

7. Voltage Regulators

7.1 Introduction

Voltage Regulator Circuits are electronic circuits which give constant DC output voltage, irrespective of variations in *Input Voltage V_i* , *current drawn by the load I_L* from output terminals, and *Temperature T* . Voltage Regulator circuits are available in discrete form using BJTs, Diodes etc and in IC (Integrated Circuit) form. The term voltage regulator is used when the output delivered is DC voltage. The input can be DC which is not constant and fluctuating (fig 7.2). If the input is AC, it is converted to DC by Rectifier and Filter Circuits and given to I.C. Voltage Regulator circuit, to get constant DC output voltage.

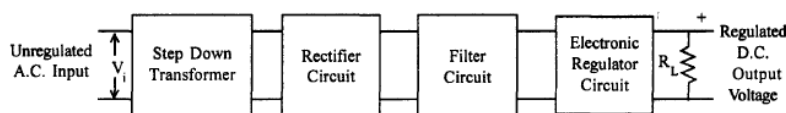


Fig7.1 Block Diagram of Voltage regulator with A.C. input

A block diagram containing the parts of a typical power supply and the voltage at various points in the unit is shown in Fig. 7.1. The unregulated ac voltage is connected to a transformer, which steps that ac voltage down to the level for the desired dc output. A diode rectifier then provides a full-wave rectified voltage that is initially filtered by a simple capacitor filter to produce a dc voltage. This resulting dc voltage usually has some ripple or ac voltage variation. A regulator circuit can use this dc input to provide a dc voltage that not only has much less ripple voltage but also remains the same dc value even if the input dc voltage varies somewhat or the load connected to the output dc voltage changes. This voltage regulation is usually obtained using one of a number of popular voltage regulator IC units.

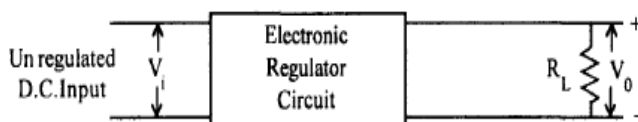


Fig7.2 Block diagram of voltage regulator with D.C input.

The term *Voltage Stabilizer* is used, if the output voltage is AC and not DC. The circuits used for voltage stabilizers are different. The voltage regulator circuits are available in IC form also. Some of the commonly used ICs are, μA 723, LM 309, LM 105, CA 3085 A.

7805, 7806, 7808, 7812, 7815: Three terminal positive Voltage Regulators.

7905, 7906, 7908, 7912, 7915: Three terminal negative Voltage Regulators.

The Voltage Regulator Circuits are used for electronic systems, electronic circuits, IC circuits, etc.

The specifications and Ideal Values of Voltage Regulators are :

Specifications	Ideal Values
Regulation (S_v):	0 %
Input Resistance (R_i):	$\infty \Omega$
Output Resistance (R_o):	0 Ω
Temperature Coefficient (S_T):	0 mv/°c.
Output Voltage V_o :	-
Output current range (I_L):	-
Ripple Rejection:	0 %

Different types of Voltage Regulators are

- Zener regulator
- Shunt regulator
- Series regulator
- Negative voltage regulator
- Voltage regulator with foldback current limiting
- Switching regulators
- High Current regulator

Two basic categories of voltage regulation are **line regulation** and **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 load varies.

Line Regulation

Line regulation can be defined as the percentage change in the output voltage for a given change in the input (line) voltage. When taken over a range of input voltage values, line regulation is expressed as a percentage by the following formula:

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

Line regulation can also be expressed in units of %/V. For example, a line regulation of 0.05%/V means that the output voltage changes 0.05 percent when the input voltage increases or decreases by one volt. Line regulation can be calculated using the following formula (Δ means "a change in"):

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

Load Regulation

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

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

Alternately, the load regulation can be expressed as a percentage change in output voltage for each mA change in load current. For example, a load regulation of 0.01 %/mA means that the output voltage changes 0.01 percent when the load current increases or decreases 1 mA.

7.2 Regulated Power Supply

An unregulated power supply consists of a transformer, a rectifier, and a filter. For such a circuit regulation will be very poor i.e. as the load varies (*load means load current*) [No load means no load current or 0 current. Full load means full load current or short circuit], we want the output voltage to remain constant. But this will not be so for unregulated power supply. The shortcomings of the circuits are:

- Poor regulation
- DC output voltage varies directly as the a.c. input voltage varies
- In simple rectifiers and filter circuits, the d.c. output voltage varies with temperature also, if semiconductor devices are used.

An electronic feedback control circuit is used in conjunction with an unregulated power supply to overcome the above three shortcomings. Such a system is called a "*regulated power supply*".

Stabilization

The output voltage depends upon the following factors in a power supply.

1. Input voltage V_i
2. Load current I_L
3. Temperature

Change in the output voltage ΔV_o can be expressed as

$$\Delta V_o = \frac{\partial V_o}{\partial V_i} \Delta V_i + \frac{\partial V_o}{\partial I_L} \Delta I_L + \frac{\partial V_o}{\partial T} \Delta T$$

$$\text{or,} \quad \Delta V_o = S_V \Delta V_i + R_O \Delta I_L + S_T \Delta T$$

where the three coefficients are defined as

Stability factor:

$$S_V = \left. \frac{\Delta V_o}{\Delta V_i} \right|_{\substack{\Delta I_L=0 \\ \Delta T=0}}$$

Output resistance:

$$R_o = \left. \frac{\Delta V_o}{\Delta I_L} \right|_{\substack{\Delta V_i=0 \\ \Delta T=0}}$$

Temperature Coefficient:

$$S_T = \left. \frac{\Delta V_o}{\Delta T} \right|_{\substack{\Delta V_i=0 \\ \Delta I_L=0}}$$

The smaller the value of the three coefficients, the better the regulation of the power supply.

7.3 Zener Diode Regulator

7.3.1 Break down mechanisms in semiconductor devices

There are three types of breakdown mechanisms in semiconductor devices.

1. Avalanche Breakdown. 2. Zener Breakdown. 3. Thermal Breakdown

1. Avalanche breakdown

When there is no bias applied to the diode, there are certain numbers of thermally generated carriers. When bias is applied, electrons and holes acquire sufficient energy from the applied potential to produce new carriers by removing valence electrons from their bonds. These thermally generated Carriers acquire additional energy from the applied bias. They strike the lattice and impart some Energy to the valence electrons. So the valence electrons will break away from their parent atom and become free carriers. These newly generated additional carriers acquire more energy from the potential (since bias is applied). So they again strike the lattice and create more number of free electrons and holes. This process goes on as long as bias is increased and the number of free Carriers gets multiplied. This is known as *avalanche multiplication*, since the number of carriers is large, the current flowing through the diode which is proportional to free carriers also increases and when this current is large, avalanche breakdown will occur.

2. Zener breakdown

Now if the electric field is very strong to disrupt or break the covalent bonds, there will be sudden Increase in the number of free carriers and hence large current and consequent breakdown. Even If thermally generated carriers do not have sufficient energy to break the covalent bonds, the Electric field is very high, then covalent bonds are directly broken. This is *Zener Breakdown*. A Junction having narrow depletion layer and hence high field intensity will have zener breakdown Effect. ($\cong 10^6 \text{V/m}$). If the doping concentration is high, the depletion region is narrow and will have high field intensity, to cause Zener breakdown.

3. Thermal breakdown

If a diode is biased and the bias voltage is well within the breakdown voltage at room temperature, there will be certain amount of current which is less than the breakdown current. Now keeping the Bias voltage as it is, if the temperature is increased, due to the thermal energy, more number of Carriers will be produced and finally breakdown will occur. This is *Thermal Breakdown*.

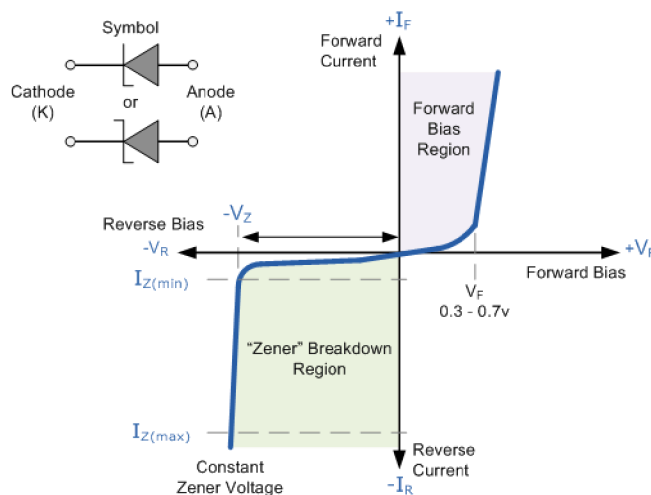
In zener breakdown, the covalent bonds are ruptured. But the covalent bonds of all the Atoms will not be ruptured. Only those atoms, which have weak covalent bonds such as an atom at the surface which is not surrounded on all sides by atoms, will be broken. But if the field strength is not greater than the critical field, when the applied voltage is removed, normal covalent Bond structure will be more or less restored. This is Avalanche Breakdown. But if the field strength is very high, so that the covalent bonds of all the atoms are

broken, then normal structure will not be achieved, and there will be large number of free electrons. This is **Zener Breakdown**.

In Avalanche Breakdown, only the excess electron, loosely bound to the parent atom will become free electron because of the transfer of energy from the electrons possessing higher energy.

7.3.2 Zener Diode

A zener diode is a silicon pn junction device that is designed for operation in the reverse-breakdown region. The breakdown voltage of a zener diode is set by carefully controlling the doping level during manufacture. We know that, when a diode reaches reverse breakdown, its voltage remains almost constant even though the current changes drastically. This symbol and volt-ampere characteristic is shown in fig 7.3.



7.3 Symbol and V-I characteristics of a zener diode

Zener diodes are designed to operate in reverse breakdown. The avalanche breakdown occurs in both rectifier and zener diodes at a sufficiently high reverse voltage. Zener breakdown occurs in a zener diode at low reverse voltages. A zener diode is heavily doped to reduce the breakdown voltage. This causes a very thin depletion region. As a result, an intense electric field exists within the depletion region. Near the zener breakdown voltage (V_Z), the field is intense enough to pull electrons from their valence bands and create current.

Zener diodes with breakdown voltages of less than approximately 5V operate predominately in zener breakdown. Those with breakdown voltages greater than approximately 5V operate predominately in avalanche breakdown. Both types however are called zener diodes. Zener diodes are commercially available with breakdown voltages of 1.8 V to 200 V with specified tolerances from 1 % to 20%.

Breakdown Characteristics

Figure 7.4 shows the reverse portion of a zener diode's characteristic curve. Notice that as the reverse voltage (V_R) is increased; the reverse Current (I_R) remains extremely small up to the "knee" of the curve. The corresponding reverse current is called the zener current, I_{zk} . At this point, the breakdown effect begins: the internal zener resistance, also called zener impedance (Z_z), begins to decrease as the reverse current increases rapidly. From the bottom of the knee, the zener breakdown voltage (V_Z) remains essentially constant although it increases slightly as the zener current, I_z , increases.

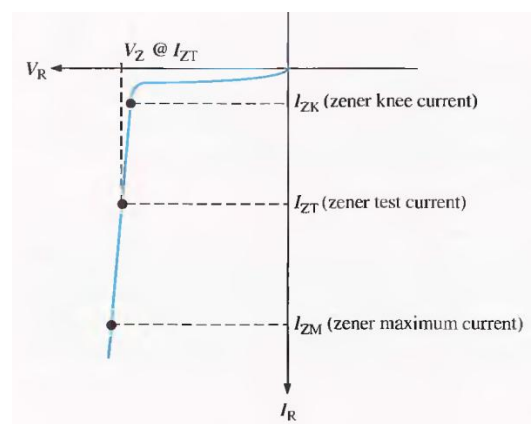


Fig 7.4 Breakdown characteristics of zener diode

7.3.3 Zener Regulator

This ability to control itself can be used to great effect to regulate or stabilize a voltage source against supply or load variations. The fact that the voltage across the diode in the breakdown region is almost constant turns out to be an important application of the zener diode as a voltage regulator. The function of a regulator is to provide a constant output voltage to a load connected in parallel with it in spite of the ripples in the supply voltage or the variation in the load current and the zener diode will continue to regulate the voltage until the diodes current falls below the minimum $I_{Z(\min)}$ value in the reverse breakdown region.

A dc voltage regulator using a zener diode is shown below. Here the load is connected across the zener diode. As said under section 7.1 there are two types of regulation: load regulation and line regulation.

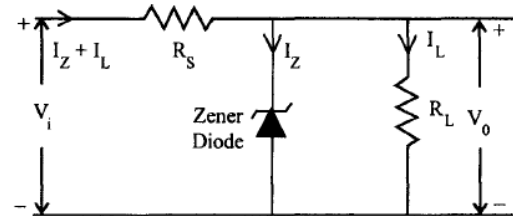


Fig 7.5 Zener voltage regulator

Any increase in the input voltage above the breakdown voltage of the zener diode, causes corresponding increase in the current through the series resistor R_s . Since the zener diode is now in breakdown region, the extra current from the supply, flows through it and not through R_L . Therefore I_L remains constant and V_o remains constant. Thus the diode protects the load from the input (line) voltage variations (*line regulation*).

Similarly, if we keep the line voltage constant and vary the load (R_L), the load current also varies. If the load current decreases (i.e. increase in R_L , $V_o = I_L R_L$ constant), the current through the diode also increases, satisfying the condition: $I_s = I_z + I_L$ (i.e. $I_L \downarrow \Rightarrow I_z \uparrow \Rightarrow I_s \text{ constant}$). If load current increases (i.e. decrease in R_L , $V_o = I_L R_L$ constant), the current through the diode also decreases, satisfying the condition: $I_s = I_z + I_L$ (i.e. $I_L \uparrow \Rightarrow I_z \downarrow \Rightarrow I_s \text{ constant}$).

Design

5.0V stabilized power supply is required to be produced from a 12V DC power supply input source. The maximum power rating P_Z of the zener diode is 2W.

Using the zener regulator circuit above calculate:

- a) The maximum current flowing through the zener diode (i.e. No load condition)

$$I_{ZM} = \frac{\text{Watts}}{\text{Voltage}} = \frac{2W}{5V} = 400mA$$

- b) The load current I_L if a load resistor of $1k\Omega$ is connected across the Zener diode. (The value of R_L or I_L or P_L should be specified in the question).

$$I_L = \frac{V_L}{R_L} = \frac{5.0V}{1000\Omega} = 5mA$$

- c) The total supply current I_s .

$$I_s = I_z + I_L$$

$$\text{and } I_{s \max} = I_{ZM} + I_L = 405mA$$

- d) The value of the series resistor, R_s , can be calculated by applying KVL at the input section.

Here $V_z = V_L = 5.0$, Hence chose a zener diode with breakdown voltage 5V.

$$R_{s \min} = \frac{V_s - V_Z}{I_s} = \frac{12 - 5V}{405mA} = 17.3\Omega$$

If the input voltage has ripples and it varies from a minimum to maximum, such that $v_s = V_s \pm \Delta V$ (for example: $v_s = 12 \pm V$, the value of the series resistance is calculate by using the following equations:

$$R_{s \min} = \frac{V_{s \min} - V_Z}{I_s} = \frac{(V_s - \Delta V) - V_Z}{I_{ZM}} \text{ and, } R_{s \max} = \frac{V_{s \max} - V_Z}{I_{ZM}} = \frac{(V_s + \Delta V) - V_Z}{I_{ZM}}, \text{ then}$$

$$R_s = \sqrt{R_{s \min} R_{s \max}}$$

Limitations of zener diode regulator

- The output voltage remains constant only when the input voltage is sufficiently large so that the voltage across the zener is V_z .
- There is limit to the maximum current that we can pass through the zener. If V_i is increased enormously, I_z increases and hence breakdown will occur.
- Voltage regulation is maintained only between these limits, the minimum current and the maximum permissible current through the zener diode. Typical values are from 10m A to 1 ampere.

7.4 Series Voltage Regulators

The basic connection of a series regulator circuit is shown in the block diagram of Fig.7.6. The series element controls the amount of the input voltage that gets to the output. The output voltage is sampled by a circuit that provides a feedback voltage to be compared to a reference voltage.

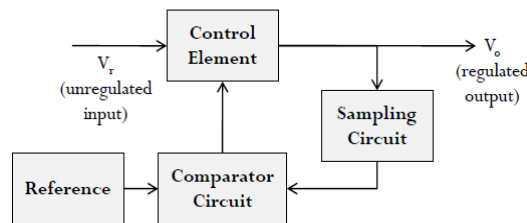
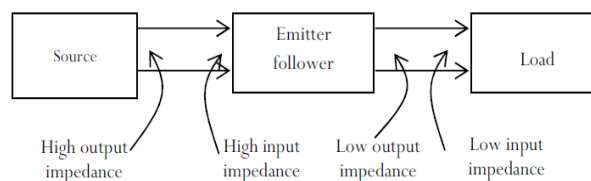


Fig.7.6 Block Diagram of Series voltage regulator

1. If the output voltage increases, the comparator circuit provides a control signal to cause the series control element to decrease the amount of the output voltage—thereby maintaining the output voltage.
2. If the output voltage decreases, the comparator circuit provides a control signal to cause the series control element to increase the amount of the output voltage.

7.4.1 Emitter-follower Regulator

If a power supply has a poor regulation, it possesses a high internal impedance. This difficulty may be avoided by using an emitter follower (unity gain-common collector amplifier) to convert from high to low impedance. Emitter follower has high input impedance and low output impedance, hence a high output impedance source can be connected to the input of an emitter follower and since the gain of emitter follower is unity and output impedance is low, the voltage at the output of emitter follower will be a low impedance source. This is called impedance matching, and is shown in fig.



The fig 7.8 shows an emitter-follower regulator. This configuration reduces the current flow in the diode. The power transistor used in this configuration is known as **pass transistor**. Because of the current amplifying property of the transistor, the current in the zener diode is small. Hence there is little voltage drop across the diode resistance, and the zener approximates an ideal constant voltage source.

Transistor Q1 is the series control element, and Zener diode D_z provides the reference voltage. The regulating operation can be described as follows:

1. If the output voltage decreases, the increased base-emitter voltage causes transistor Q1 to conduct more, thereby raising the output voltage—maintaining the output constant.
2. If the output voltage increases, the decreased base-emitter voltage causes transistor Q1 to conduct less, thereby reducing the output voltage—maintaining the output constant.

The current through resistor R is the sum of zener current I_Z and the transistor base current $I_B (= I_L/\beta \cong I_L/\beta)$, where β is the current gain of transistor.

$$I_L = I_Z + I_B.$$

The output voltage across R_L resistance is given by

$$V_O = V_Z - V_{BE}, \text{ where } V_{BE} \gg 0.7 \text{ V}$$

Therefore, $V_O = \text{constant}$.

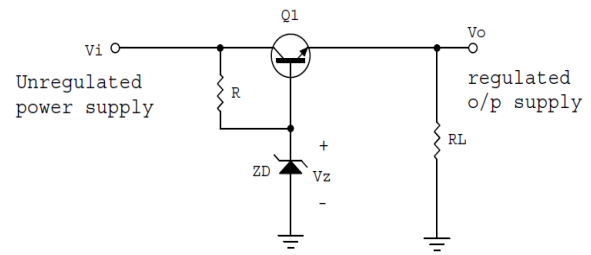


Fig.7.7 Emitter Follower output (series) Regulator

The emitter current is same as load current. The current I_R is assumed to be constant for a given supply voltage. Therefore, if I_L increases, it needs more base currents, to increase base current I_Z decreases. The difference in this regulator with zener regulator is that in later case the zener current decreases (increases) by same amount by which the load current increases (decreases). Thus the current range is less, while in the shunt regulators, if I_L increases by ΔI_L then I_B should increase by $\Delta I_L/\beta$ or I_Z should decrease by $\Delta I_L/\beta$. Therefore the current range control is more for the same rating zener.

In a power supply the power regulation is basically, because of its high internal impedance. In the circuit discussed, the unregulated supply has resistance R_s of the order of 100 ohm. The use of emitter follower is to reduce the output resistance and it becomes approximately,

$$r_o = (R_z + h_{ie}) / (1 + h_{fe}),$$

where r_o represents the output resistance after the emitter follower has been added. R_z represents the dynamic resistance of the zener diode. h_{ie} is the input resistance of the transistor, and $h_{fe}(=\beta)$ is the current gain of the transistor.

The voltage stabilization ratio S_V is approximately

$$S_V = \partial V_o / \partial V_i = R_z / (R_z + R)$$

S_V can be improved by increasing R . This increases V_{CE} and power dissipated in the transistor. Other disadvantages of the circuit are:

- No provision for varying the output voltage since it is almost equal to the zener voltage.
- Change in V_{BE} and V_z due to temperature variations appear at the output since the transistor is connected in series with load, it is called series regulator and transistor is allow series pass transistor.

7.3.2 Series Pass Transistor Voltage Regulator

The voltage regulation (i.e., change in the output voltage as load voltage varies (or input voltage varies) can be improved, if a large part of the increase in input voltage appears across the control transistor, so that output voltage tries to remain constant, i.e., increase in V_i results in increased V_{CE} so that output almost remains constant. But when the input increases, there may be some increase in the output but to a very smaller extent. This increase in output acts to bias the control transistor. This additional bias causes an increase in collector to emitter voltage which will compensate for the increased input.

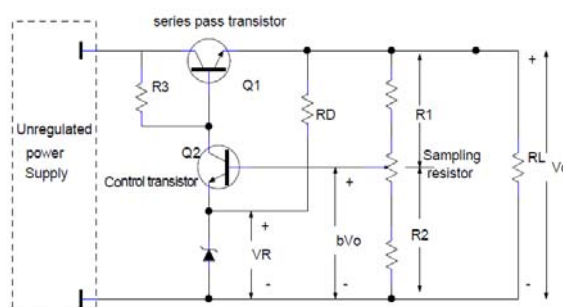


Fig 7.8 Series voltage regulator circuit

If the change in output were amplified before being applied to the control transistor, better stabilization would result.

Above fig shows a series voltage regulated power supply. Q_1 is the series pass element of the series regulator. Q_2 acts as the difference amplifier. D is the reference zener diode. A fraction of the output voltage bV_o (b is a fraction, which is taken across R_2 and the potentiometer) is compared with the reference voltage V_R . The difference $(bV_o - V_R)$ is amplified by the transistor Q_2 . Because the emitter of Q_2 is not at ground potential, there is constant voltage V_R . Therefore the net voltage to the Base - Emitter of the transistor Q_2 is $(bV_o - V_R)$. As V_o increases, $(bV_o - V_R)$ increases.

When input voltage increases by ΔV_i , the base-emitter voltage of Q_2 increases. So Collector current of Q_2 increases and hence there will be large current change in R_3 . Thus all the change in V_i will appear across R_3 itself. V_{BE} of the transistor Q_1 is small. Therefore the drop across $R_3 = V_{CB}$ of $Q_1 \approx V_{CE}$ of Q_1 since V_{BE} is small. Hence the increase in the voltage appears essentially across Q_1 only. This type of circuit takes care of the increase in input voltages only. If the input decreases, output will also decrease. (If the output were to remain constant at a specified value, even when V_i decreases, buck and boost should be there. The tapping of a transformer should be changed by a relay when V_i changes), r_o is the output resistance of the unregulated power supply which precedes the regulator circuit, r_o is the output resistance of the rectifier, filter circuit or it can be taken as the resistance of the DC supply in the lab experiment.

$$\begin{aligned} \text{The expression for stability factor } S_v &= \frac{\Delta V_o}{\Delta V_i} \\ &= \frac{R_1 + R_2}{R_1} \frac{(R_1 || R_2) + h_{ie2} + (1 + h_{fe2})R_z}{h_{fe2}R_z} \end{aligned}$$

where R_z represents the equivalent resistance of the zener diode D . The output impedance of the circuit is found to be

$$R_o = \frac{r_o + \frac{R_3 + h_{ie1}}{1 + h_{fe1}}}{1 + G_m(R_3 + r_o)}$$

where r_o is the output resistance of the transistor, h_{ic} is the current gain, and h_{ie} is the input resistance.

Op-Amp series regulator

Another version of series regulator is that shown in Fig 7.9. below. The op-amp (operational amplifier-here it act as a comparator) compares the Zener diode reference voltage with the feedback voltage from sensing resistors R_1 and R_2 . If the output voltage varies, the conduction of transistor Q_1 is controlled to maintain the output voltage constant. The output voltage will be maintained at a value of $V_o = \left(1 + \frac{R_2}{R_1}\right)V_z$.

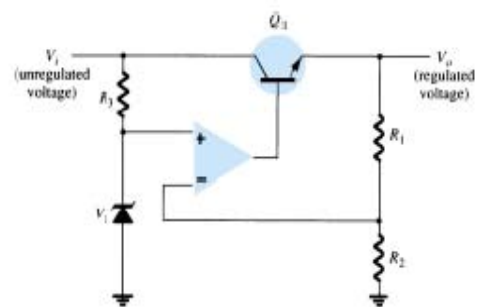


Fig 7.9 Op-amp series regulator circuit.

Current-limiting circuit

One form of short-circuit or overload protection is current limiting, as shown in Fig 7.10. As load current I_L increases, the voltage drop across the short-circuit sensing resistor R_{SC} increases. When the voltage drop across R_{SC} becomes large enough, it will drive Q_2 on, diverting current from the base of transistor Q_1 , thereby reducing the load current through transistor Q_1 , preventing any additional current to load R_L . The action of components R_{SC} and Q_2 provides limiting of the maximum load current.

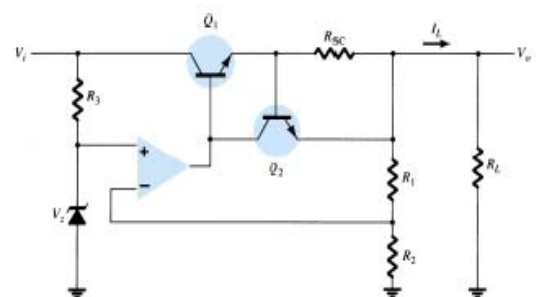


Fig 7.10 Current-limiting voltage regulator.

Foldback limiting

Current limiting reduces the load voltage when the current becomes larger than the limiting value. The circuit of Fig. 7.11 provides foldback limiting, which reduces both the output voltage and output current protecting the load from over current, as well as protecting the regulator. Foldback limiting is provided by the additional voltage divider network of R_4 and R_5 in the circuit of Fig. 7.11 (over that of Fig. 7.10). The divider circuit senses the voltage at the output (emitter) of Q_1 . When I_L increases to its maximum value, the voltage across R_{SC} becomes large enough to drive Q_2 on, thereby providing current limiting. If the load resistance is made smaller, the voltage driving Q_2 on becomes less, so that I_L drops when V_L also drops in value-this action being foldback limiting. When the load resistance is returned to its rated value, the circuit resumes its voltage regulation action.

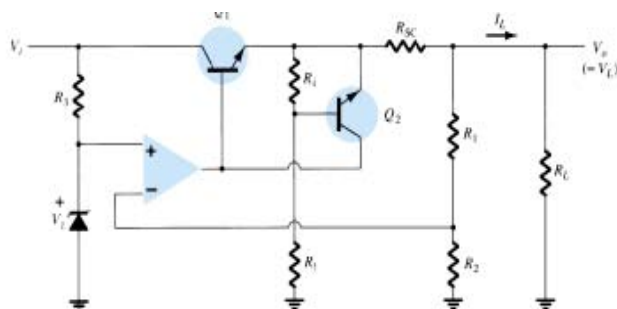


Fig 7.11 Foldback-limiting series regulator circuit.

Short Circuit Overload Protection

Overload means overload current (or short circuit). A power supply must be protected further from damage through overload. In a simple circuit, protection is provided by using a fuse, so that when current excess of the rated values flows, the fuse wire will blow off, thus protecting the components. This fuse wire is provided before r_o . Another method of protecting the circuit is by using diodes. (Zener diodes can also be employed, but such a circuit is relatively costly).

The diodes D_1 and D_2 will start conducting only when the voltage drop across R_s exceeds the current in voltage of both the diodes D_1 and D_2 . In the case of a short circuit the current I_s will increase up to a limiting point determined by

$$I_s = \frac{V_{Y1} + V_{Y2} - V_{BE1}}{R_s}$$

When the output is short circuited, the collector current of Q_2 will be very high I_s . R_s will also be large.

- The two diodes D_1 and D_2 start conducting.
- The large collector current of Q_2 passes through the diodes D_1 and D_2 and not through the transistor Q_1 .
- Transistor Q_1 will be safe, D_1 and D_2 will be generally s_i diodes, since cut in voltage is 0.6V. So $I_s R_s$ drop can be large.

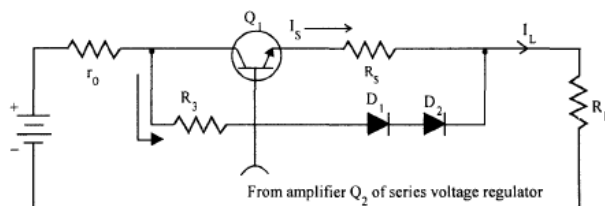


Fig7.12 Circuit for short circuit protection.