CHAPTER 32

Regulated and Switching Power Supplies

32.1. INTRODUCTION

Almost all electronic devices used in electronic circuits need a dc source of power to operate. The source of dc power is used to establish the dc operating points (Q-points) for the passive and active electronic devices incorporated in the system. The dc power supply is typically connected to each and every stage in an electronic system. It means that the single requirement common to all phases of electronics is the need for a supply of dc power. For portable low-power systems batteries may be used, but their operating period is limited. Thus, for long time operation frequent recharging or replacement of batteries become much costlier and complicated. More frequently, however, electronic equipment is energized by a *power supply,* derived from the standard industrial or domestic ac supply by transformation, rectification, and filtering. The combination of a transformer, a rectifier and a filter constitutes an *ordinary dc power supply,* also called an *unregulated power supply.*

The block diagram of an ordinary power supply is depicted in Fig. 32.1. Usually, a small dc voltage, in the range of 2–24 volts is required for the operation of different electronic circuits, while in India, single-phase ac supply is available at 230 V. So a small step-down transformer is used at the beginning which reduces the voltage level according to the needs. Next block is a rectifier which converts the sinusoidal ac voltage into pulsating dc. In the last there is a filter block which reduces the ripples (ac components) from the rectifier output voltage. The filter is a device which passes dc component to the load and blocks ac components of the rectifier output.

For many applications in electronics, unregulated power supply is not good enough because of the following reasons.

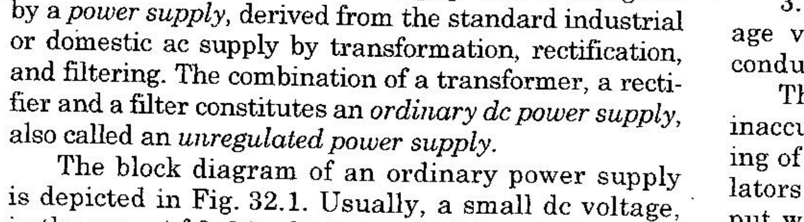

Fig. 32.1. *Block Diagram of an Unregulated Power Supply*

1. *Poor regulation.* The output voltage does not remain constant as the load varies. The internal resistance of an ordinary power supply is relatively large (more than 30 Ω). So output voltage is significantly affected by the magnitude of current drawn from the supply. The voltage drop in the internal resistance of the supply increases directly with an increase in load current.

2. *Variations in the ac supply mains.* The permissible variation in the ac supply mains voltage as per Indian Electricity Rules is 6% of its rated value. But in India, the variations in ac mains voltage is much more than this (sometimes it may vary from 180 V to 260 V). The dc output voltage being proportional to the input ac voltage, therefore, varies largely.

3. *Variations in temperature.* The dc output voltage varies with temperature, particularly if semiconductor devices are employed.

These variations in dc output voltage may cause inaccurate or erratic operation or even malfunctioning of many electronic circuits. For instance, in oscillators the frequency will shift, in transmitters output will get distorted, and in amplifiers the operating point will shift causing bias instability.

Some feedback arrangement (acting as a voltage regulator) is employed in conjunction with an unregulated power supply to overcome the above mentioned three shortcomings and also to reduce the ripple voltage. Such a system is called a *regulated power supply.*

In many applications, it is important to protect the power supply output against inadvertant short-circuits that might destroy either the circuit under test or operation of the supply itself. Thus current limiting circuits are often incorporated into the regulator design.

Power supplies are becoming steadily more sophisticated in terms of performance objectives and application strategies. A commercial power supply is typically a complex system that makes use of ICs to reduce ripple, improve regulation, and widen control options. Programmable power supplies are also available to allow remote operation that is useful in many settings.

A *regulated power supply* is an electronic circuit that is designed to provide a constant dc voltage of predetermined value across load terminals irrespective of ac mains fluctuations or load variations.

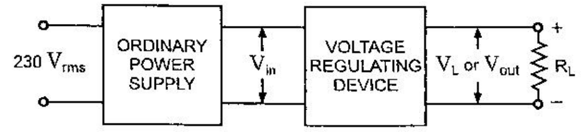

Fig. 32.2. *Regulated Power Supply*

A regulated power supply essentially consists of an ordinary power supply and a voltage regulating device, as illustrated in Fig. 32.2. The output from an ordinary power supply is fed to the voltage regulating device that provides the final output. The output voltage remains constant irrespective of variations in the ac input voltage or variations in output (or load) current.

Figure 32.3 shows the complete circuit of a regulated power supply with a transistor series regulator as a regulating device. The ac voltage, typically 230 V_{rms} is connected to a transformer which transforms that ac voltage to the level for the desired dc output. A bridge rectifier then provides a fullwave rectified voltage that is initially filtered by a π-(or C-L-C) filter to produce a dc voltage. The resulting dc voltage usually has some ripple or ac voltage variation. A regulating circuit uses this dc input to provide a dc voltage that not only has much less ripple voltage but also remains constant even if the input dc voltage varies somewhat or the load connected to the output dc voltage changes. The regulated dc supply is available across a voltage divider.

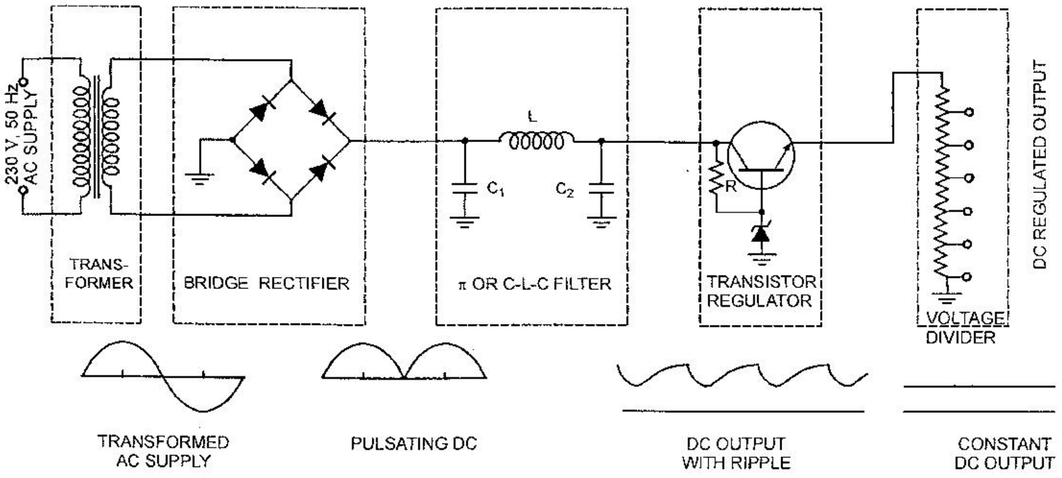

Fig. 32.3. *Complete Regulated Power Supply Circuit*

Often more than one dc voltage is required for the operation of electronic circuits. A single power supply can provide as many voltages as are required by using a voltage (or potential) divider, as illustrated in the figure. As illustrated in Fig. 32.3, a potential divider is a single tapped resistor connected across the output terminals of the supply. The tapped resistor may consists of two or three resistors connected in series across the supply. In fact, bleeder resistor may also be employed as a potential divider.

32.2. POWER SUPPLY CHARACTERISTICS

The quality of power supply depends on different factors such as its load voltage, load current, voltage regulation, source regulation, output impedance, ripple rejection etc. Some of the characteristics of regulated power supplies are discussed below.

1. Load Regulation. The load regulation, abbreviated LR (also called the load effect), is the change in regulated output voltage when the load current changes from minimum to maximum value *i.e.*

$$LR = V_{NL} - V_{FL} \quad ...(32.1)$$

where V_{NL} is load voltage at no load and V_{FL} is the load voltage at full load. In this equation V_{NL} occurs when the load resistance is infinite (*i.e.* out terminals are open-circuited) and V_{FL} occurs when the load resistance is of the minimum value where voltage regulation is lost.

Load regulation is usually expressed in percentage and is given as

$$\% \ LR = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100 \quad ...(32.2)$$

For an ideal power supply output voltage should be independent of dc load current and the percentage load regulation should be equal to zero.

2. Minimum Load Resistance. The load resistance at which a power supply delivers its full-load rated current at rated voltage is referred to as a *minimum load resistance*, $R_{L\,(min)}$.

$$i.e. \ R_{L\,(min)} = \frac{V_{FL}}{I_{FL}} \quad ...(32.3)$$

The value of full-load current I_{FL} should never increase beyond that mentioned in the data sheet of the power supply. For instance, if a data sheet specifies that the power supply will provide an output voltage of 24 V at a maximum rated current of 0.2 A, then minimum load resistance that can be connected across the supply is $R_{min} = \frac{24}{0.2} = 120\ \Omega$. If any attempt is made to decrease the value of load resistance R_L below this value, the rated dc output voltage will not be available.

3. Source or Line Regulation. The input line voltage has a nominal value of 230 V but in practice, there are considerable variations in ac supply mains voltage. Since this ac supply mains voltage is the input to the ordinary power supply, the filtered output of the bridge rectifier is almost directly proportional to the ac mains voltage. Filtered output of the bridge rectifier is the input to the voltage regulating device.

Another way of specifying the quality of a regulated power supply is by its *source regulation* (also called the *source effect* or *line regulation*) abbreviated as SR. The source regulation, SR is defined as the change in regulated output voltage for a specified range of line voltage, typically 230 V ± 10 percent. The defining equation is

$$SR = V_{HL} - V_{LL} \qquad \text{...(32.4)}$$

where V_{HL} is output voltage with high input ac line voltage and V_{LL} is output voltage with low input ac line voltage.

The percentage of source regulation is given as

$$\% \, SR = \frac{V_{HL} - V_{LL}}{\text{Nominal load voltage}} \times 100$$

$$= \frac{SR}{V_{\text{nominal}}} \times 100 \qquad \text{...(32.5)}$$

The output voltage under specific operating conditions is known as the nominal load (or output) voltage.

4. Output Impedance. A regulated power supply is a very stiff dc voltage source. This means that the output resistance is very small (in milliohms). Even though the external load resistance is varied, almost no change is seen in the load voltage. An ideal voltage source has an output impedance of zero. Modern regulated power supplies approach ideal voltage sources.

5. Ripple Rejection. Voltage regulators stabilize the output voltage against variations in input voltage. Ripple is equivalent to a periodic variation in the input voltage. Thus, a voltage regulator attenuates the ripple that comes in with the unregulated input voltage. Since a voltage regulator uses negative feedback, the distortion is reduced by the same factor as the gain. Ripple rejection is a measure of a power supply's ability to reject ripple voltages and is usually expressed in decibels.

32.3. STABILIZATION

Since the output dc voltage V_{out} of regulated power supply depends on the input unregulated dc voltage (output from the bridge rectifier-filter circuit) V_{in}, load current I_L and temperature T, the change in output voltage (ΔV_{out}) of a power supply can be expressed as follows:

$$\Delta V_{out} = \frac{\delta V_{out}}{\delta V_{in}} \Delta V_{in} + \frac{\delta V_{out}}{\delta I_L} \Delta I_L + \frac{\delta V_{out}}{\delta T} \times \Delta T$$

$$= S_v \Delta V_{in} + R_{out} \Delta I_L + S_T \Delta T \qquad \text{...(32.6)}$$

The three coefficients S_v, R_{out} and S_T used in above equation are defined as follows:

Source regulation factor or stability factor

$$S_v = \left. \frac{\Delta V_{out}}{\Delta V_{in}} \right|_{\substack{\Delta I_L = 0 \\ \Delta T = 0}} \qquad \text{...(32.7)}$$

Hence stability factor S_v is the ratio of change in output voltage to the change in input voltage provided that load current and temperature remain constant.

$$\text{Output resistance, } R_{out} = \left. \frac{\Delta V_{out}}{\Delta I_L} \right|_{\substack{\Delta V_{in} = 0 \\ \Delta T = 0}} \qquad \text{...(32.8)}$$

i.e. output resistance R_{out} is defined as the ratio of change in output voltage to the change in load current provided that input voltage and temperature remain constant.

$$\text{Temperature coefficient, } S_T = \left. \frac{\Delta V_{out}}{\Delta T} \right|_{\substack{\Delta V_{in} = 0 \\ \Delta I_L = 0}} \qquad \text{...(32.9)}$$

Thus the rate of change in output voltage with respect to temperature is called the temperature coefficient provided that input voltage and load current are maintained constant.

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

32.4. VOLTAGE REGULATORS

The *regulator* may be constructed from a zener diode, and/or discrete transistors, and/or integrated circuits. All voltage regulators must have a stable voltage reference source which is provided by a special type of diode operated in reverse breakdown called a *breakdown diode*, or *zener* diode.

The primary function of a voltage regulator is to maintain a constant dc output voltage. However, it also rejects ac ripple voltage that is not removed by the filter. The regulator may also include protective functions such as short-circuit protection, current limiting, thermal shutdown, or over-voltage protection.

32.5. DISCRETE TRANSISTOR VOLTAGE REGULATORS

Basically there are two types of transistor voltage regulators viz. (*i*) series voltage regulators and the (*ii*) shunt voltage regulators. Each type of circuit can provide an output dc voltage that is regulated or maintained at a predetermined value even if the input voltage varies or the load connected to the output terminal changes.

32.5.1. Series Voltage Regulators. The basic connection of a series voltage regulator circuit is shown in the block diagram given in Fig. 32.4.

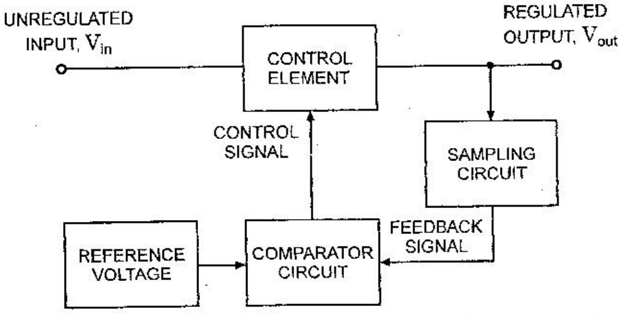

Fig. 32.4. *Block Diagram of a Series Voltage Regulator*

The series element controls the magnitude 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.

If the output voltage increases, the comparator circuit provides a control signal to cause the series control element to reduce the magnitude of the output voltage—thereby maintaining the output voltage. On the other hand, if the output voltage falls, the comparator circuit provides a control signal to cause the series control element to increase the magnitude of output voltage.

1. Transistor Series Voltage Regulator or Emitter Follower Voltage Regulator. A simple series voltage regulator using an NPN transistor and a zener diode is shown in Fig. 32.5. This circuit is called a *series regulator* because collector and emitter terminals of the transistor are in series with the load, as illustrated in the figure. This circuit is also called an *emitter follower voltage regulator* because transistor Q is connected in emitter follower configuration. Here, the transistor Q is termed a series-pass transistor. The unregulated dc supply (or filtered output from the rectifier) is fed to the input terminals and regulated output voltage V_{out} is obtained across the load resistor R_L. Zener diode provides the reference voltage and the transistor acts as a variable resistor, whose resistance varies with the operating conditions (base current I_B). The principle of operation of such a regulator is based on the fact that a large proportion of the change in supply (or input) voltage appears across the transistor and, therefore output voltage tends to remain constant.

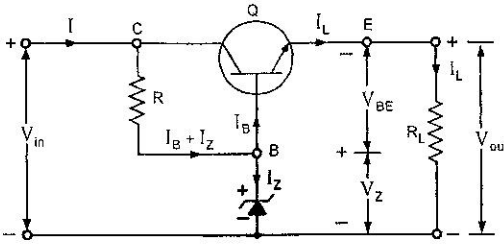

Fig. 32.5. *Transistor Series Voltage Regulator*

Keeping in mind the polarities of different voltages we have

$$V_{out} = V_Z - V_{BE} \qquad ...(32.10)$$

The base voltage of the transistor remains almost constant being equal to that across the zener diode, V_Z.

Operation (*i*) Let the supply (or input) voltage increase which will cause the output voltage V_{out} to increase. An increase in output voltage V_{out} will result in decrease of V_{BE} because V_Z is fixed and decrease in V_{BE} will reduce the level of conduction. This will lead to increase in the collector-emitter resistance of the transistor causing an increase in collector to emitter voltage and as a result the output voltage will be reduced. Thus output voltage will remain constant. Similar explanation can be given for decrease in supply voltage.

(*ii*) Now let us consider the effect of change in load on the output voltage—say current is increased by decrease in R_L. Under such a situation the output voltage V_{out} tends to fall and, therefore, V_{BE} tends to increase. As a result the conduction level of the transistor will increase leading to decrease in the collector-emitter resistance. The decrease in the collector-emitter resistance of the transistor will cause the slight increase in input current to compensate for the decrease in R_L. Thus the output voltage being equal to $I_L R_L$ remains almost constant. Similar explanation will hold true for increase in R_L.

The *advantage* of such a circuit is that the changes in zener current are reduced by a factor β and thus the effect of zener effect is greatly reduced and much more stabilized output is obtained.

Output voltage from a series regulator, $V_{out} = (V_Z - V_{BE})$, and maximum load current $I_{L(max)}$ can be the maximum emitter current that the transistor Q is capable of passing. For a 2N3055 transistor, load current I_L could be 15 A. When load current I_L is zero, the current drawn from the supply is approximately $(I_Z + I_{C(min)})$. The zener regulator (resistor R and zener diode form a simple zener regulator) has to supply only the base current of the transistor. The emitter follower voltage regulator is, therefore, much more efficient than a simple zener regulator.

Limitations. 1. The output voltage cannot be maintained absolutely constant because both V_{BE} and V_Z decrease with the increase in room temperature. Further, V_{BE} increases slightly with the increase in load.

2. The output voltage cannot be changed as there is no provision for it in the circuit.

3. It cannot provide good regulation at high currents because of small amplification provided by one transistor.

4. It has poor regulation and ripple suppression with respect to input variations as compared to other regulators.

5. The power dissipation of a pass transistor is large because it is equal to $V_{CC} I_C$ and almost all variation appears at V_{CE} and the load current is approximately equal to collector current. Thus for heavy load currents pass transistor has to dissipate a lot of power and therefore, becomes hot.

Because of above limitations application of this regulator is limited to low output voltages.

2. Controlled Transistor Series Regulator. A controlled transistor series regulator is shown in Fig. 32.6. The circuit is quite similar to that of a simple transistor series voltage regulator except that an additional transistor Q_2 is inserted in the circuit. The emitter terminal of this transistor Q_2 is connected to the negative terminal of input supply through a zener diode. The base of this additional transistor is connected to the variable tap of a potentiometer.

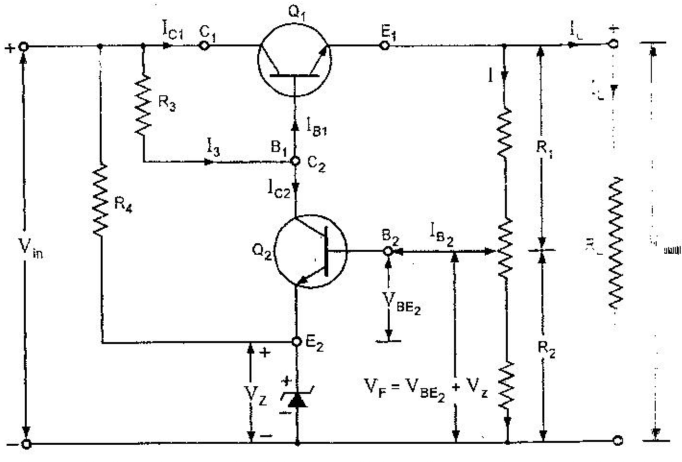

Fig. 32.6. *Controlled Transistor Series Regulator or Negative Feedback Regulator*

This voltage regulator employs the principle of negative feedback to hold the output voltage almost constant despite variations in supply voltage and/or load current. That is why this regulator is also called a *negative feedback regulator*.

Transistor Q_1, the *control element*, is called the *pass transistor* because all the load current flows through it. Zener diode and resistor R_4 act as a *reference element*. The voltage divider (or potentiometer) consisting of resistors R_1 and R_2 samples the output voltage and delivers a negative feedback voltage to the base of transistor Q_2 and this feedback voltage ($V_F = V_{BE_2} + V_z$) controls the collector current of transistor Q_2.

Operation. Suppose the output voltage increases (due to any reason), the voltage across R_2 is also increased as it is part of the output circuit. This causes an increase in voltage ($V_{BE_2} + V_z$). As a result I_{B_2} and also I_{C_2} increases. Assuming I_3 relatively constant, I_{B_1} decreases. Decrease in base current of transistor Q_1 causes the increase in collector-emitter resistance of transistor Q_1. This causes an increase in $V_{C_1E_1}$ thereby off-setting the increase in output voltage. Thus output voltage remains constant. Reverse happens should the output voltage decrease.

The voltage V_2 provided by the potential divider R_1-R_2 must be equal to the sum of the base-emitter voltage of transistor Q_2 and the zener diode *i.e.*,

$$V_{BE\,2} + V_z = V_2 = \frac{R_2}{R_1 + R_2} V_{out}$$

$$\text{or} \quad V_{out} = \frac{R_1 + R_2}{R_2} (V_{BE\,2} + V_z)$$

$$= \left(1 + \frac{R_1}{R_2}\right)(V_{BE\,2} + V_z) = A_f (V_{BE\,2} + V_z) \quad ...(32.11)$$

Thus the regulated output voltage is equal to the closed-loop gain multiplied by the sum of zener voltage and base-emitter voltage of transistor Q_2 (the sensing element).

Like emitter follower regulator this regulator also has the drawback of excessive power dissipation. Due to this high power dissipation output of the power supply is limited to 30-40 V, as safe value of V_{CE} is 50 V.

Another drawback of this regulator is that it has no overload/short-circuit protection.

3. Controlled Transistor Series Regulator With Overload and Short-Circuit Protection. If the load resistance R_L is reduced or load terminals are shorted accidentally, a very large load current will flow in the circuit shown in Fig. 32.6. It may destroy the pass transistor Q_1, diode or possibly some other component. Fuse protection will not prove adequate because the transistor may get damaged in a very small fraction of a second.

To avoid this situation, a *current limiting circuit* is added to a series regulator, as illustrated in Fig. 32.7.

The current limiting circuit consists of a transistor Q_3 and a resistor R_5 (approximately 1 Ω) connected between base and emitter terminals of transistor Q_3. With normal load current, transistor Q_3 remains off because the voltage drop across resistor R_5 is small (less than about 0.7 V necessary for making the transistor Q_3 on). Under this condition, the circuit works normally, as described above. With the excessive load current (exceeding $\frac{0.6}{1}$ *i.e.* 0.6 A or 600 mA) the voltage drop across R_5 becomes large enough to turn transistor Q_3 on. The collector current of transistor Q_3 flows through R_3 thereby decreasing the base voltage of transistor Q_1. This results in reduction of the conduction level of transistor Q_1. Thus further increase in load current is prevented.

Figure 32.8 summarizes the current limiting. When load resistance R_L is infinite, the output voltage is regulated and has a value of V_{REG}. The load current I_L is zero for this operating condition. When R_L decreases, the load current I_L increases up to the point where R_L becomes equal to $R_{L\,(min)}$. At this minimum load resistance, I_L equals 600 mA and V_{BE} equals 0.6 V. Beyond this point, transistor Q_3 turns on and the current limiting sets in. Further decrease in R_L produces decrease in output voltage, and regulation is lost. When R_L is zero, the load current I_L is limited to a value between 600 mA and 700 mA. The load current with shorted-load terminals is symbolized as I_{SL}. When the load terminals are shorted in Fig. 32.7, the voltage across resistor R_5 is

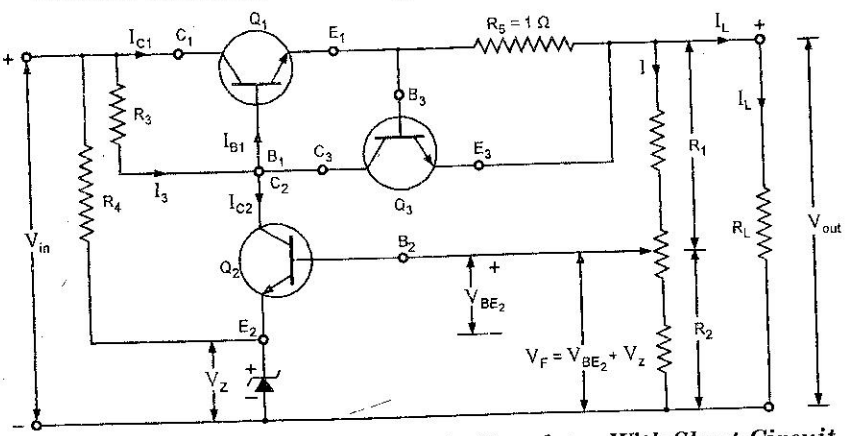

Fig. 32.7. *Controlled Transistor Series Regulator With Short-Circuit Protection*

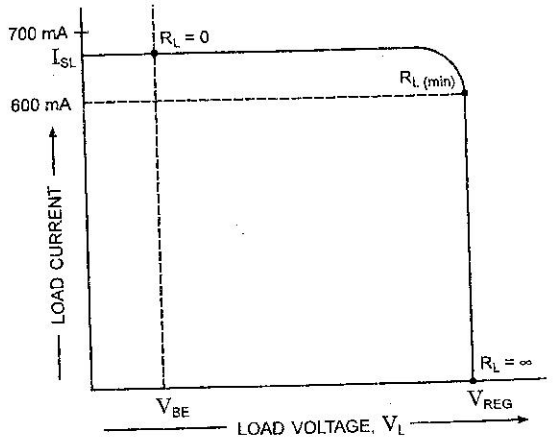

Fig. 32.8

$$V_{BE} = I_{SL}\, R_5 \quad \text{or} \quad I_{SL} = \frac{V_{BE}}{R_5} \qquad ...(32.12)$$

where V_{BE} is typically between 0.6 and 0.7 V.

The minimum load resistance where regulation is lost can be estimated with the following equation

$$R_{L\,(min)} = \frac{V_{REG}}{I_{SL}} \qquad ...(32.13)$$

The exact value of $R_{L\,(min)}$ will be slightly less or greater than this.

The simple current limiting circuit also has a drawback of large power dissipation across the series pass transistor. With a short across the load, almost all the input voltage appears across the pass transistor. So the pass transistor has to dissipate approximately

$$P_v = (V_{in} - V_{BE})\, I_{SL} \qquad ...(32.14)$$

where V_{BE} is the base-emitter voltage of Q_3, the *current-limiting transistor*.

4. Foldback Current Limiting. A problem with the simple current limiting circuit just discussed is that there is a large amount of power dissipation in series pass transistor Q_1 while the regulator remains short-circuited. The foldback current limiting circuit is the solution of above problem. The circuit of a transistor series voltage regulator with foldback current limiting facility is illustrated in Fig. 32.9.

In this circuit base of transistor Q_3 is biased by a voltage divider network consisting of resistors R_6 and R_7. The load current I_L flows through resistor R_5, causing a voltage drop of $I_L R_5$ (approximately) across it. Thus a voltage of $(I_L R_5 + V_{out})$ acts across the voltage divider $(R_6 - R_7)$ network. The voltage applied to the base of transistor Q_3 is equal to the voltage drop across resistor R_7 and is given as

$$V_{B_3} = \frac{R_7}{R_6 + R_7}\,(I_L R_5 + V_{out}) = K\,(I_L R_5 + V_{out}) \qquad ...(32.15)$$

$$\text{where } K = \frac{R_7}{R_6 + R_7}$$

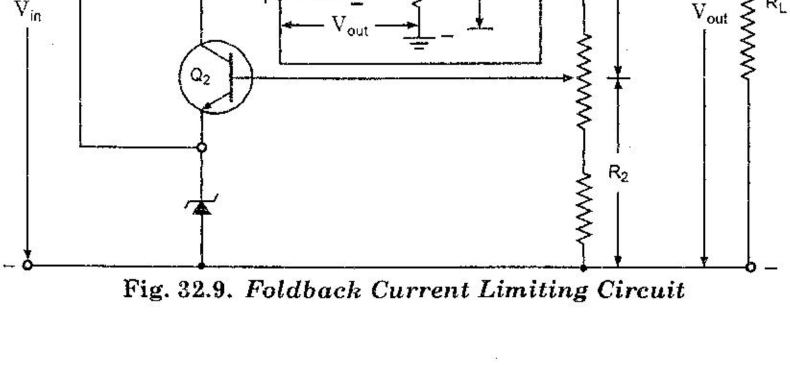

Fig. 32.9. *Foldback Current Limiting Circuit*

Emitter of transistor Q_3 is connected to the positive terminal of V_{out}. Applying Kirchhoff's voltage law to closed mesh of Q_3 shown in the figure we have

$$V_{out} + V_{BE_3} = V_{B_3}$$

$$\text{or } V_{BE_3} = V_{B_3} - V_{out}$$

$$= K(I_L R_5 + V_{out}) - V_{out}$$

$$= K\, I_L R_5 + (K - 1)V_{out} \qquad ...(32.16)$$

Thus the magnitude of base drive of transistor Q_1 is by this V_{BE_3}.

Now if load resistance decreases, may be due to any reason, load current I_L will increase causing voltage drop $I_L R_5$ to increase. This causes V_{B_3} to increase and therefore V_{BE_3} to increase. This makes transistor Q_3 *on* in a stronger way. The increased collector current I_{C_3} of transistor Q_3 flows through the resistor R_3 thereby decreasing the base voltage of transistor Q_1. This results in reduction of the conduction level of transistor Q_1. Thus further increase in load current is prevented.

From Eq. (32.16) it is obvious that V_{BE_3} in this circuit is much more than that was in circuit illustrated in Fig. 32.7 (only $I_L R_5$). It means that the increment in load current is limited by larger amount in circuit shown in Fig. 32.9.

Due to reduction in load resistance R_L, V_{BE_3} increases to a level so that transistor Q_3 gets saturated. Now collector current I_{C_3} becomes constant. Any further decrease in R_L will have no effect on I_{C_3}. The corresponding load current is $I_{L\,(max)}$ and is given as

$$I_{L\,(max)} = \frac{V_{BE_3}}{K R_5} + \frac{(1 - K)}{K R_5}\, V_{out} \qquad ...(32.17)$$

Beyond this point V_{BE_3} also drops due to saturation. Therefore according to Eq. (32.17) load current I_L begins decreasing with decrease in R_L from $R_{L\,(min)}$, as illustrated in Fig. 32.10. When load resistance R_L is zero *i.e.* when output terminals get shorted the output voltage V_{out} becomes equal to zero. Substituting $V_{out} = 0$ in Eq. (32.17) we have

$$I_{SL} = \frac{V_{BE_3}}{K R_5} \qquad ...(32.18)$$

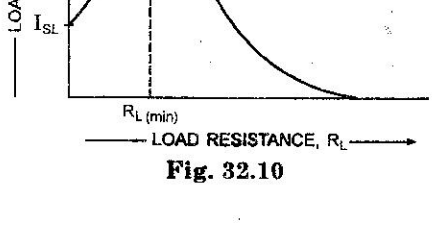

Fig. 32.10

i.e. shorted-load current I_{SL} is very much smaller than maximum load current $I_{L\,(max)}$ proving the foldback current limiting. The smaller I_{SL} limits power dissipation in pass transistor Q_1 preventing it from being damaged. This is the main advantage of this circuit.

32.5.2. Shunt Voltage Regulator. A shunt voltage regulator provides regulation by shunting current away from the load. The block diagram of such a voltage regulator is depicted in Fig. 32.11. The input unregulated voltage provides current to the load. Some of this current is shunted away by the control element to maintain the regulated output voltage across the load. If the output voltage tends to change due to change in load, the sampling circuit provides a feedback signal to a comparator circuit which then provides a control signal to vary the magnitude of current shunted away from the load. For example, when the output voltage tends to fall, the sampling circuit provides a feedback signal to the comparator circuit which then provides a control signal to draw lesser shunt current, providing more load current, thereby keeping the regulated voltage constant.

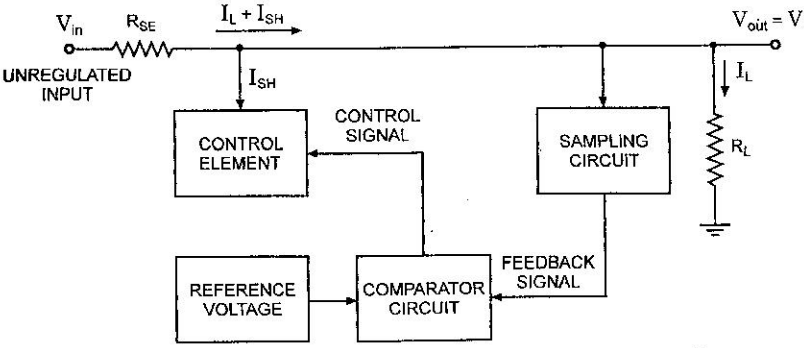

Fig. 32.11. ***Block Diagram of a Shunt Voltage Regulator***

1. Transistor Shunt Voltage Regulator. A shunt voltage regulator using an NPN transistor and a zener diode is shown in Fig. 32.12. A series resistance R_{SE} is connected in series with the unregulated (or input), supply. Zener diode is connected across the base and collector terminals of the NPN transistor and the transistor is connected across the output, as shown in Fig. 32.12.

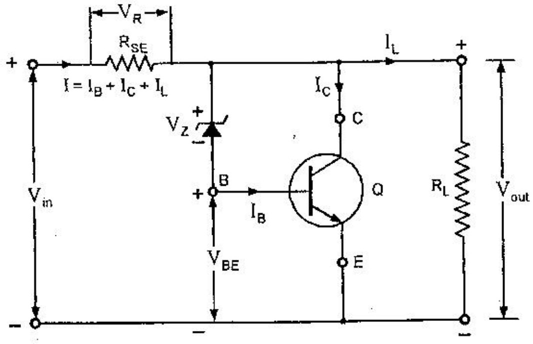

Fig. 32.12. ***Transistor Shunt Voltage Regulator***

Unregulated voltage is reduced, due to voltage drop in series resistance R_{SE}, by an amount that depends on the current supplied to the load R_L. The voltage across the load is fixed by the zener diode and transistor base-emitter voltage V_{BE}.

Output voltage is given as

$$V_{out} = V_Z + V_{BE} = V_{in} - I\,R_{SE} \qquad \text{...(32.19)}$$

Since both V_Z and V_{BE} remain nearly constant so output voltage V_{out} remains nearly constant. This is explained below :

If the input (or supply) voltage increases, it causes increase in V_{out} and V_{BE} resulting in increase in base current I_B and therefore, increase in collector current I_C ($I_C = \beta\, I_B$). Thus with the increase in supply voltage, supply current I increases causing more voltage drop in series resistance R_{SE} and thereby reducing the output voltage. This decrease in output voltage is enough to compensate the initial increase in output voltage. Thus output voltage remains almost constant. Reverse happens should the supply voltage decrease.

If the load resistance R_L decreases, output current I_L increases and this increase in output current is supplied by decrease in base and collector currents I_B and I_C. Thus the input current I remains almost constant causing no change in voltage drop across series resistance R_{SE}. Thus output voltage V_{out} being the difference of supply voltage (fixed) and series resistor drop V_R (fixed) remains constant. Reverse happens should the load resistance increase.

Limitations. (*i*) There is considerable power loss in series resistor R_{SE}.

(*ii*) A large proportion of supply current I flows through the transistor rather than to load.

(*iii*) There are problems of over-voltage protection in the circuit.

For the above reasons, a series voltage regulator is preferred over the shunt voltage regulator.

2. Improved Transistor Shunt Voltage Regulator. An improved transistor shunt voltage regulator circuit is illustrated in Fig. 32.13. The zener diode provides a reference voltage in order that the voltage across R_1 senses the output voltage. As the output voltage V_{out} tends to change, the current shunted by transistor Q_1 is varied in order to maintain the output voltage constant. Transistor Q_2 provides a larger base current to transistor Q_1 than the circuit

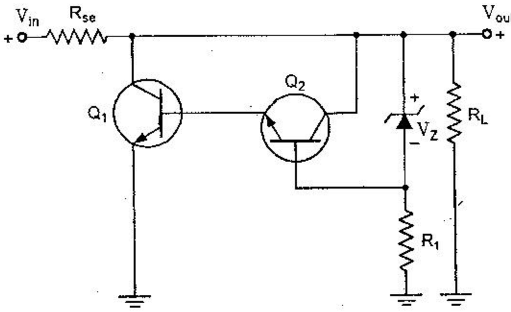

Fig. 32.13. ***Improved Transistor Shunt Voltage Regular Circuit***

shown in Fig. 32.12, so that the regulator handles a larger load current. The output votlage is set by the zener voltage and that across the two transistor base emitters.

$$V_{out} = V_Z + V_{BE_2} + V_{BE_1} \quad ...(32.20)$$

32.5.3. Limitations of Transistorized Power Supplies. The stabilized voltage that can be obtained from transistorized power supplies is limited, to about 30 – 40 V only, because maximum safe value of V_{CE} is about 50 V. This puts a limit to the use of transistorized power supplies.

32.6. OP-AMP REGULATORS

32.6.1. Op-Amp Series Voltage Regulator Circuit. Op-amp series voltage regulator circuit is shown in Fig. 32.14. The op-amp compares the zener diode reference voltage with the feedback voltage from sensing resistors R_f and R_1. If the output voltage varies, the conduction of transistor Q_1 is controlled to maintain the output voltage constant. The op-amp places a negligible load on the zener diode, allowing it to operate at a *single fixed* point. This results in a very stable output from the zener diode. Also, the zener diode no longer must absorb large swings in the current. Hence it can be replaced by a low-power, highly precise reference diode.

The output voltage will be maintained at a value given by the following equation :

$$V_{out} = V_z\left(1 + \frac{R_f}{R_1}\right) \quad ...(32.21)$$

The output voltage can be varied simply by varying R_f in the circuit.

To bias the transistor, the output voltage of the op-amp must exceed the circuit's output voltage V_{out} by 0.7 V.

i.e. $V_{op\text{-}amp} = V_{out} + 0.7\ V \quad ...(32.22)$

Cautions : 1. The peak value of input voltage (input voltage from the filter) must be kept below the maximum supply voltage for the op-amp (op-amps with rather high supply voltage ratings are available).

2. The voltage from the filter must be at least 2 V above the output voltage V_{out}. This is essential in order to keep the op-amp out of saturation and to keep the zener diode in its breakdown region

i.e. $V_{peak} \le \pm V_{supply\ rating\ of\ op\text{-}amp} \quad ...(32.23)$

$V_{min} \ge V_{out} + 2\ V \quad ...(32.24)$

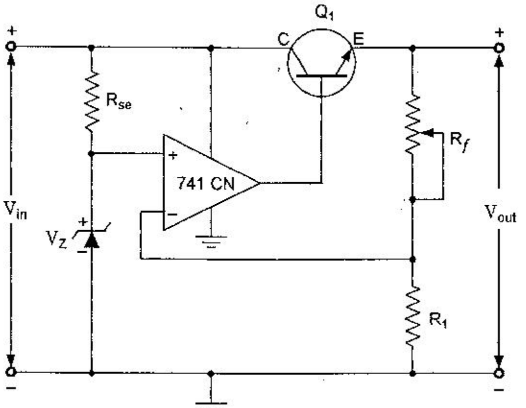

Fig. 32.14. *Op-Amp Series Voltage Regulator Circuit*

The worthnoting point is that the minimum output voltage is V_z, when R_f is shorted. Hence it is necessary that the selected zener diode have a voltage smaller than the lowest desired output voltage.

Finally, making of R_f the potentiometer needs care. Making R_f a potentiometer and running the wiper all the way down to ground will remove all negative feedback. The output voltage will be driven to $+V_{sat}$, as the op-amp would be operating as a comparator.

The op-amp only has to provide the base current. This is then multiplied by the transistor β to give load current. The transistor β is determined by equation

$$\beta \ge \frac{I_{output}}{I_{op\text{-}amp\ max}} \quad ...(32.25)$$

Also, the transistor must be able to dissipate the power generated:

$$P_{c\ max} = (V_{dc} - V_{out})I_{output} \quad ...(32.26)$$

where V_{dc} is the dc output voltage from the filter, V_{out} is the output (or load) dc voltage and I_{output} is the output (or load) current.

32.6.2. Current Limiting Circuit. One form of short-circuit or overload protection is current limiting, as illustrated in Fig. 32.15. With the increase in output or load current, 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 transistor 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 resistor R_L. The action of components R_{sc} and Q_2 thus provides limiting of the maximum load current.

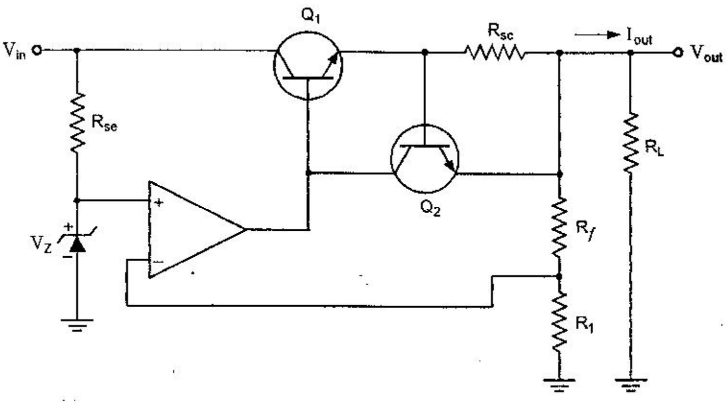

Fig. 32.15. *Current Limiting Voltage Regulator*

32.6.3. Foldback Limiting. Current limiting reduces the output voltage when the output current exceeds the limiting value. The circuit given in Fig. 32.16 provides foldback limiting, which **reduces both the**