Solution

1. Ripple factor in the case of π-type CLC filter is given by

$$r = \sqrt{2} \times (X_C/R_L) \times (X_{C1}/X_{L1})$$

2. $X_C = 1/2\pi fC$ where $f = 100$ Hz because of full-wave rectification.
3. $X_C = 1/(2 \times 3.14 \times 100 \times 100 \times 10^{-6}) = 15.92\ \Omega = X_{C1}$.
4. $R_L = 1000\ \Omega$ and $X_{L1} = 2\pi fL = 628.3\ L$.
5. From the expression of ripple factor,

   $X_{L1} = \sqrt{2} \times (X_C/R_L) \times (X_{C1}/r) = 1.414 \times (15.92/1000) \times (15.92/0.001) = 358.4$

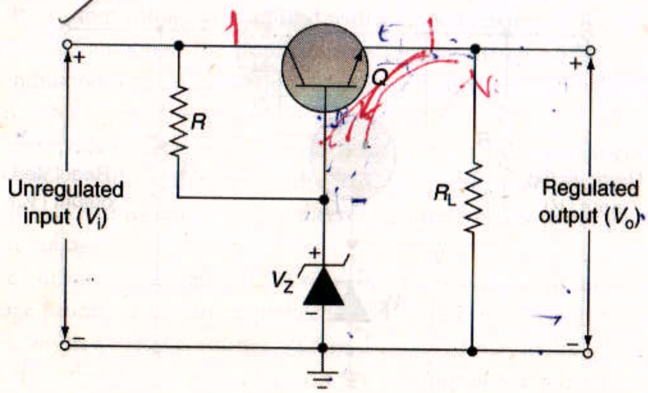
   Therefore, $L = 358.4/628.3 = 0.57$ henry.
6. Value of resistance required to replace the inductance and still provide the same ripple is equal to the inductive reactance.
7. Therefore, required value of resistance, $R = X_{L1} = 358.4\ \Omega$.

14.5 Linear Regulators

As outlined earlier, the regulator circuit in a power supply ensures that the load voltage (in the case of voltage regulated power supplies) or the load current (in the case of current regulated power supplies) is constant irrespective of variations in the line voltage or load resistance. In the present section are discussed different types of linear voltage regulator circuits. Three basic types of linear voltage regulator configurations include the emitter–follower regulator, series-pass regulator and shunt regulator. Each one of these is briefly described in the following sections.

Emitter–Follower Regulator

Figure 14.15 shows the basic positive output emitter–follower regulator. The emitter voltage, which is also the output voltage, remains constant as long as the base voltage is held constant. A Zener diode connected at the base ensures this. The regulated output voltage in this case is $(V_Z - 0.7)$ V. The emitter–base voltage of the transistor is assumed to be 0.7 V. Another way of explaining the regulation action provided by the



$V_o\uparrow$ $V_{BE}\downarrow$ $V_{CE}\uparrow$ $V_o\downarrow$

~~$V_o =$~~ 1

$V_{in} = V_{CE} + V_o$

Figure 14.15 | Emitter–follower regulator for positive output voltages.

circuit is as follows. When the output voltage tends to increase, the emitter–base voltage of the series transistor decreases thus decreasing its conduction. This increases collector–emitter drop across the transistor to maintain a constant output voltage. When the output voltage tends to decrease, the emitter–base voltage increases thus increasing the conduction of the transistor. This decreases the collector–emitter drop across the transistor again maintaining a constant output voltage. Owing to high inherent current gain of the series-pass transistor, a low-power Zener diode can be used to regulate high value of load current. The base current in this case needs to be only $[1/(1 + h_{fe})]$ times the load current. Figure 14.16 shows the emitter–follower regulator circuit for negative output voltages. The regulated output voltage in this case is $-(V_Z - 0.7)$ V. If the load current is so large that it is beyond the capability of the Zener diode to provide the requisite base current, a Darlington combination can be used instead of a single transistor series-pass element (Figures 14.17 and 14.18). The regulated output voltages for the Darlington emitter–follower regulators of Figures 14.17 and 14.18 are $(V_Z - 1.4)$ and $-(V_Z - 1.4)$ V, respectively.

Series-Pass Regulator

The emitter–follower regulator circuit discussed in the previous section is also a type of series-pass regulator where the conduction of the series transistor decides the voltage drop across it and hence the output voltage. The Zener diode provides the reference voltage that controls the conduction of the transistor depending

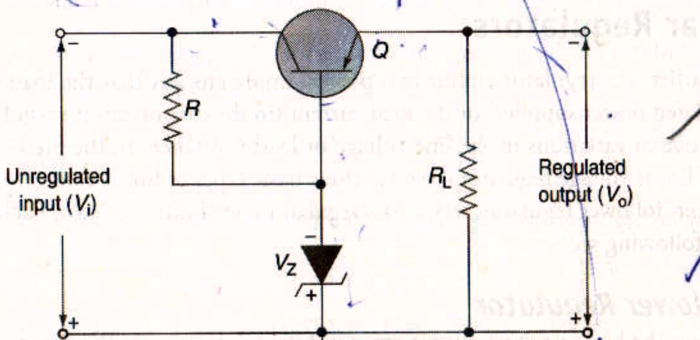


Figure 14.16 | Emitter–follower regulator for negative output voltage.

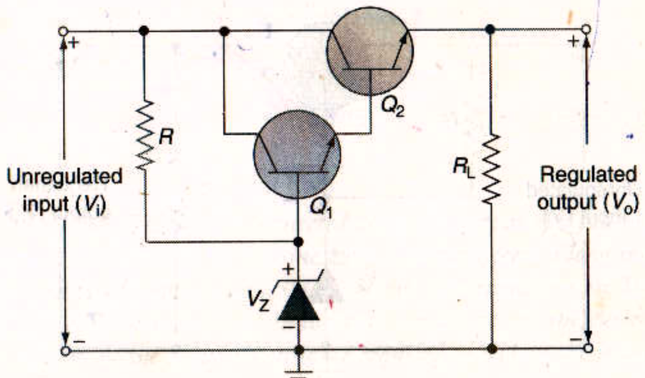


Figure 14.17 | Emitter–follower regulator using Darlington transistor pair (positive output).

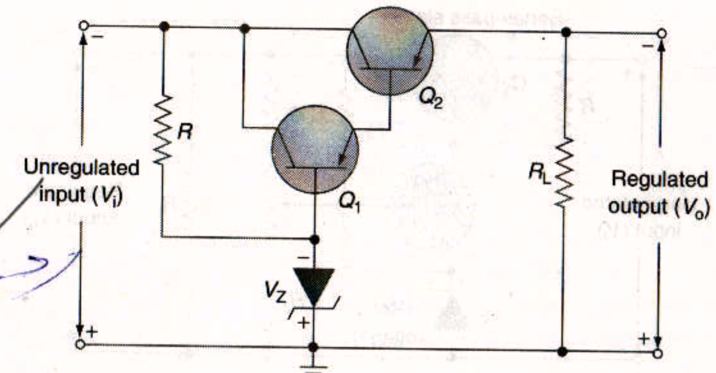


Figure 14.18 | Emitter–follower regulator using Darlington transistor pair (negative output).

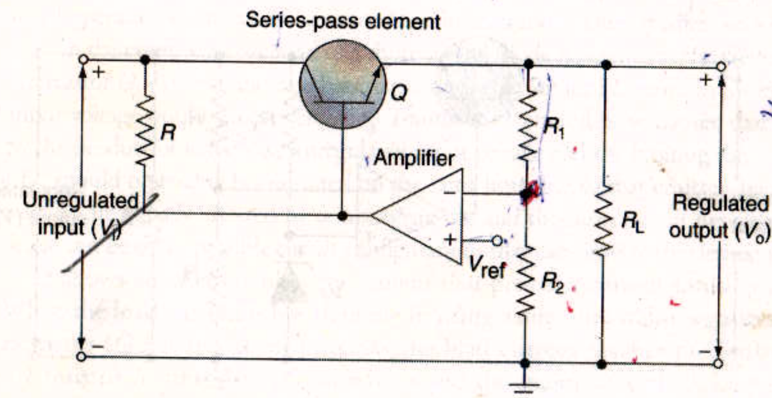


Figure 14.19 | Series-pass linear regulator.

upon the output voltage. Figure 14.19 shows the basic constituents of an improved series-pass-type linear regulator that is capable of providing much better regulation specifications. The series-pass element, a bipolar transistor in the circuit shown, again works like a variable resistance with the conduction of the transistor depending upon the base current. The regulator circuit functions as follows.

A small fraction of the output voltage is compared with a known reference DC voltage and their difference is amplified in a high-gain DC amplifier. The amplified error signal is then fed back to the base of the series-pass transistor to alter its conduction so as to maintain essentially a constant output voltage. The regulated output voltage in this case is given by $V_{ref} \times (R_1 + R_2)/R_2$.

As the output voltage tends to decrease due to decrease in input voltage or increase in load current, the error voltage produced as a result of this causes the base current to increase. The increased base current increases transistor conduction thus reducing its collector–emitter voltage drop, which compensates for the reduction in the output voltage.

Similarly, when the output voltage tends to increase due to increase in input voltage or decrease in load current, the error voltage produced as a consequence is of the opposite sense. It tends to decrease transistor conduction thus increasing its collector–emitter voltage drop again maintaining a constant output voltage. The regulation provided by this circuit depends upon the stability of the reference voltage and the gain of the DC amplifier. A typical series-pass regulator circuit using a bipolar transistor as the error amplifier is

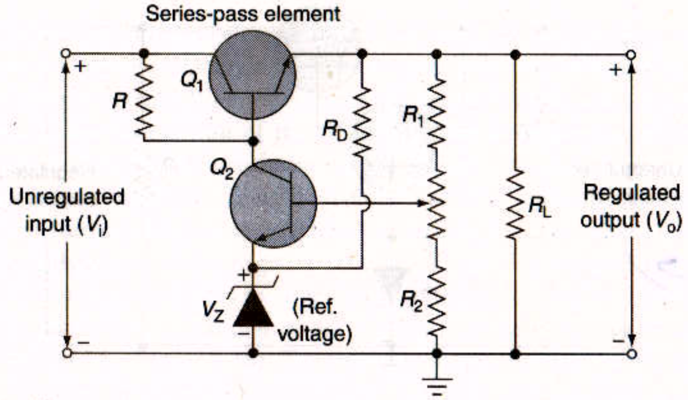


Figure 14.20 | Series-pass linear regulator using bipolar transistor as error amplifier.

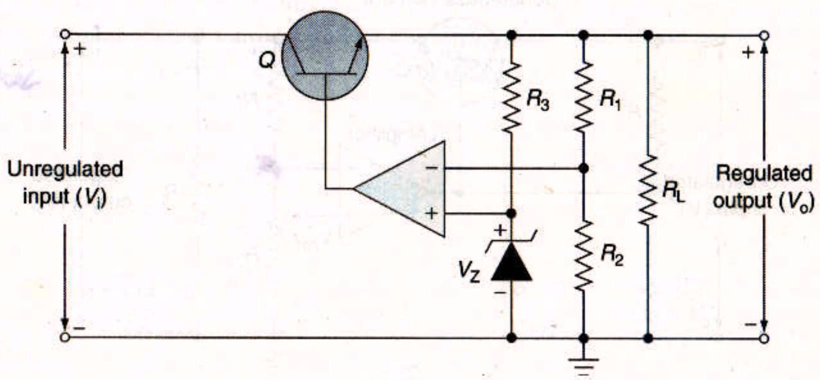


Figure 14.21 | Series-pass linear regulator using opamp-based as error amplifier.

shown in Figure 14.20. Figure 14.21 shows another series-pass regulator circuit that uses an operational amplifier as the error amplifier. The operation of the circuit is similar to that of transistor-based one.

As compared to the emitter–follower type series-pass regulator, the one with an error amplifier in the feedback loop and discussed in this section provides better regulation due to the gain provided by the error amplifier. In this case, given change in output voltage causes a relatively much larger change in the base current of the series-pass element.

Current Limiting

The power dissipated in the series-pass transistor is the product of its collector–emitter voltage and the load current. As the load current increases within a certain range, the collector–emitter voltage decreases due to the feedback action keeping the output voltage as constant. The series-pass transistor is so chosen that it can safely dissipate the power under normal load conditions. If there is an overload condition due to some reason or the other, the transistor is likely to get damaged if such a condition is allowed to persist for long. In the worst case, if there were a short circuit on the output, the whole unregulated input would appear across the series-pass element increasing the power dissipation to prohibitively large magnitude eventually destroying the transistor. Even a series-connected fuse does not help in such a case, as the thermal time constant of the transistor is much smaller than that of the fuse. Thus it is always desirable to build overload protection or current limiting protection in the linearly regulated power supply design. One such configuration is shown in Figure 14.22.

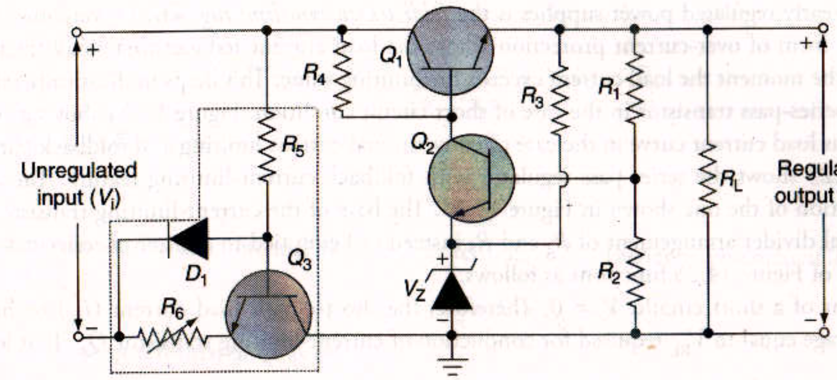


Figure 14.22 | Series-pass linear regulator with overload protection.

Under normal operating conditions, transistor Q_3 is in saturation. Thus, it offers very little resistance to the load current path. In the event of an overload or a short circuit, diode D_1 conducts thus reducing the base drive to transistor Q_3. Transistor Q_3 offers an increased resistance to the flow of load current. In the event of a short circuit, the whole of input voltage would appear across Q_3. Transistor Q_3 should be so chosen that it can safely dissipate power given by the product of worst-case unregulated input voltage and the limiting value of current. Diode D_1 and transistor Q_3 should preferably be mounted on the same heat sink so that emitter–base junction of Q_3 and P–N junction of D_1 are equally affected by temperature rise and the short circuit limiting current is as per the preset value. There can be other possible circuit configurations that can provide the desired protection function.

Figure 14.23 shows another circuit arrangement that provides current-limiting action and overload protection. When the load current is less than the limiting value, the circuit regulates the output voltage normally. Transistor (Q_3) is in cut-off state. As the load current reaches the limiting value, which is determined by resistor R_5, transistor Q_3 conducts and the major part of Q_1 base current gets routed through Q_3, substantially reducing its base drive.

The current-limiting feature described in the previous paragraphs has the advantage of protecting the series-pass transistor and rectifier diodes in the case of any accidental shorting of the output. However, the circuit suffers from the disadvantage of large power dissipation in the series-pass transistor in the event of an output short circuit. The power dissipated in this case is approximately equal to the product of the unregulated input voltage and the limiting value of the load current. A common form of current-limiting feature

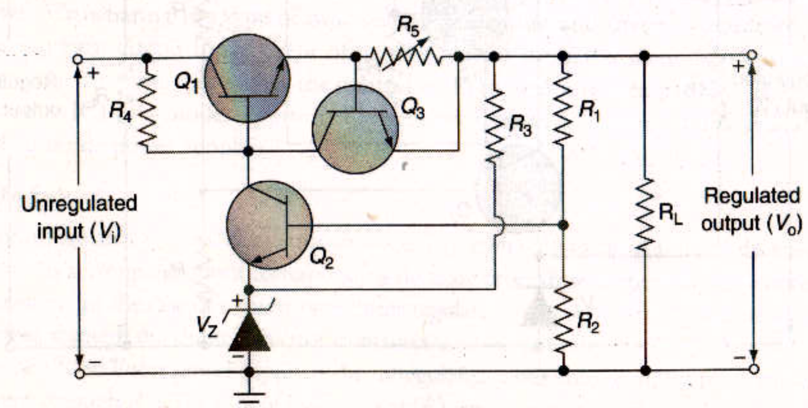


Figure 14.23 | Series-pass linear regulator with overload protection.

practiced in linearly regulated power supplies is the *foldback current limiting,* which overcomes this shortcoming. It is a form of over-current protection where the load current reduces to a small fraction of the limiting value the moment the load current exceeds the limiting value. This helps in drastically reducing the dissipation in series-pass transistor in the case of short circuit condition. Figure 14.24 shows a comparison of voltage versus load current curve in the case of conventional current limiting and foldback current limiting. Figure 14.25 shows the series-pass regulator with foldback current-limiting feature. The circuit is a slight modification of the one shown in Figure 14.23. The base of the current-limiting transistor Q_3 is fed from a potential divider arrangement of R_6 and R_7 instead of being tied to emitter of series-pass transistor Q_1. The circuit of Figure 14.25 functions as follows.

In the event of a short circuit, $V_o = 0$. Therefore, the short-circuit load current (I_{SL}) is the one that produces a voltage equal to V_{BE} required for conduction of current-limiting transistor Q_3. That is,

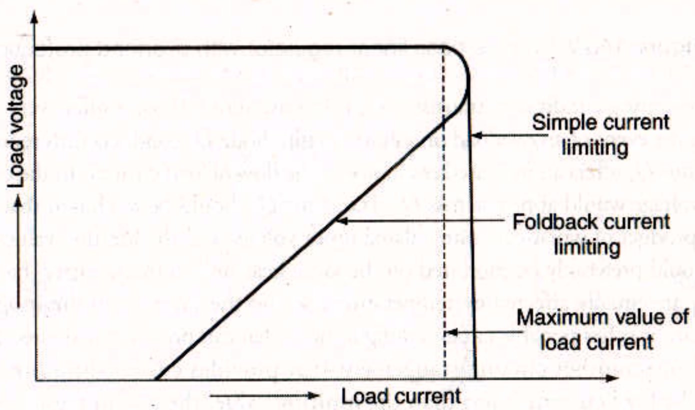


Figure 14.24 | Foldback current limiting.

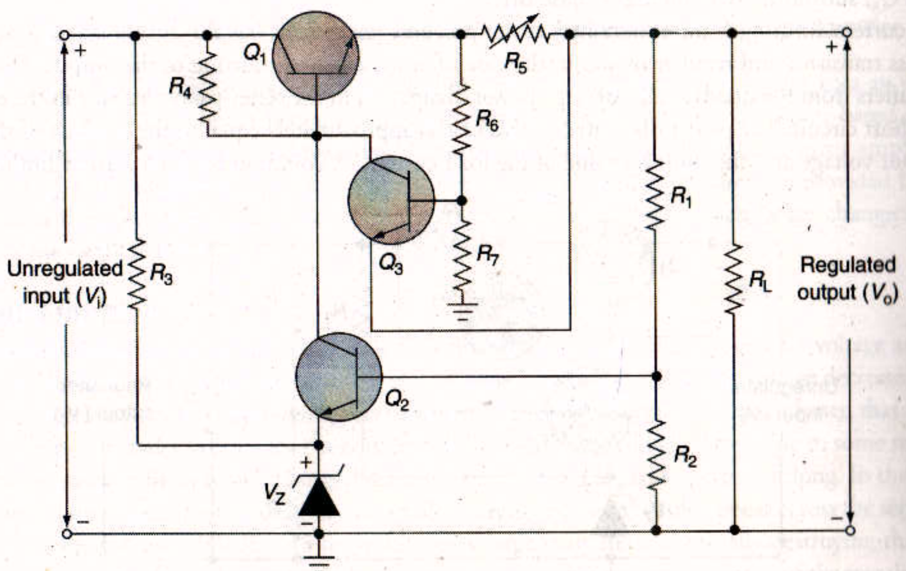


Figure 14.25 | Series regulator with foldback current limiting.

$$V_{BE} = (I_{SL} \times R_5) \times \frac{R_7}{R_6 + R_7} = K \times I_{SL} \times R_5$$

where $K = R_7/(R_6 + R_7)$. This gives

$$I_{SL} = \frac{V_{BE}}{K \times R_5} \tag{14.30}$$

When the output is not shorted, potential of Q_3 emitter terminal is V_o. Therefore, potential of its base terminal (V_{B3}) is given by

$$V_{B3} = V_o + V_{BE} = V_o + K \times I_{SL} \times R_5$$

Potential of the emitter terminal of Q_1 is given by

$$V_{E1} = \frac{V_o + K \times I_{SL} \times R_5}{K} \tag{14.31}$$

Therefore, maximum value of load current (I_{max}) under these conditions is given by

$$I_{max} = \left(\frac{1}{R_5}\right) \times \left[\left\{\frac{(V_o + K \times I_{SL} \times R_5)}{K}\right\} - V_o\right] \tag{14.32}$$

$$I_{max} = \frac{V_o + K \times I_{SL} \times R_5 - V_o \times K}{K \times R_5} \tag{14.33}$$

$$I_{max} = \frac{V_o \times (1-K) + K \times I_{SL} \times R_5}{K \times R_5} \tag{14.34}$$

$$I_{max} = I_{SL} + \left(\frac{V_o \times (1-K)}{K \times R_5}\right) \tag{14.35}$$

Equation (14.35) shows that the maximum load current or the limiting value of the load current is larger than the short-circuit current. Typical value of K is such that the maximum load current is about two to three times the short-circuit load current.

Other types of protection features that are usually built into power supplies include crowbaring and thermal shutdown. Crowbaring is a type of over voltage protection and thermal shutdown disconnects the input to the regulator circuit in the event of temperature of the active device(s) exceeding a certain upper limit. It may be mentioned here that the control and protection functions are usually provided by an integrated circuit (IC) in a modern power supply. A wide range of control ICs is available for both linear and switched mode power supplies.

Shunt Regulator

In a series-type linear regulator, the pass element is connected in series with the load and any decrease or increase in the output voltage is accompanied by a corresponding decrease or increase in the collector–emitter voltage of the series-pass transistor. In the case of a shunt-type linear regulator (Figure 14.26), regulation is provided by a change in the current through the shunt transistor to maintain a constant output voltage. The regulated output voltage in a shunt regulated linear power supply is the unregulated input voltage minus drop across the resistor R_1. Now, the current through R_1 is the sum of load current (I_L) and current through shunt transistor (I_S). As the output voltage tends to decrease, the base current through the transistor reduces with the result that its collector current (I_S) decreases too. This reduces drop across R_1 and the output voltage is restored to its nominal value.

Similarly, the tendency of the output voltage to increase is accompanied by an increase in current through the shunt transistor consequently increasing voltage drop across R_1, which in turn maintains a constant output voltage. A Darlington combination in place of shunt transistor enhances the current capability (Figure 14.27). The regulated output voltages in the case of shunt regulator circuits of Figures 14.26 and 14.27 are $(V_Z + V_{BE})$ and $(V_Z + 2V_{BE})$, respectively. Another shunt regulator configuration is shown in Figure 14.28. In this case, the base terminal of the shunt transistor is driven by the output of an opamp. A reference voltage and the sample of output voltage drive the two inputs of the opamp. If the two voltages differ, the output of opamp forces the shunt element to conduct more or less current through it, thus maintaining a constant output voltage.

Shunt regulator is not as efficient as a series regulator for the simple reason that the current through the series resistor in the case of shunt regulator is the sum of load current and shunt transistor current and it dissipates more power than the series-pass regulator with same unregulated input and regulated output specifications. In a shunt regulator, the shunt transistor also dissipates power in addition to the power dissipated in the series resistor. The only advantage with a shunt regulator is its simplicity and that it is inherently protected against overload conditions.

$V_o = V_Z + V_{BE}$

$V_{in} = V_R + V_o$

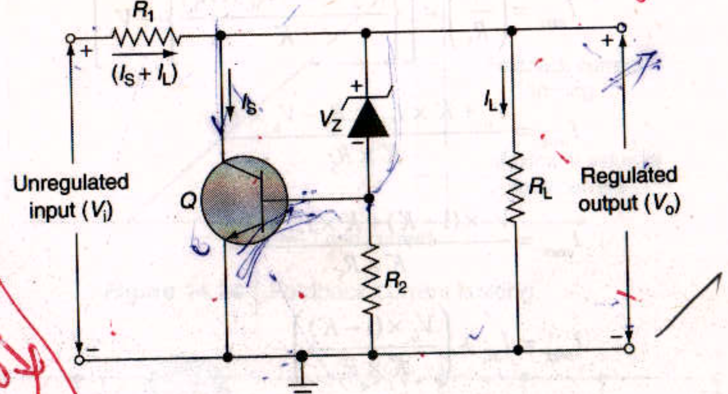
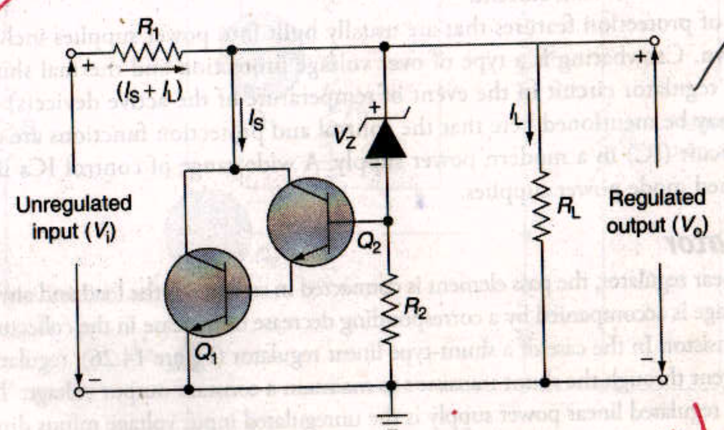


Figure 14.26 | Shunt regulator.



$V_Z + 2V_{BE}$

Figure 14.27 | Shunt regulator with Darlington transistor pair.

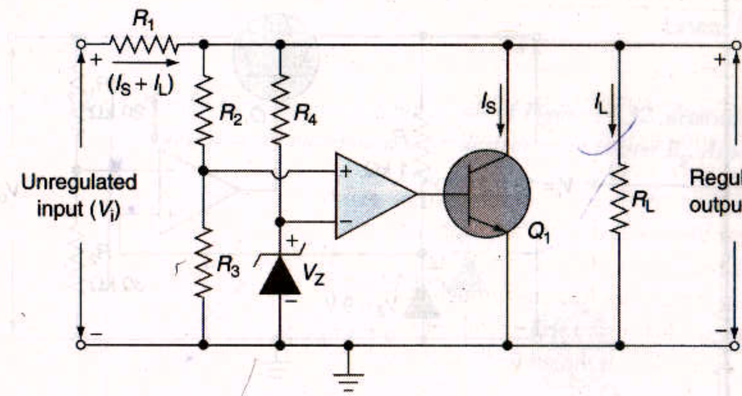


Figure 14.28 | Opamp-based shunt regulator circuit.

EXAMPLE 14.9 *Refer to the emitter-follower regulator circuit of Figure 14.29. Determine (a) regulated output voltage; (b) current through the Zener diode. Assume β of the transistor as 50, V_{BE} (Q) = 0.7 V, forward voltage drop of diode D_1 = 0.7 V, Zener diode voltage (V_Z) = 12 V.*

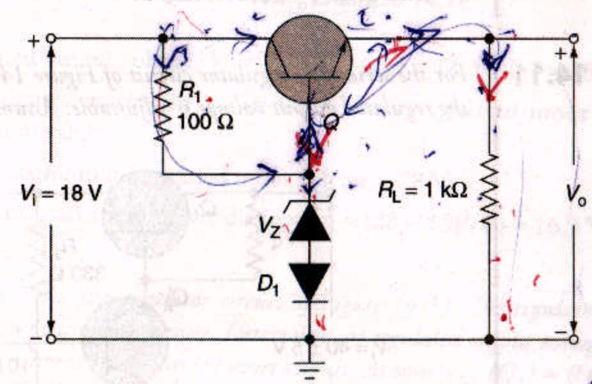


Figure 14.29 | Example 14.9.

Solution

1. Regulated output voltage, $V_o = V_Z + V_{D1} - V_{BE}\,(Q) = 12 + 0.7 - 0.7 = 12$ V.
2. Therefore, $V_{CE}\,(Q) = 18 - 12 = 6$ V.
3. Current through resistor $R_1 = (18 - 12.7)/100 = 0.053$ A = 53 mA. Part of this current flows towards the base terminal of Q and the rest flows through the series combination of the Zener diode and diode D_1.
4. Now, load current = 12/1000 = 0.012 A and β of transistor $Q = 50$.
5. Base current of transistor $Q = 0.012/(1 + \beta) = 0.012/51 = 0.24$ mA.
6. Therefore, current through Zener diode = $53 \times 10^{-3} - 0.24 \times 10^{-3} = 52.76$ mA.

$V_{CE} = 6V$

EXAMPLE 14.10 *Refer to the opamp-based series-pass regulator circuit of Figure 14.30. Determine the regulated output voltage.*

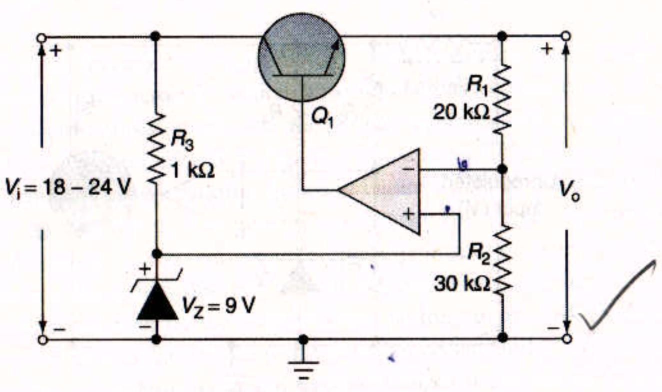


Figure 14.30 | Example 14.10.

Solution

1. The regulated output voltage is the one for which voltage at the inverting input of opamp equals the Zener voltage.
2. That is, $V_o \times 30 \times 10^3/(30 \times 10^3 + 20 \times 10^3) = 9$ or $0.6 \times V_o = 9$.
3. This gives $V_o = 9/0.6 = 15$ V.

EXAMPLE 14.11 *For the series-pass regulator circuit of Figure 14.31, determine the range over which the regulated output voltage is adjustable. Assume V_{BE} $(Q_2) = 0.7$ V.*

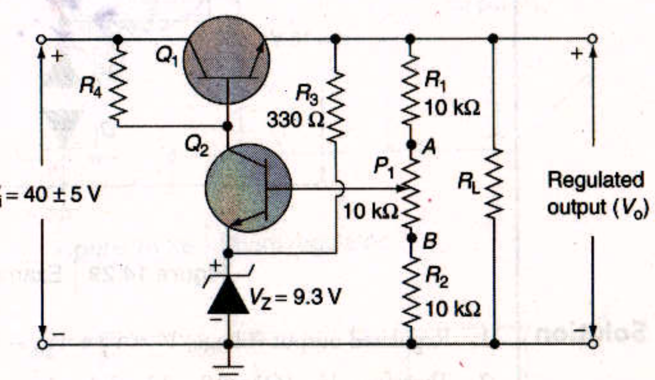


Figure 14.31 | Example 14.11.

Solution

1. Regulated output voltage when the potentiometer P_1 is at position A is given by

$$(9.3 + 0.7) \times [(10 \times 10^3 + 20 \times 10^3)/(20 \times 10^3)] = 15 \text{ V}$$

2. Regulated output voltage when the potentiometer P_1 is at position B is given by

$$(9.3 + 0.7) \times [(10 \times 10^3 + 20 \times 10^3)/(10 \times 10^3)] = 30 \text{ V}$$

3. Therefore, regulated output voltage is adjustable from 15 V to 30 V.

EXAMPLE 14.12 *For the basic shunt regulator circuit of Figure 14.32, determine (a) regulated output voltage and (b) maximum power dissipation in resistor R_S. Assume V_{BE} $(Q_1) = 0.7$ V.*

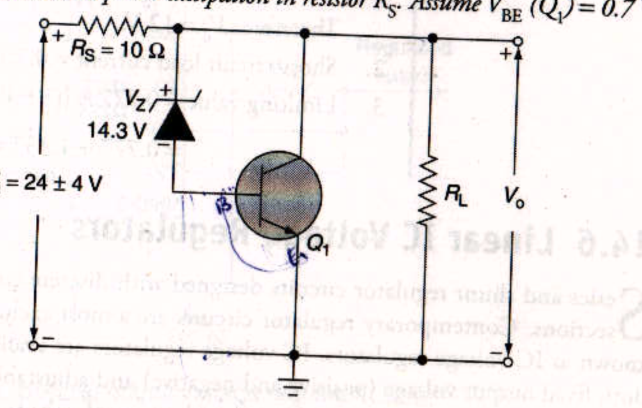


Figure 14.32 | Example 14.12.

Solution

1. Regulated output voltage, $V_o = V_Z + V_{BE}$ $(Q_1) = 14.3 + 0.7 = 15$ V.
2. R_S dissipates maximum power when the unregulated input voltage has maximum value.
3. Now, maximum unregulated input voltage = 28 V.
4. Therefore, maximum power dissipation = $(28 - 15)^2/10 = 16.9$ W.

EXAMPLE 14.13 *Refer to the series-pass regulator circuit of Figure 14.33. The regulator circuit has foldback current-limiting feature. Determine (a) regulated output voltage, (b) limiting value of current in the case of short circuit. Assume V_{BE} $(Q_2) = 0.6$ V and V_{BE} $(Q_1) = V_{BE}$ $(Q_3) = 0.7$ V.*

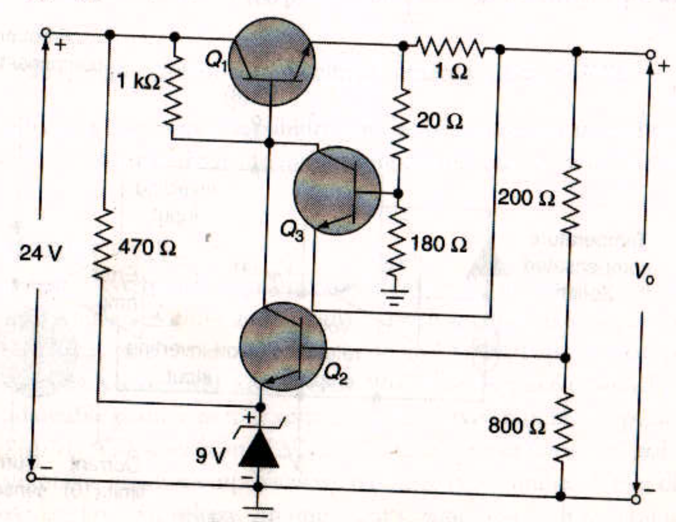


Figure 14.33 | Example 14.13.

Solution

1. Regulated output voltage V_o is given by

$$V_o \times 800/1000 = 9.6$$

Therefore, $V_o = 12$ V.

2. Short-circuit load current = 0.7/0.9 × 1 = 0.777 A.
3. Limiting value = 0.777 + [(1 − 0.9) × 12]/(0.9 × 1) = 0.777 + 1.2/0.9

$$= 0.777 + 1.333 = 2.11 \text{ A}$$

14.6 Linear IC Voltage Regulators

Series and shunt regulator circuits designed with discrete components were discussed in the preceding sections. Contemporary regulator circuits are almost exclusively configured around one or more ICs known as IC voltage regulators. IC voltage regulators are available to meet a wide range of requirements. Both fixed output voltage (positive and negative) and adjustable output voltage (positive and negative) IC regulators are commercially available in a wide range of voltage, current and regulation specifications. These have built-in protection features such as current limit, thermal shutdown and so on.

General-Purpose Precision Linear Voltage Regulator

IC 723 is one such general-purpose adjustable output voltage regulator that can be used in positive or negative output power supplies as series, shunt and switching regulator. The internal schematic arrangement of IC 723 resembles the typical circuit for a series-pass linear regulator and comprises a temperature compensated reference, an error amplifier, a series-pass transistor and a current limiter with access to remote shutdown (Figure 14.34).

Figures 14.35 and 14.36 show the basic circuits for building low positive output voltage (2 – 7 V) and high positive output voltage (7 – 37 V) regulator circuits. In the case of the circuit arrangement of Figure 14.35, the regulated output voltage is given by $V_{ref} \times [R_2/(R_1 + R_2)]$. In the case of the circuit arrangement of Figure 14.36, the output voltage is given by $V_{ref} \times [(R_1 + R_2)/R_2]$. In both cases, recommended value of R_3 is $(R_1 \times R_2)/(R_1 + R_2)$] and $R_{SC} = 0.6/I_{SC}$, where I_{SC} is short-circuit limiting current value.

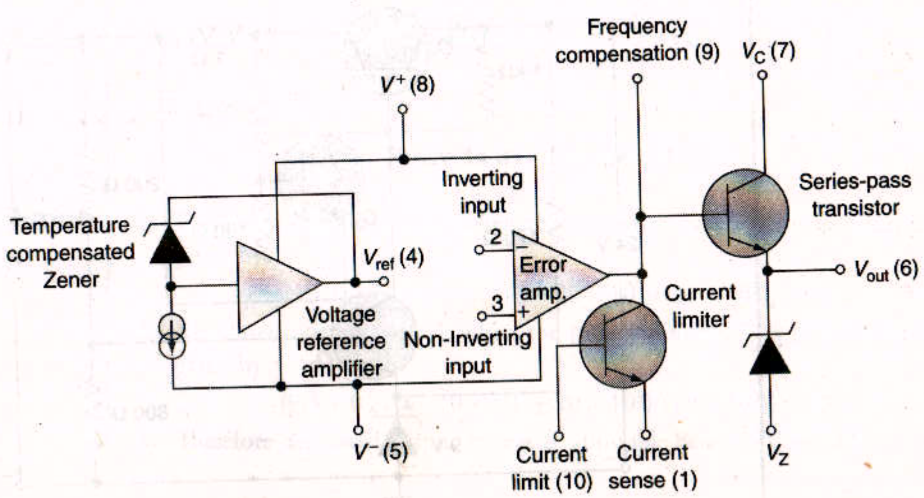


Figure 14.34 | Internal schematic arrangement of IC 723.

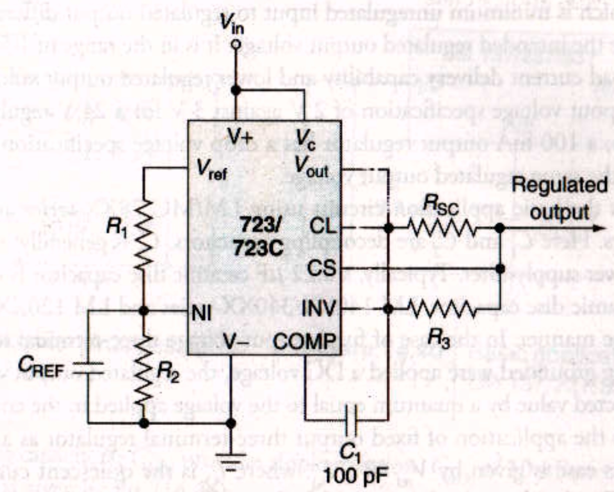


Figure 14.35 | Low positive output voltage regulator using IC 723.

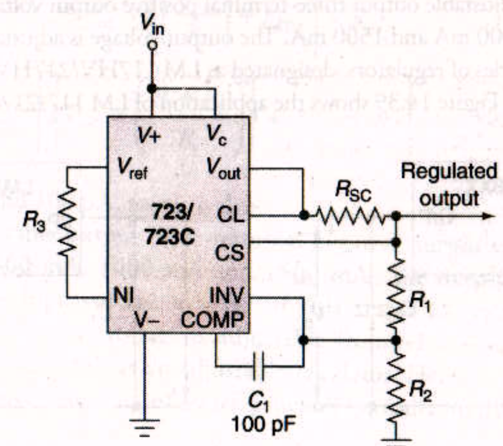


Figure 14.36 | High positive output voltage regulator using IC 723.

Regulator circuits with enhanced load current capability can also be configured around regulator IC 723 with the help of external bipolar transistors. These and many more circuits can be found in application notes of IC 723.

Three-Terminal Regulators

In their basic operational mode, three-terminal regulators require virtually no external components. These are available in both fixed output voltage (positive and negative) as well as adjustable output voltage (positive and negative) types in current ratings of 100 mA, 500 mA, 1.5 A and 3.0 A. Popular fixed positive output voltage types include LM/MC 78XX-series and LM 140XX/340XX-series three-terminal regulators. LM 117/217/317 is a common adjustable positive output voltage regulator type number. Popular fixed negative output voltage types include LM/MC 79XX-series and LM 120XX/320XX-series three-terminal regulators. LM 137/237/337 is a common adjustable negative output voltage regulator type number. A two-digit number in place of "XX" indicates the regulated output voltage. An important specification of three-terminal regulators is the dropout voltage, which is minimum unregulated input to regulated output differential voltage required for the regulator to produce the intended regulated output voltage. It is in the range of 1.5 V to 3 V and is lower for regulators with lower load current delivery capability and lower regulated output voltage value. For example, a 5 V regulator has a dropout voltage specification of 2 V against 3 V for a 24 V regulator for the same current delivery capability. Also, a 100 mA output regulator has a drop voltage specification of 1.7 V against 3 V for 1500 mA regulator for the same regulated output voltage.

Figure 14.37 shows the basic application circuits using LM/MC 78XX-series and LM/MC 79XX-series three-terminal regulators. Here C_1 and C_2 are decoupling capacitors. C_1 is generally used when the regulator is located far from the power supply filter. Typically, a 0.22 μF ceramic disc capacitor is used for C_1. Capacitor C_2 is typically a 0.1 μF ceramic disc capacitor. LM 140XX/340XX-series and LM 120XX/320XX-series regulators are also used in the same manner. In the case of fixed output voltage three-terminal regulators, if the common terminal instead of being grounded were applied a DC voltage, the regulated output voltage in that case would be greater than the expected value by a quantum equal to the voltage applied to the common terminal.

Figure 14.38 shows the application of fixed output three-terminal regulator as a constant current source. The load current in this case is given by $V_{ref}/R + I_Q$, where I_Q is the quiescent current, typically 8 mA for 78XX-series regulators. For details on the features and facilities of three-terminal regulators and their application circuits, one can refer to data sheets and application notes provided by manufacturers of these devices.

LM 117/217/317 is an adjustable output three-terminal positive output voltage regulator and is available in current ratings of 500 mA, 1000 mA and 1500 mA. The output voltage is adjustable from 1.2 V to 37 V. In the high-voltage version of this series of regulators, designated as LM 117HV/217HV/317HV, the output voltage is adjustable from 1.2 V to 57 V. Figure 14.39 shows the application of LM 117/217/317 as an adjustable regulator.

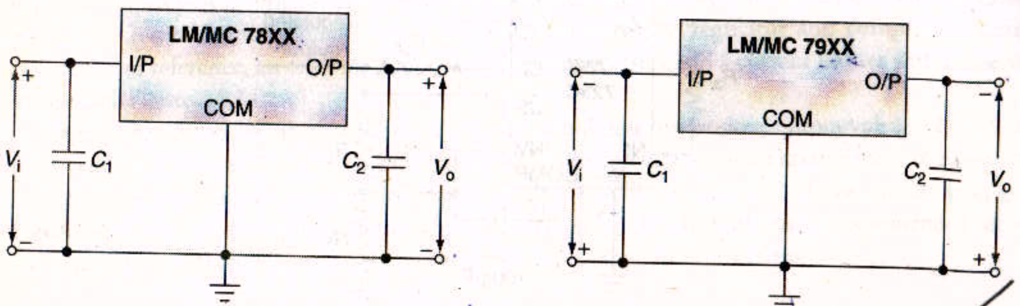


Figure 14.37 | Basic application circuits using three-terminal regulators.

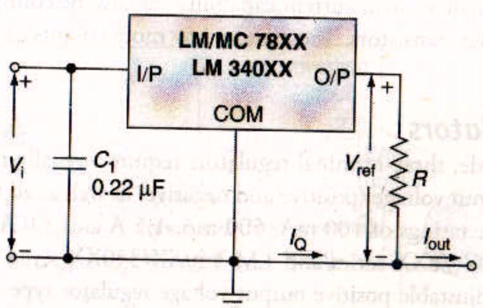


Figure 14.38 | Three-terminal regulator as a constant current source.

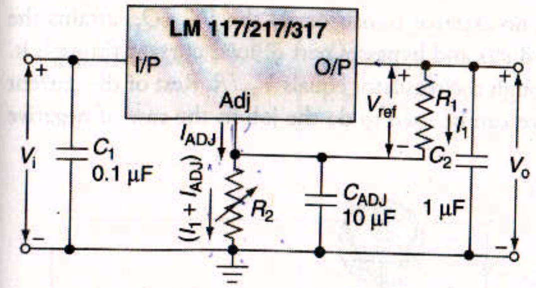


Figure 14.39 | Basic application circuit using LM 117/217/317.

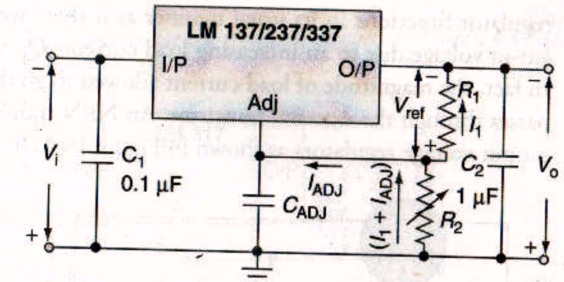


Figure 14.40 | Basic application circuit using LM 137/237/337.

Here C_1 and C_2 are decoupling capacitors; C_{ADJ} provides ripple rejection. C_{ADJ} of 10 μF provides typically 80 dB rejection. The output voltage is given by Eq. (14.36):

$$V_o = V_{ref} + \left[\left(\frac{V_{ref}}{R_1}\right) + I_{ADJ}\right] \times R_2 \tag{14.36}$$

$$V_o = \left[\left\{V_{ref} \times \left(\frac{R_1 + R_2}{R_1}\right)\right\} + I_{ADJ} \times R_2\right] \tag{14.37}$$

V_{ref} and I_{ADJ} are typically 1.25 V and 100 µA, respectively.

LM 137/237/337 is an adjustable output three-terminal negative output voltage regulator and is available in current ratings of 500 mA, 1000 mA and 1500 mA. The output voltage is adjustable from −1.2 V to −37 V. In the high-voltage version of this series of regulators, designated as LM 117HV/217HV/317HV, the output voltage is adjustable from −1.2 V to −47 V. Figure 14.40 shows the application of LM 137/237/337 as an adjustable regulator. Here C_1 and C_2 are decoupling capacitors; C_{ADJ} provides ripple rejection. C_{ADJ} of 10 µF provides typically 80 dB rejection. The output voltage is given by

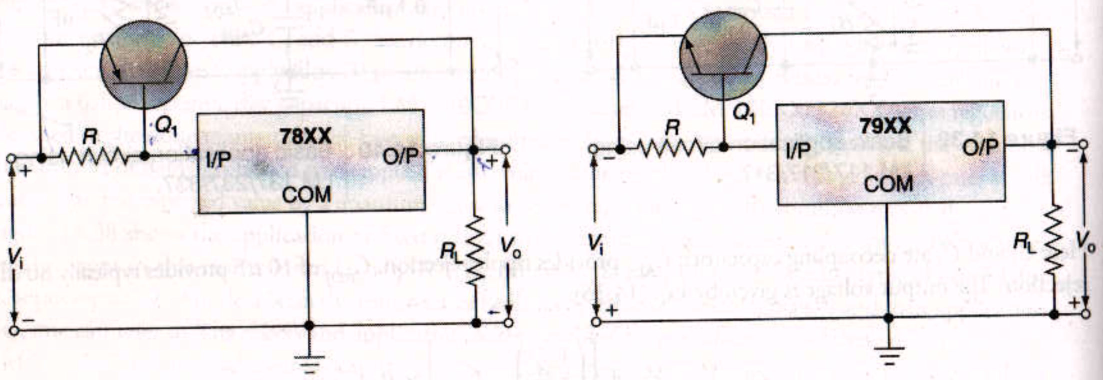
$$V_o = -\left[\left\{V_{ref} \times \left(\frac{R_1 + R_2}{R_1}\right)\right\} + I_{ADJ} \times R_2\right] \tag{14.38}$$

Here V_{ref} and I_{ADJ} are typically −1.25 V and 100 µA, respectively.

Boosting Current Delivery Capability

The load current delivery capability of three-terminal regulators can be increased to more than what they can deliver for a given unregulated input to regulated output voltage differential by using an external transistor. It may be mentioned here that the power dissipated in the regulator is the product of load current and input–output differential voltage. As the power dissipation increases beyond the rated value, the regulator usually goes to thermal shutdown mode. In this mode, the internal series-pass transistor becomes non-conducting, thus allowing the device to cool down.

Figure 14.41(a) shows the typical circuit where an external transistor is used to boost the load current delivery capability of the regulator. In this case, as long as V_{BE} (Q_1) remains below its cut-in voltage, the regulator functions in its usual manner as if there were no external transistor. As the V_{BE} (Q_1) attains the cut-in voltage due to an increasing load current, Q_1 conducts and bypasses part of load current through it. In fact, the magnitude of load current allowed to go through the regulator equals V_{BE}/R. Rest of the current passes through the external transistor. An NPN transistor can be used to do the job in the case of negative output voltage regulators as shown in Figure 14.41(b).



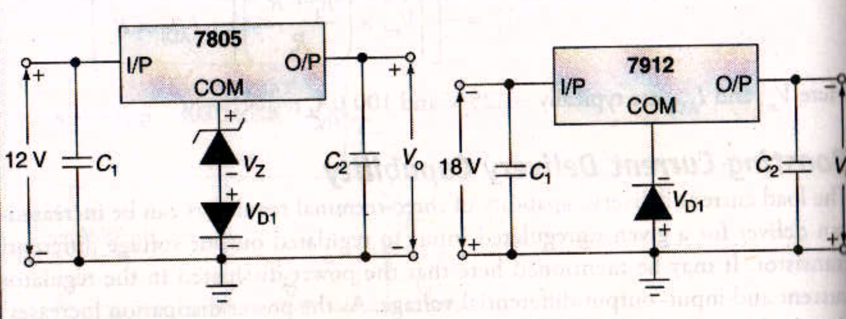
(a) (b)

Figure 14.41 | Use of external transistor to boost current delivery capability.

EXAMPLE 14.14 *Refer to the three-terminal regulator circuits of Figures 14.42(a) and (b). Determine the regulated output voltages in the two cases given that $V_Z = 3.3$ V and $V_{D1} = 0.7$ V.*

Solution

1. For the circuit of Figure 14.42(a)
$$V_o = 5 + V_Z + V_{D1} = 5 + 3.3 + 0.7 = 9 \text{ V}$$
2. For the circuit of Figure 14.42(b)
$$V_o = -12 - V_{D1} = -(12 + 0.7) = -12.7 \text{ V}$$



(a) (b)

Figure 14.42 | Example 14.14.

EXAMPLE 14.15 *Determine the regulated output voltage for the regulator circuit of Figure 14.43 given $V_{ref} = 1.25$ V.*

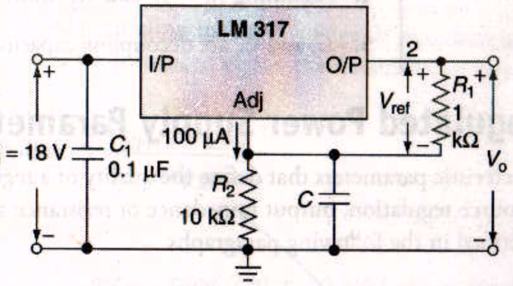


Figure 14.43 | Example 14.15.

Solution

1. The regulated output voltage is sum of voltages across resistors R_1 and R_2. It is given by
$$V_o = V_{ref} + \left[\left(\frac{V_{ref}}{R_1}\right) + I_{ADJ}\right] \times R_2$$
2. Substituting the values, we get
$$V_o = 1.25 + [(1.25/10^3) + 10^{-4}] \times 10 \times 10^3 = 14.75 \text{ V}$$

EXAMPLE 14.16 *Using IC voltage regulator-type number LM 7812, design a circuit that generates a variable output voltage adjustable from +15 V to +20 V from an unregulated input of +24 V. Assume quiescent current to be negligible.*

Solution

1. Figure 14.44 shows the basic circuit configuration. The output voltage V_o in this case is given by
$$V_o = 12 + [V_o \times R_2/(R_1 + R_2)]$$
$$V_o \times [1 - R_2/(R_1 + R_2)] = 12$$
$$V_o = 12 \times [1 + R_2/R_1]$$
2. V_o (min) = 15 = 12 × [1 + R_2/R_1], which gives R_2 (min) = $R_1/4$.

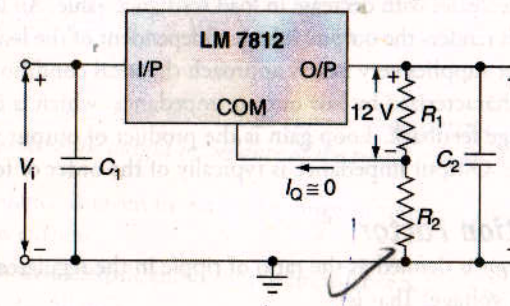


Figure 14.44 | Example 14.16.

3. V_o (max) = 20 = 12 × [1 + R_2/R_1], which gives R_2 (max) = $2R_1/3$.
4. Assuming R_1 = 47 kΩ, R_2 (min) = 11.75 kΩ and R_2 (max) = 31.3 kΩ.
5. C_1 and C_2 are decoupling capacitors and can be 0.1 μF ceramic disks each.

14.7 Regulated Power Supply Parameters

The characteristic parameters that define the quality of a regulated power supply include load regulation, line or source regulation, output impedance or resistance and ripple rejection factor. Each one of these is briefly described in the following paragraphs.

Load Regulation

Load regulation is defined as change in regulated output voltage of the power supply as the load current varies from zero (no-load condition) to maximum rated value (full-load condition). It is usually expressed as a percentage of full-load voltage. That is

$$\text{Percentage load regulation} = \left[\frac{V_{NL} - V_{FL}}{V_{FL}}\right] \times 100 \tag{14.39}$$

Since $V_{FL} \cong V_{NL}$, load regulation may be expressed as a percentage of no-load voltage.

Line Regulation

Line regulation is defined in terms of variation of regulated output voltage for a specified change in line voltage. It is usually expressed as percentage of nominal regulated output voltage. As an example, if the nominal regulated output voltage of 10 V varies by ±1% for a specified variation in line voltage, line regulation in that case would be (0.2/10) × 100 = 2%.

Output Impedance

Output impedance is an important parameter of a regulated power supply. It determines the load regulation of the power supply. The regulated power supply may be represented by a Thevenin's equivalent circuit comprising a voltage source equal to the open circuit voltage across power supply output terminals in series with impedance equal to the output impedance of the power supply. The voltage appearing across the load resistance is equal to the open circuit voltage minus drop across output impedance of the power supply. The voltage drop increases with increase in load current resulting in reduction of voltage across the load. Another way of explaining the same is that the output impedance of the power supply and the load resistance form a potential divider. The load voltage decreases with decrease in load resistance value. An ideal power supply has an output impedance of zero, which renders the output voltage independent of the load resistance value.

Practical power supplies very nearly approach the ideal condition because of emitter–follower nature of regulator circuit characterized by low output impedance, which is further reduced by a factor of (1 + loop gain) due to voltage feedback. Loop gain is the product of output voltage feedback factor and the gain of the error amplifier. Output impedance is typically of the order of few milli-ohms.

Ripple Rejection Factor

Ripple rejection factor is defined as the ratio of ripple in the regulated output voltage to the ripple present in unregulated input voltage. That is

$$\text{Ripple rejection factor} = \frac{V_{RIPPLE}\,(\text{output})}{V_{RIPPLE}\,(\text{input})} \tag{14.40}$$

When expressed in decibels, ripple rejection equals

$$20\log\left[\frac{V_{RIPPLE}\,(\text{output})}{V_{RIPPLE}\,(\text{input})}\right]\text{dB}$$

Ripple in unregulated input is nothing but a periodic variation in input voltage. It manifests at the output with a reduced value. Again, the factor by which ripple is reduced equals the de-sensitivity factor (1 + loop gain) due to negative feedback. That is

$$V_{RIPPLE}\,(\text{output}) = \frac{V_{RIPPLE}\,(\text{input})}{1 + \text{Loop gain}}$$

EXAMPLE 14.17

A regulated power supply operates from 220 ± 20 VAC. It produces a no-load regulated output voltage of 24 ± 0.5 VDC. Also, the regulated output voltage falls from 24 VDC to 23.8 VDC as the load changes from no-load to full-load condition for the nominal value of input voltage. Determine (a) line regulation and (b) load regulation.

Solution

1. Line regulation = (24.5 – 23.5)/24 = 1/24 = 0.0417 = 4.17%
2. Load regulation = (24 – 23.8)/23.8 = 0.2/23.8 = 0.0084 = 0.84%

EXAMPLE 14.18

A regulated power supply provides a ripple rejection of –80 dB. If the ripple voltage in the unregulated input were 2 V, determine the output ripple.

Solution

1. Ripple rejection in dB is given by

$$20\log\left[\frac{\text{Output ripple}}{\text{Input ripple}}\right] = -80\text{ dB}$$

2. Therefore,

$$\log\left[\frac{\text{Output ripple}}{\text{Input ripple}}\right] = -4$$

$$\frac{\text{Output ripple}}{\text{Input ripple}} = 10^{-4}$$

3. Therefore, output ripple = 2 × 10^{-4} V = 0.2 mV.

EXAMPLE 14.19

Figure 14.45 shows load voltage versus load current characteristics of a regulated power supply. Determine the output impedance of the power supply.

Solution

1. Output impedance is given by ratio of change in output voltage for known change in load current.
2. From the given characteristic curve, output impedance = (24 – 23.5)/(10 – 0) = 0.5/10 = 0.05 Ω = 50 mΩ.

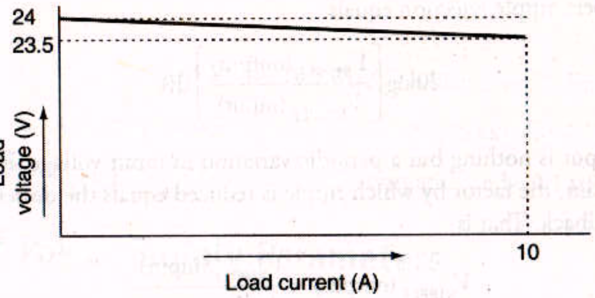


Figure 14.45 | Example 14.19.

EXAMPLE 14.20 *Refer to the three-terminal regulator circuit of Figure 14.46. Determine (a) load current; (b) current through LM 7812; (c) current through external transistor; (d) power dissipated in LM 7812. Take V_{BE} $(Q_1) = 0.7$ V.*

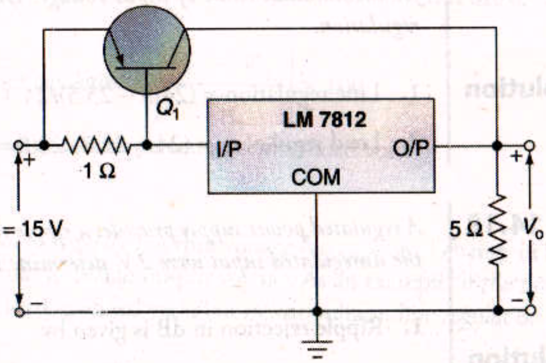


Figure 14.46 | Example 14.20.

Solution

1. Load current = 12/5 = 2.4 A.
2. Current through regulator = 0.7/1 = 0.7 A.
3. Current through external transistor = 2.4 − 0.7 = 1.7 A.
4. Voltage appearing at regulator input = 15 − 0.7 = 14.3 V.
5. Therefore power dissipated in the regulator = (14.3 − 12) × 0.7 = 1.61 W.

KEY TERMS

Emitter–follower regulator
Filter circuit
Line regulation
Load regulation
Output impedance
Peak inverse voltage
Ratio of rectification
Rectifier circuit
Regulator circuit
Ripple factor
Ripple frequency
Ripple rejection factor
Series-pass linear regulator
Shunt regulator
Three-terminal regulator
Transformer
Transformer utilization factor