


FIGURE 13–14 A discrete shunt regulator

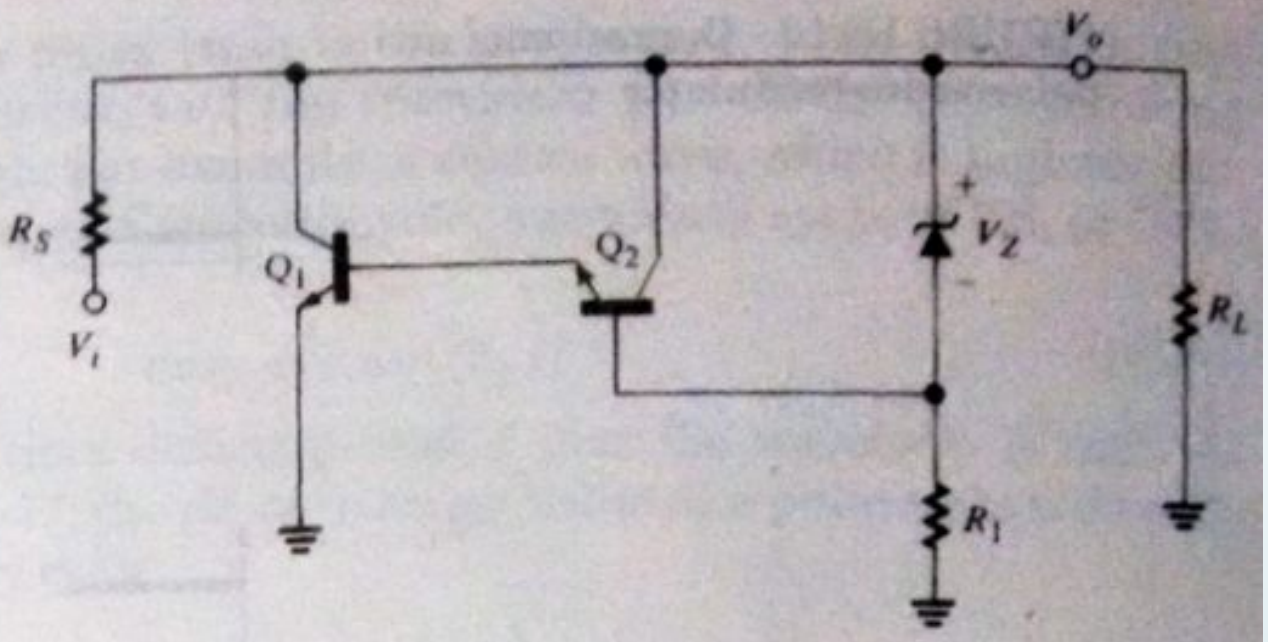
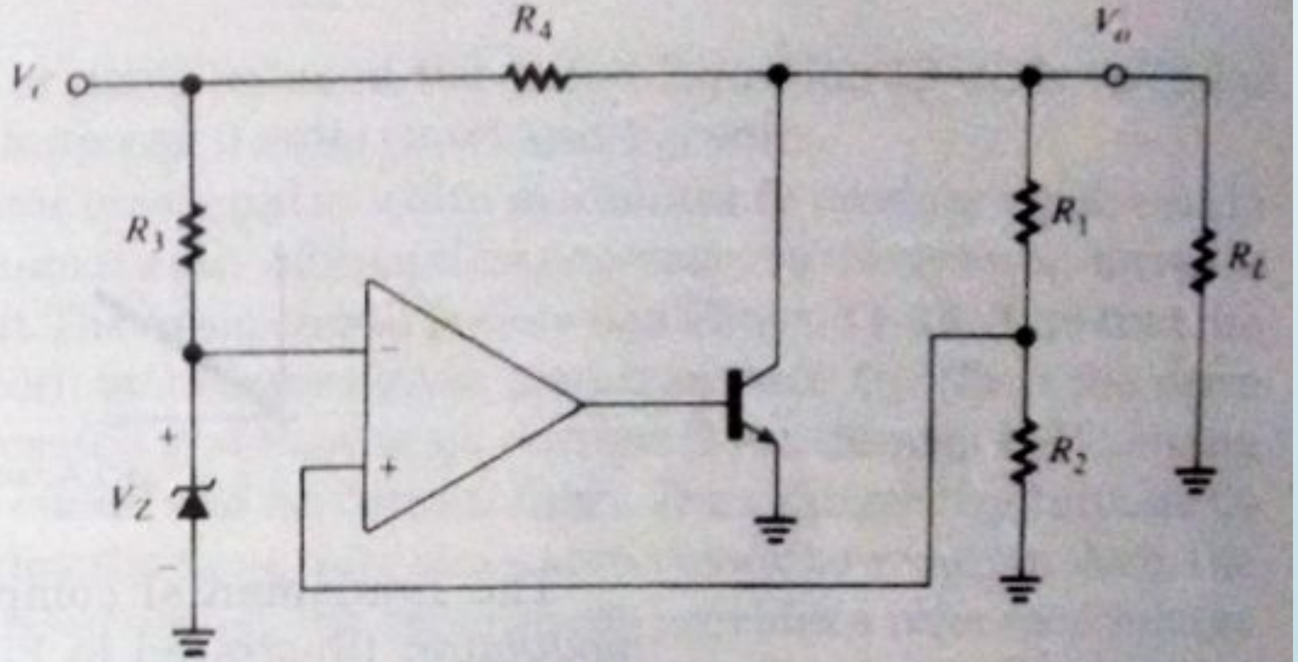


FIGURE 13–15 A shunt voltage regulator incorporating an operational amplifier



then conducts less heavily and shunts less current from the load, allowing the load voltage to rise. Conversely, an increase in V_o causes both Q_1 and Q_2 to conduct more heavily, and more current is diverted from the load.

Figure 13–15 shows a shunt regulator incorporating an operational amplifier. Resistors R_1 and R_2 form a voltage divider that feeds a voltage proportional to V_o back to the noninverting input. This voltage is greater than the reference voltage V_Z applied to the inverting input, so the output of the amplifier is a positive voltage proportional to $V_o - V_Z$. If V_o decreases, the amplifier output decreases and Q_1 conducts less heavily. Thus, less current is diverted from the load and the output voltage rises.

One advantage of the shunt-regulator circuit shown in Figure 13–15 is that it has inherent current limiting. It is clear that the load current cannot exceed V_i/R_4, which is the current that would flow through R_4 if the output were short-circuited. Because load current must flow through R_4, the power dissipation in the resistor may be quite large, particularly under short-circuit conditions.

Integrated Circuit Voltage Regulator:

- One advantage of IC voltage regulators is that properties like thermal compensation, short circuit protection & surge protection can be built into the device. Most of the commonly used IC voltage regulators are 3–terminal devices.
- **Types:**
  a) Fixed IC voltage regulator
  b) Variable IC voltage regulator

Fixed IC voltage regulator

- The 78XX series of IC regulator is most popular for fixed positive output voltage and the 79XX series of IC regulators is for fixed negative output voltage.

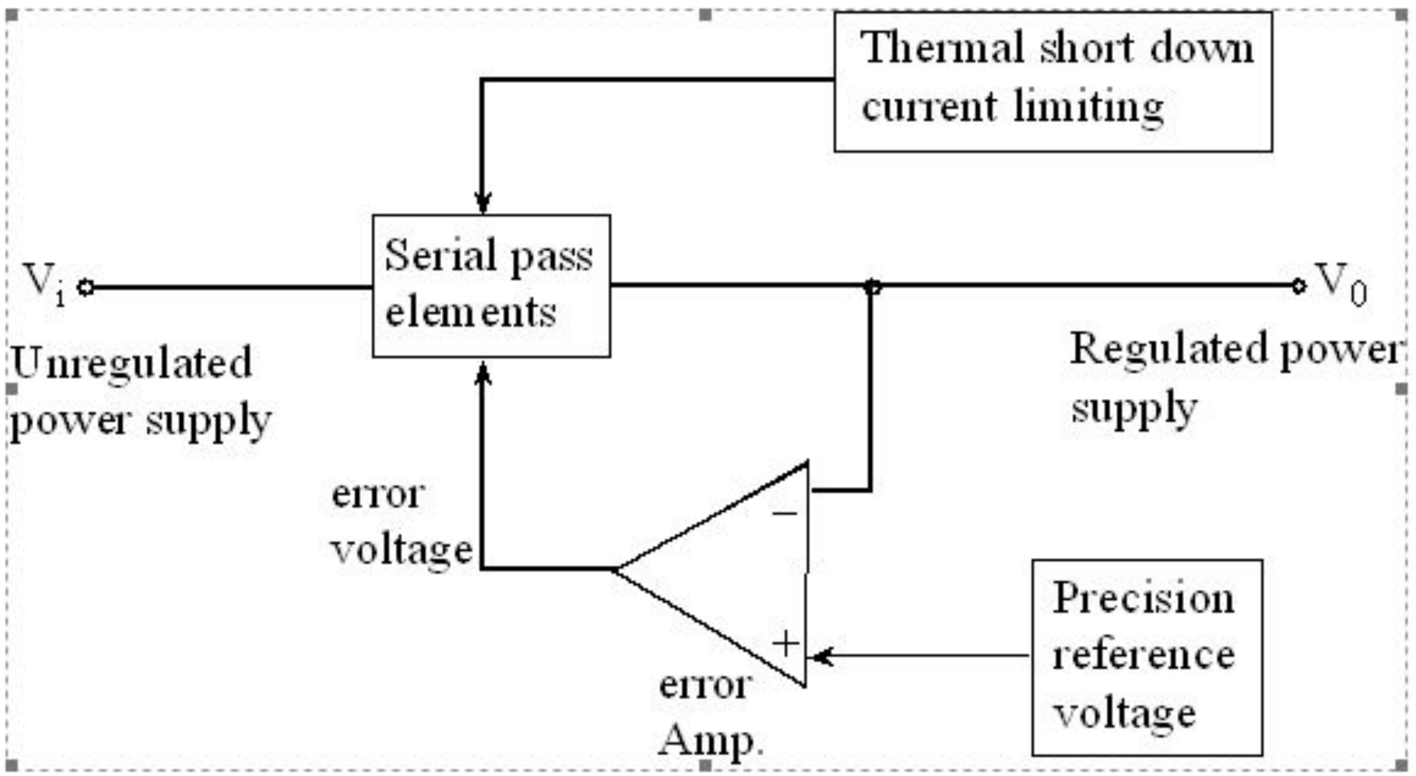


Fig.6.6 (a) Block Diagram of Fixed IC Voltage Regulator

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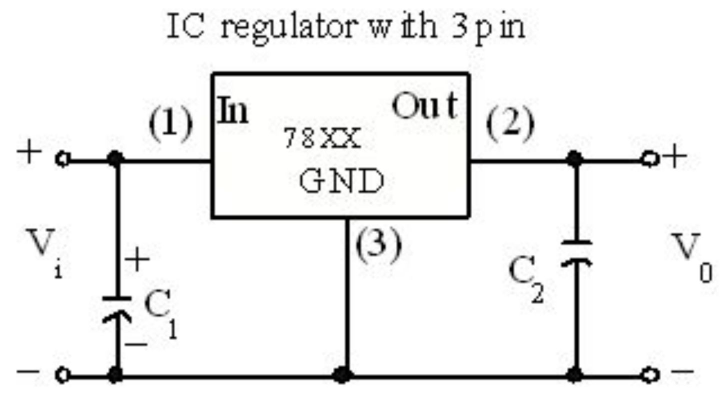


Fig.6.6 (b) Connection of fixed positive IC voltage regulator

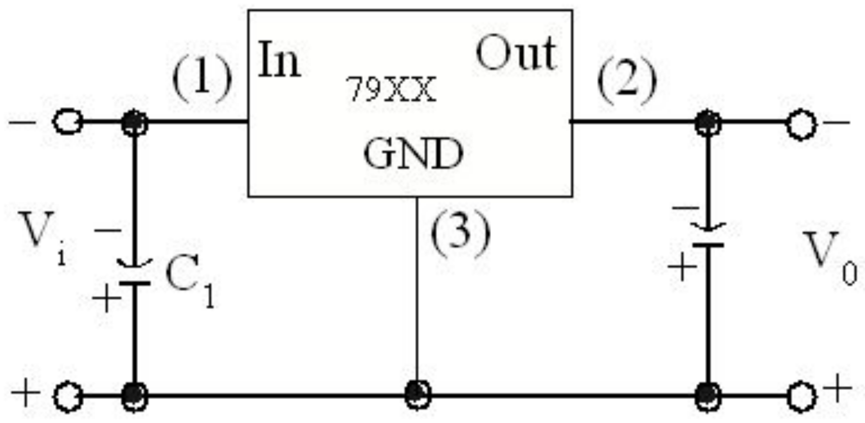
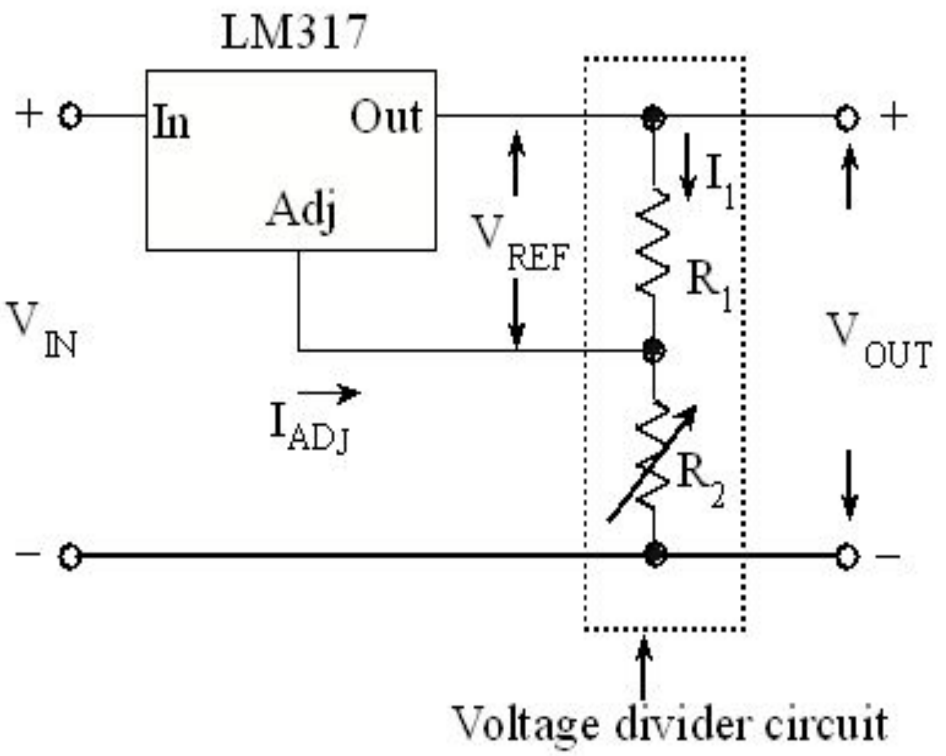


Fig.6.6(c) Connection of fixed negative IC voltage regulator.

Variable IC voltage regulator: (Adjustable type)



6.6(d) Connection of LM317 adjustable Voltage Regulator

The desired output voltage

$$V_O = I_1 R_1 + (I_1 + I_{Adj}) R_2$$

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

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

With typical IC value;

$V_{REF} = 1.25V$ & $I_{ADJ} = 100\ \mu A$

$$\boxed{\therefore\ V_O \cong V_{REF}\left(1 + \frac{R_2}{R_1}\right) = 1.25\left(1 + \frac{R_2}{R_1}\right)}$$

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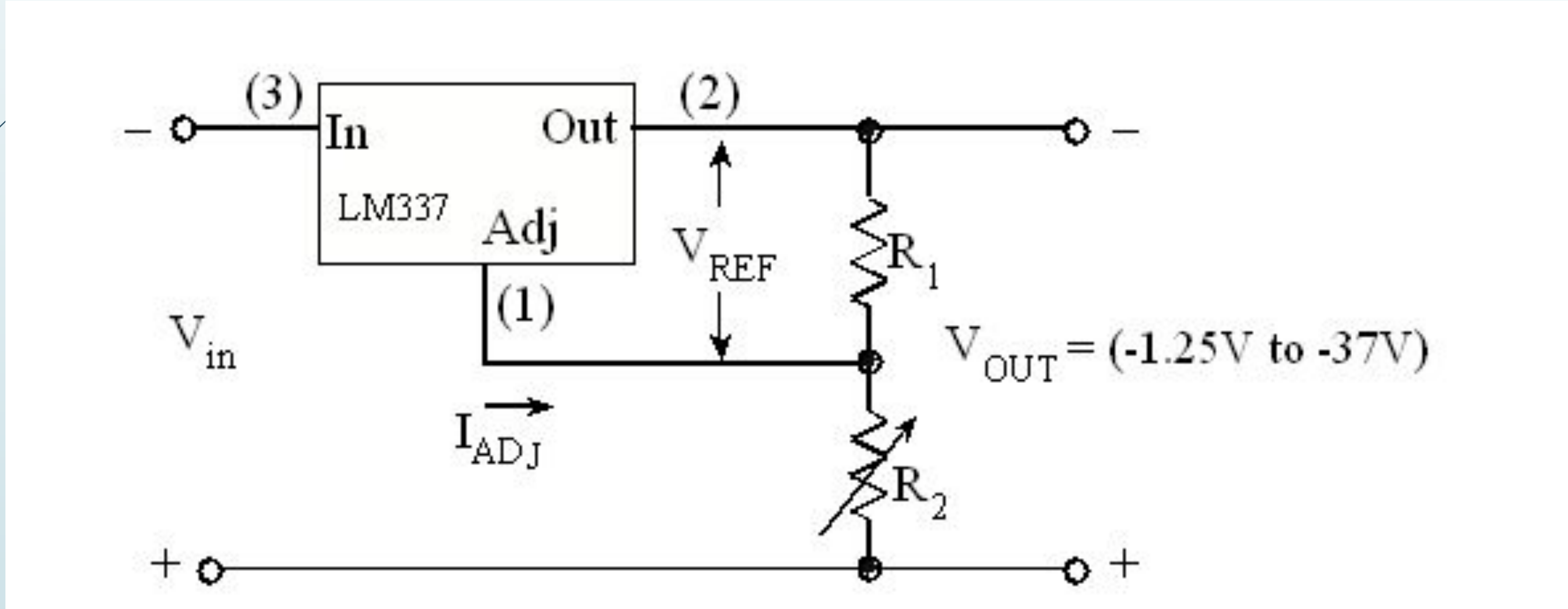
- For variable negative IC
- Voltage regulator use LM337 as;



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