2

Chapter

Rectifier Circuits

2.1 EXPERIMENTS IN RECTIFIERS

2.1.1 Aim of the Experiment

To construct the following circuits, observe respective waveforms, and make relevant measurements:

a. Half-wave rectifier
b. Full-wave rectifier (using centre-tapped transformer)
c. Full-wave rectifier (bridge type) using semiconductor diodes

2.1.2 Apparatus and Components

1N 4001 diodes, resistors, capacitors, inductors, 230-V/12-V, 1-A transformer, dual-beam oscilloscope (DBO), multimeters, moving-iron meters, etc.

2.1.3 Design Steps for Full-Wave Bridge Rectifier

In this section, we give the design of the full-wave bridge rectifier. The designs of the half-wave and full-wave (CT) rectifiers follow similar steps and are given in the Appendix.

Specifications

- Input voltage available : 230-V AC, 50 Hz
- Output DC voltage $V_{O(DC)}$ required : 12 V
- DC load current I_L required : 50 mA

Step 1: Design of the Power Transformer

The DC output voltage of a full-wave rectifier (FWR) is given by the expression

$$V_{O(DC)} = 2V_{max}/\pi$$

where V_{max} is the maximum value of the required secondary voltage. Given $V_{O(DC)} = 12$ V

$$V_{max} = 12\pi/2 = 18.85 \text{ V}$$

Thus, we find that the secondary transformer must supply an AC peak value of 18.85 V. The required turns ratio of the power transformer, therefore, is

$$n = (N_2/N_1) = (V_2/V_1) = 18.85/230\sqrt{2} = 0.058$$

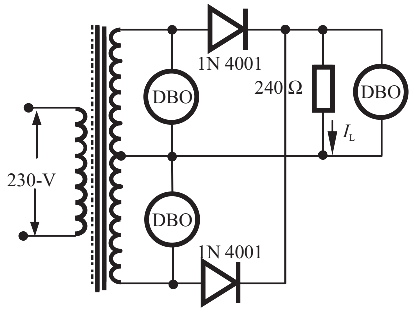


Fig. 2.2 *CT FWR*

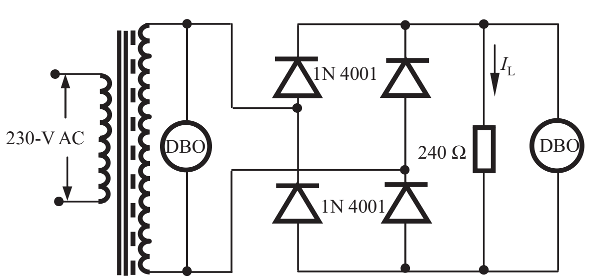
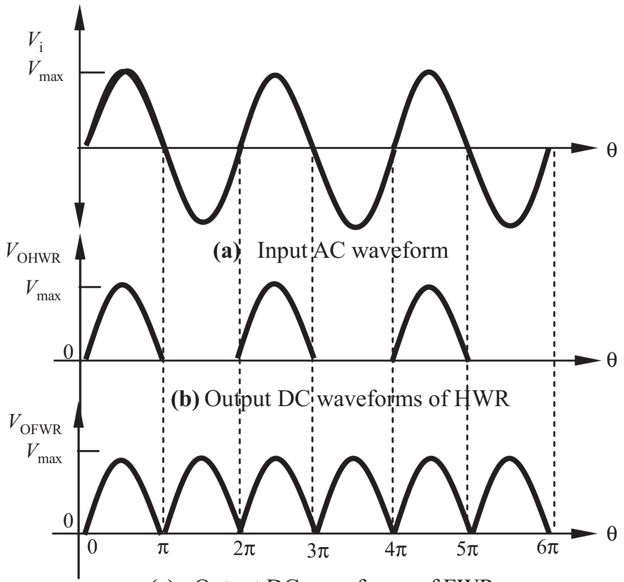


Fig. 2.3 *Bridge FWR*



(a) Input AC waveform

(b) Output DC waveforms of HWR

(c) Output DC waveforms of FWR

Fig. 2.4 *Waveforms associated with HWR and FWR*

After the waveforms are observed, we measure their peak amplitudes on the DBO. It can be seen that the input and output amplitudes are more or less the same because the voltage drops across the DC resistance of the transformer and the dynamic forward resistance of the diode are usually negligible in comparison with the load resistance R_L.

From Fig. 2.4 (b), we compute the DC and RMS values of the output voltage of the HWR, respectively, using the expressions:

$$V_{O(DC)\text{-}HWR} = V_{max}/\pi$$

$$V_{O(rms)\text{-}HWR} = V_{max}/2$$

Similarly, these values for the FWR are, respectively,

$$V_{\text{O(DC)-FWR}} = 2V_{\text{max}}/\pi$$
$$V_{\text{O(rms)-FWR}} = V_{\text{max}}/\sqrt{2}$$

However, we can also measure the DC voltages accurately using a moving-coil DC voltmeter.

Similarly, the RMS values can be measured accurately by using a moving-iron (RMS-reading) voltmeter. For these measurements, true RMS-reading digital voltmeters (DVMs) are also currently available in the market, which are more accurate and inexpensive than the corresponding analog meters. It is therefore advisable to use these digital meters. One problem that may arise is that they are very accurate at lower frequencies (say, 50 to 1000 Hz); however, they may not operate at frequencies higher than 1000 Hz. In such cases, it is advisable to choose a DVM or DMM (digital multimeter) that can operate at much higher frequencies (in the range of a few MHz). The DC and RMS values of the circulating current can also be measured using the DMM. Currently, we have dual-beam oscilloscopes with flat LCD screens, which are capable of performing as oscilloscopes as well as DMMs.

2.2 BRIDGE RECTIFIER WITH CAPACITOR-INPUT FILTER

2.2.1 Design Steps

Specifications

- DC output voltage : 12 V
- DC load current : 50 mA
- Ripple content : 0.01

The expression for ripple factor of a capacitor-input filter bridge rectifier is given by

$$r = 1/4\sqrt{3}\, fCR_L$$

where f is the applied frequency, C is the capacitor to be designed, and R_L is the load resistance. Also,

$$R_L = V_{\text{O(DC)}}/I_L = 12\text{ V}/0.05\text{ A} = 240\ \Omega$$

Substituting $R_L = 240\ \Omega$ and $f = 50$ Hz in the expression for the ripple factor, we get

$$C = 1/4\sqrt{3} \times 50 \times 240 \times 0.01 = 1202.8\ \mu\text{F}$$

Choose $C = 1500\ \mu\text{F}/25\text{ V}$ (as the maximum output DC voltage $V_{\text{O(DC)}} = 12$ V, the voltage rating of C may be fixed as $2 \times V_{\text{O(DC)}} \approx 25$ V).

The other design aspects, viz., that of designing the transformer and selecting the diodes, remain the same as in Section 2.1.

2.2.2 Bridge Rectifier with L-Section Filter

Specifications

- DC output voltage : 12 V
- DC output current : 50 mA
- Ripple content : 0.01

Design Steps

The expression for ripple factor of an L-section filter circuit

$$r = 1/8.5\ \omega^2 LC$$

where L = value of the inductor, C = value of the capacitor, and ω = angular frequency of the power supply. The *critical inductance*

$$L_C = R_L/3\omega$$

where R_L = load resistance. Given

$$R_L = V_{O(DC)}/I_L = 12\text{ V}/50\text{ mA} = 240\ \Omega$$

and f = 50 Hz, we obtain by computation

$$L_C = 240/3 \times 2\pi \times 50 = 0.25\text{ H}$$

From this, we find that the actual inductor used must have a value > L_C. Since $L > 0.25$ H, a standard choke of 1 H/1 A is used as the inductor. Now, substituting the values of r and L we get the value of capacitor C = 120 μF / 25 V.

2.2.3 Bridge Rectifier with π-Section Filter

Specifications

- DC output voltage : 12 V
- Diode current : 50 mA
- Ripple content : 0.01

Design Steps

The expression for the ripple factor of a π-section filter is given by

$$r = \sqrt{2}/\omega^3 C^2 L R_L$$

Substituting for r, ω and R_L

$$C^2 L = \sqrt{2}/(0.01)\ (2\pi \times 50)^3 \times 240 = 19 \times 10^{-9}$$

Choosing L = 1 H, and letting $C_1 = C_2 = C$, from the above equation, we get the value C = 138 μF. Therefore, we choose a nearest higher value of C = 200 μF.

2.2.4 Transformer Design

Consider the design of the L-C filter given above. Here, the power transformer T, inductor L, and the diodes are all assumed to have DC resistances. Let

- The DC resistance of the transformer secondary winding = 20 Ω
- The forward dynamic resistance of diodes = 10 Ω
- The DC resistance of the inductor = 20 Ω
- Then, the total resistance R in series with the inductor = 20 + 10 + 20 = 50 Ω

The maximum value of the transformer secondary voltage

$$V_{\max} = \frac{\pi}{2}\,[V_{O(DC)} + I_L R] = \frac{\pi}{2}\,(12 + 0.05 \times 50) = 22.78\text{ V}$$

Therefore, RMS value of the secondary voltage

$$V_{rms} = V_{max}/\sqrt{2} = 16.1 \text{ V}$$

Selecting a small factor-of-safety, we assume that the transformer may supply an RMS secondary voltage of 25 V. Therefore, we choose a 230-V/25-V transformer with a current rating of $2I_L = 1$ A. The same transformer may be used with the π-section filter.

2.2.5 Experimental Procedure for Half-Wave / Full-Wave Rectifier with Filters

The above experiments are repeated with C, L and π filters. In all these cases, we observe the respective waveforms and measure the output DC and RMS voltages as well as currents. We also compute the ripple factor in each case and compare it with the specified value to see whether our designs have met the given set of specifications. The various rectifier experimental set-ups and corresponding output waveforms are shown in Figs. 2.5 to 2.8. All the the diodes used are of the 1N 4001 type.

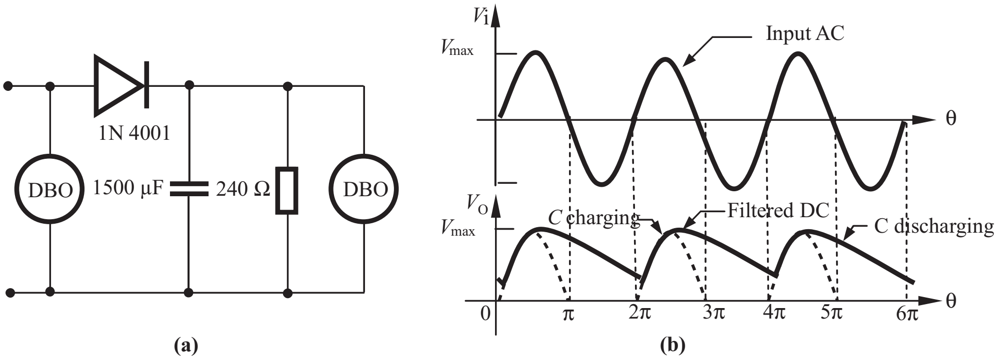


Fig. 2.5 *(a) Set-up of HWR with C-filter; (b) Waveforms of HWR with C filter*

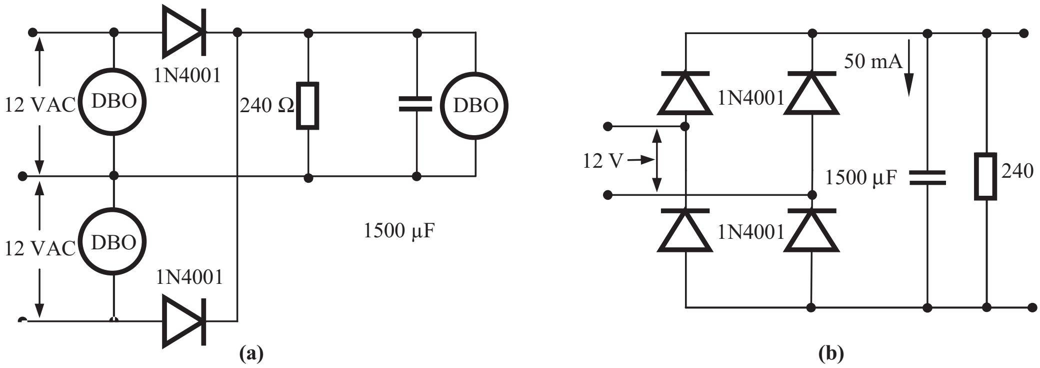
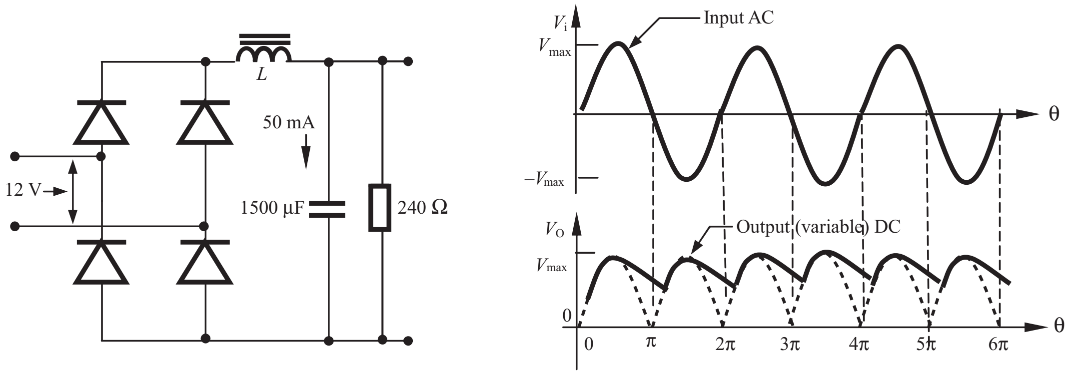


Fig. 2.6 *(a) C-T FWR with C filter; (b) Bridge rectifier with C filter*

2.3 SIMPLE ZENER-VOLTAGE REGULATOR

2.3.1 Aim of the Experiment

To construct a simple Zener-voltage regulator and obtain its various regulations.



(a) (b)

Fig. 2.7 *(a) FWR with L-C filter; (b) Waveforms of FWR with L-C filter*

2.3.2 Apparatus and Components

As per the circuit diagram shown in Fig. 2.8.

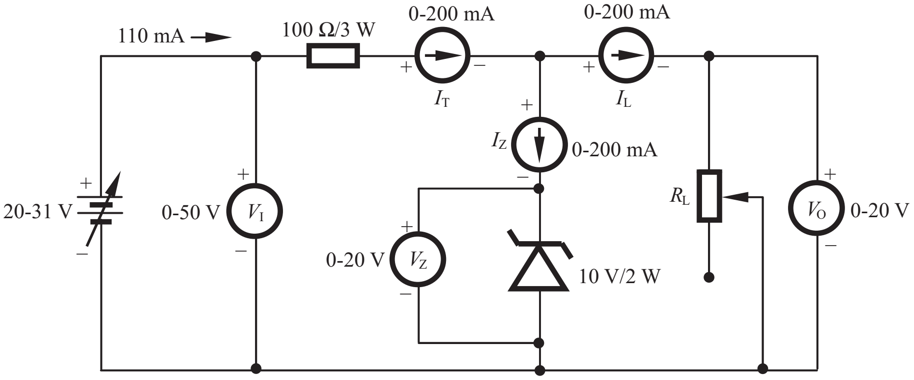


Fig. 2.8 *Simple Zener-voltage regulator*

2.3.3 Design Steps

Specifications

• Input voltage	:	20-V AC (minimum)
• Output voltage	:	10-V DC
• Load current	:	10 mA to 100 mA (variable)

Step 1: Choice of the Zener Diode

Here, since the required output voltage $V_O = 10$ V, we select a Zener diode with a breakdown voltage of 10 V. This diode must have an $I_{Z\,min} = 10$ mA and an $I_{Z\,max} = 100$ mA. Also, the power rating of the Zener-diode is calculated from the expression

$$V_Z I_Z = 10\text{ V} \times 100\text{ mA} = 1\text{ W}$$

Therefore, we choose a 10-V/2-W Zener diode.

$$\text{Line regulation} = \left[\frac{\Delta V_\text{O}}{\Delta V_\text{I}} \times 100\%\right]_{I_\text{L} = \text{constant}}$$

where ΔV_I is the change in the input voltage and ΔV_O is the corresponding change in the output voltage, when the load current is held constant and the input voltage is changed. The line regulation is sometimes called the *input-regulation factor* S_V.

$$\text{Load regulation} = \left[\frac{\Delta V_\text{O}}{\Delta I_\text{O}} \times 100\%\right]_{V_\text{I} = \text{constant}}$$

where ΔI_O and ΔV_O are the respective changes in the output current and voltage for a change in the load resistance, when the input voltage is kept constant. Load regulation is also called *output resistance* r_o. For the ideal case, $r_\text{o} = 0$, as the circuit must deliver power to the load without getting itself loaded.

2.4 EMITTER-FOLLOWER REGULATOR

2.4.1 Aim of the Experiment

To construct an emitter-follower voltage regulator and find its regulation characteristics.

2.4.2 Apparatus and Components

As shown in Fig. 2.9.

2.4.3 Design Steps

Specifications

• Input voltage	:	20 V to 30 V DC (variable)
• Output voltage	:	10-V DC (approximately)
• Load current	:	10 mA to 100 mA (variable)
• Output impedance r_o	:	As low as possible

However, it can also be seen from the figure that

$$V_\text{O} = V_\text{Z} - V_\text{BEQ}$$

where V_Z = Zener voltage, and V_BEQ = base-emitter bias of T. Assuming that desired output voltage $V_\text{O} = 10$ V, we find that the Zener diode must have a voltage of 10 + 0.6 = 10.6 V. However, it is difficult to get a Zener diode of 10.6 V in the free market. So, we assume a Zener diode of 10 V and find that the output in this case is of 9.4 V only. We obtain the load resistance

$$R_\text{L} = V_\text{O}/I_\text{L} = 9.45/50 \text{ mA} = 188\ \Omega$$

Assume a Zener-diode current of 10 mA (to ensure the active-region operation of the Zener diode). If SL 100 (with $\beta_\text{min} = 40$) is chosen, then its base current $I_\text{B} = I_\text{L}/\beta = 50 \text{ mA}/40 = 1.25$ mA. This makes $I_\text{R} = I_\text{B} + I_\text{Z} = 10 + 1.25 = 11.25$ mA. Assuming that the unregulated input is 30 V,

$$R = \frac{(V_\text{I} - V_\text{Z})}{I_\text{R}} = \frac{(30 - 10)}{11.25 \text{ mA}} = 941\ \Omega = 1.77\ \text{k}\Omega$$

2.4.4 Experimental Procedure

Construct the circuit as shown in Fig. 2.9. Then, we first check the base-emitter voltage of the SL 100 transistor. If it is found to be in the range of 0.6 V to 0.7 V, the circuit will function properly. However, if it is different from this range, the circuit need not function properly. In that case, we change the 1.8-kΩ potentiometer and bring the base-emitter voltage of the transistor to about 0.65 V.

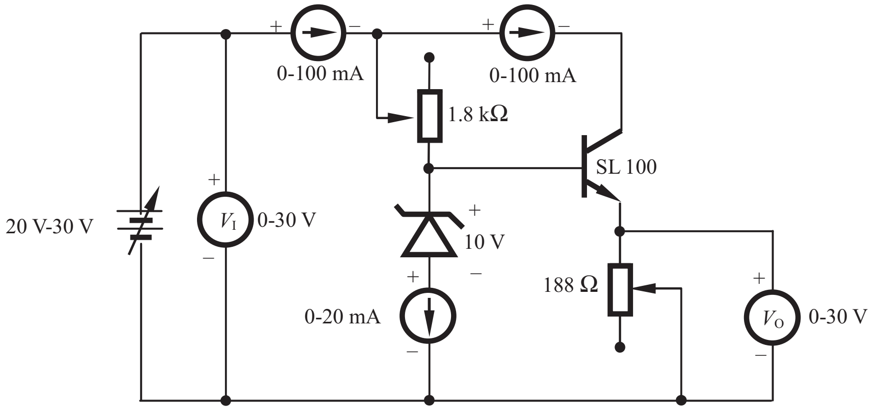


Fig. 2.9 *Emitter-follower regulator*

We expect the output voltage to be approximately 10 – 0.65 = 9.35 V. The current meters should read the expected currents of 50 mA (total current), 10 mA (Zener current) and 40 mA (load current), respectively.

Now, vary the input voltage between 20 V and 30 V in 1-V steps and note down the corresponding output voltages. Tabulation is made as shown in Table 2.2.

Table 2.2 R_L fixed at 188 Ω

Trial	V_I	V_O
1	20 V	9.4 V
2	21 V	.
3	22 V	.
.	.	.
.	.	.

Table 2.3 V_I fixed at 10 V

Trial	V_O	I_L
1	9.4 V	40 mA
2	.	.
3	.	.
.	.	.
.	.	.

The experiment is repeated by setting the input at 10 V and varying the 188-Ω load resistance. The experimental observations are then made as shown in Table 2.3.

The respective regulation factors can now be calculated using the formulae given below:

$$\text{Voltage regulation} = \left[\frac{V_{NL} - V_{FL}}{V_{FL}}\right] \times 100\%$$

where V_{NL} is the no-load output voltage (i.e., output voltage when the load current $I_L = 0$), and V_{FL} is the full-load output voltage (i.e., output voltage when the load current is the maximum).

= 45 + 5 = 50 V. Also, $V_{I\ min}$ = 5 + 5 = 10 V. These then represent the maximum and minimum values of input voltage that permits regulation by the circuit designed.

Step 2: Selection of Load Resistance R_L

We have

$$R_L = V_O / I_L$$

Substituting values

$$R_L = 10/50\ \text{mA} = 200\ \Omega/2\ \text{W}.$$

Step 3: Design of the DC Amplifier

In our problem, we have I_{E2} = 61 mA, and β_{min} of SL 100 = 40. Therefore, we get $I_{C1} = I_{B2}$ = 61/40 = 1.5 mA Since BC 107 is capable of handling this current easily and safely, we use BC 107 as T_1.

Step 4: Design of R'_A, R'_B and R_C

Let us assume that the current I_{R2} through R_1 and R_2 be $I_{R2} = I_L/50$. The large dividing factor of 50 is chosen to avoid excessive drain from the load current. This current also must be able to supply the required base current of T_1. In order to supply this base current, and avoid excessive loading effect on l_{R2}, we choose $I_{R2} >> I_{B1}$, the base current of T_1. Using these, and substituting values, we get

$$I_{R2} = 50\ \text{mA}/50 = 1\ \text{mA}$$

Note that $I_{R2} >> I_{B1}$ in this case, since

$$I_{B1} = I_{C1}/\beta_{min} = 0.015\ \text{mA}\ (1.5\ \text{mA}/100)$$

Thus, the above choice of I_{R2} is justified. If this is not the case, recalculations must be made so that these conditions are met with.

Now, to design the bias resistors, we find that

$$R_1 + R_2 = V_o/I_{R2}$$

where V_O is also the voltage across R_1 and R_2. Substituting values, we obtain

$$R_1 + R_2 = 10\ \text{V}/1\ \text{mA} = 10\ \text{k}\Omega$$

For proper biasing adjustments, we choose a pot such that

$$R_1 + R_2 = R_A + R_B + R_C$$

where R_A and R_C are randomly fixed as 1 kΩ each (some low value), so that

$$R_B = R_1 + R_2 - 2\ \text{k}\Omega$$

Substituting values

$$R_B = 8.2\text{-k}\Omega\ \text{pot}$$

By choosing a potentiometer of value much larger than R_A and R_C, we can adjust the base voltage of T_1 to keep it in the active region. Also

$$V_{R1} = V_Z + V_{BE1Q}$$

where V_Z = Zener voltage, and V_{BE1Q} = active base-emitter voltage of T_1. Usually, we choose the Zener diode such that

$$V_z = V_O/2$$

Step 5: Design of Zener-biasing Resistor R_Z

We have V_Z = 10/2 = 5 V. Therefore, choose a Zener diode having a breakdown voltage of 5.1 V. From Fig. 2.15 we find that

$$V_{RZ} = V_O - V_Z$$

where V_{RZ} is the voltage across the Zener-biasing resistor R_Z. Now, we find that $R_Z = V_{RZ}/I_Z$. Substituting values, we have $R_Z = (10 - 5)$ V/10 mA = 470 Ω (nearest standard value).

Step 6: Design of *R*

Resistor R is to supply the base current of T_2 and the collector current of T_1. This is computed as

$$R = V_R/I = V_R/2I_{C1}$$

where V_R = voltage at point X, and $I = I_{C1} + I_{B2}$ is the current through R. Now,

$$V_R = V_{BE2Q} + V_O$$

where V_{BE2Q} = base-emitter voltage of T_2 = 0.65 V. Substituting values, we get

$$V_R = 10 + 0.65 = 10.65 \text{ V}$$

Now,

$$V_R = V_{I\,min} - (V_O + V_{BE2Q})$$

Substituting values

$$V_R = 15 - (10 + 0.65) = 4.35 \text{ V}$$

Therefore,

$$R = 4.35 \text{ V}/3 \text{ mA} = 1.5 \text{ k}\Omega \text{ (nearest standard value).}$$

For better regulation, we require the current I to be a *constant.* This is because, only if I is constant, I_{B2} will decrease as I_{C1} increases, and vice-versa. To make I constant, we replace R with a *constant-current source.*

2.5.4 Design of the Constant-Current Source

To design a constant-current amplifier, we have the required collector current

$$I_{C3} = 3 \text{ mA } (= I_{C1} + I_{B2})$$

Since I_{C3} = 3 mA, the values of R_5, R_4 and R_E can be computed as

$$R_5 = 12 \text{ k}\Omega/3 = 3.9 \text{ k}\Omega,\ R_4 = 68 \text{ k}\Omega/3 = 22 \text{ k}\Omega,\ R_E = 1 \text{ k}\Omega/1.5 = 330\ \Omega$$

where we have used the values of the SA (i.e., 12 kΩ, 68 kΩ, and 1 kΩ).

2.5.5 Design of Fold-Back Current-Limiting Circuit

Design Steps

Fold-back protection is obtained by connecting a resistor R_S = 1 Ω in series with the load and transistor T_2. The power rating of this resistor is

$$P_{RS} = 2\, I_L^2 R_S = 2 \times 50 \times 50 \times 10^{-6} \times 1 = 5 \text{ mW}$$

Hence, choose a 1-Ω/1-W resistor as R_S. We have, from the fundamental theory of fold-back protection, the equation for load current

$$I_L = I_S + \frac{1 - B}{BR_S}$$

where I_S is the load current under short-circuit condition, and feedback factor $B = R_6/(R_6 + R_7)$. We have I_L = 50 mA, and R_S = 1 Ω. For fold-back circuit, we must have $I_S < I_L$. Assuming I_S = 25 mA, we get the value of

$$B = 0.025 = R_6/(R_6 + R_7)$$

The voltage regulations can now be computed using the expression:

$$\text{Voltage regulation} = \left[\frac{V_{\text{NL}} - V_{\text{FL}}}{V_{\text{FL}}}\right] \times 100\%$$

where V_{NL} is the output voltage when the load current $I_{\text{L}} = 0$ (i.e., output open-circuited), and V_{FL} is the output voltage when the load current is the maximum.

To obtain the **line regulation**, we keep the load current at a constant value and then vary the input voltage and notice the corresponding output voltage. Notice that to keep load current I_{O} at constant value, we need keep the load resistance R_{L} constant at the designed value of 240 ohms. The results are tabulated as shown in Table 2.5. The line regulation, also called the *input-regulation factor* S_{V}, can then be computed using the expression

$$\text{Line regulation} = \left[\frac{\Delta V_{\text{O}}}{\Delta V_{\text{I}}} \times 100\%\right]_{I_{\text{L}} = \text{constant}}$$

where ΔV_{I} is the change in the input voltage and ΔV_{O} is the corresponding change in the output voltage, when the load current is held constant and the input voltage is changed.

Table 2.5 Computation of line regulation

Trial	R_{L}	I_{O}	V_{I}	V_{O}
1	240	.	.	.
2	240	.	.	.
3	240	.	.	.
.	.	.	.	.
				.

Finally, to obtain the **load regulation**, we keep the input voltage V_{I} constant at some specified value, and then vary the load resistance and notice the corresponding value of output voltage. The results are tabulated as shown in Table 2.6. The load regulation can then be computed using the expression

$$\text{Load regulation} = \left[\frac{\Delta V_{\text{O}}}{\Delta I_{\text{O}}} \times 100\%\right]_{V_{\text{I}} = \text{constant}}$$

where ΔI_{O} is the change in the output current for a change in the load resistance, and ΔV_{O} is the corresponding change in the output voltage, when the input is held constant. This is also called *output resistance* r_{o}. For the ideal case, $r_{\text{o}} = 0$, as the circuit must deliver power to load without getting itself loaded.

Table 2.6 Computation of load regulation

Trial	V_{I}	R_{L}	$I_{\text{L}} = I_{\text{O}}$	$V_{\text{L}} = V_{\text{O}}$
1	.	.	.	.
2	.	.	.	.
3	.	.	.	.
.	.	.	.	.
.	.	.	.	.

2.9 Construct an emitter-follower regulator to meet the following specifications:

Input voltage : 20 V - 30 V DC (variable)
Output voltage : 8 V DC (approximately)
Load current : 10 mA to 500 mA (variable)
Output impedance r_o : As low as possible

Obtain the line, load and voltage regulations in this case.

2.10 Construct a series-voltage to meet the following specifications:

Input voltage : 20 V - 30 V DC (variable)
Output voltage : 10 V DC (approximately)
Load current : 10 mA to 500 mA (variable)
Output impedance r_o : As low as possible

Obtain the line, load and voltage regulations in this case.