Feedback in Amplifiers

10.1 INTRODUCTION

The term *feedback* implies transfer of energy from the output of a system to its input. If a portion (or the whole) of the output signal of an amplifier is fed back and superimposed on the input signal, the performance of the amplifier changes significantly. The amplifier is then said to be a *feedback amplifier*.

Feedback can be of two types : negative feedback and positive feedback. When the feedback signal diminishes the magnitude of the input signal, the feedback is called *negative, inverse* or *degenerative feedback*. Negative feedback reduces the overall gain of the amplifier. If the feedback signal enhances the magnitude of the input signal, the feedback is referred to as *positive, direct* or *regenerative feedback*. The overall gain of the amplifier is increased by positive feedback.

Despite the reduction in the overall gain of the amplifier, negative feedback offers many advantages, and is therefore used extensively in electronic circuits. On the contrary, positive feedback causes an instability in the gain of the amplifier and distorts the input signal. Therefore, it is not generally used in amplifiers. It is used in oscillators and sometimes in narrowband amplifiers and radio receivers because it increases the signal power.

10.2 TRANSFER GAIN OF A FEEDBACK AMPLIFIER

Fig. 10.1 shows the block diagram of a feedback amplifier consisting of a basic or an internal amplifier and a feedback network. The transfer gain of the internal amplifier is $A = V_o/V_i$, where V_i is its input voltage and V_o the output voltage. The feedback network can contain passive elements like resistors inductors or capacitors and active elements like transistors. A portion $V_f = \beta V_o$ is extracted from the output voltage V_o and added to, or subtracted from, the externally applied input signal voltage V_s by the feedback network. The input voltage of the basic amplifier is thus $V_i = V_s \pm V_f$. The positive sign holds for positive feedback and the negative sign for negative feedback. The fraction $\beta = V_f/V_o$ is known as the *feedback fraction*, the *feedback ratio*, the *reverse transfer ratio* or the *reverse transmission factor*.

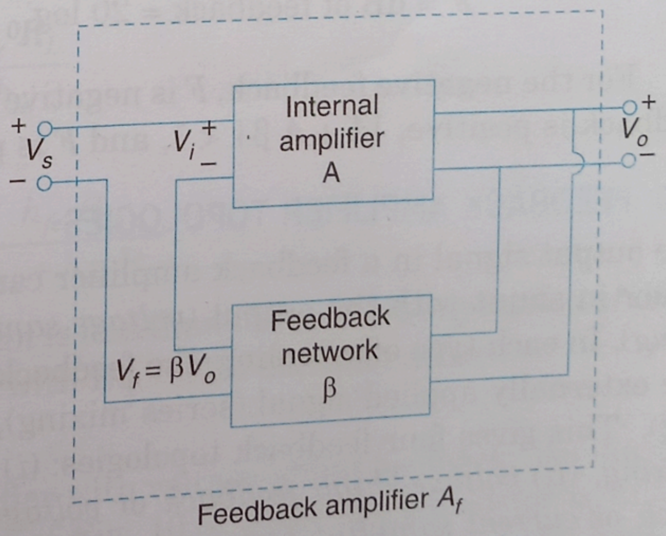

Fig. 10.1 Block diagram of a feedback amplifier.

The whole system in the dashed box in Fig. 10.1 constitutes the feedback amplifier. The *transfer gain* A_f of the feedback amplifier is the ratio of the output voltage V_o to the externally applied input signal voltage V_s, i.e.

$$A_f = \frac{V_o}{V_s} \tag{10.1}$$

If $V_i = V_s - V_f$, we have

$$V_o = AV_i = A(V_s - V_f). \tag{10.2}$$

Since $V_f = \beta V_o$, Eq. (10.2) gives

$$V_o(1 + A\beta) = AV_s \quad \text{or,} \quad A_f = \frac{V_o}{V_s} = \frac{A}{1 + A\beta} \tag{10.3}$$

In the absence of any feedback $\beta = 0$, and $A_f = A$. Thus A represents the transfer gain without feedback. The quantity $-A\beta$ is termed the *loop gain*, because it gives the product of the gains of the branches making up the loop. It is also called the *feedback factor*, the *return ratio* or the *loop transmission*.

The difference between unity and the loop gain, i.e. $(1 + A\beta)$ is referred to as the *return difference*. The gain A_f with feedback is sometimes called the *closed-loop gain*. The quantity A is the gain without feedback, but including the loading effect of the feedback network. A is known as the *open-loop gain*.

In Eq. (10.3), both A and β can be real (positive or negative) quantities or complex functions of frequency.

If $|1 + A\beta| > 1$, we have $|A_f| < |A|$, which characterises negative feedback. If $|1 + A\beta| < 1$, we obtain $|A_f| > |A|$, which gives positive feedback. If $|1 + A\beta| = 0$, $|A_f| = \infty$, implying that the amplifier gives an output signal even in the absence of an input signal; the amplifier then becomes an *oscillator*.

The feedback introduced into an amplifier is usually expressed in decibel (dB) by the relationship

$$F = \text{dB of feedback} = 20 \log_{10}\left|\frac{A_f}{A}\right| = 20 \log_{10}\left|\frac{1}{1 + A\beta}\right|. \tag{10.4}$$

For the negative feedback, F is negative since $|1 + A\beta| > 1$ for such a feedback. When the feedback is positive, $|1 + A\beta| < 1$, and F is positive.

10.3 FEEDBACK AMPLIFIER TOPOLOGIES

The output signal in a feedback amplifier can be sampled by connecting the feedback network either in shunt with the output (*voltage sampling*) or in series with the output (*current sampling*). In each type of sampling, the feedback signal can be returned to the input in series with the externally applied signal (series mixing), or in shunt with the external signal (shunt mixing). This gives four feedback topologies: (*i*) *voltage-series feedback* or *voltage sampling-series mixing*, (*ii*) *voltage-shunt feedback* or *voltage sampling-shunt mixing*, (*iii*) *current-series feedback* or *current sampling-series mixing*, and (*iv*) *current shunt feedback* or *current sampling-shunt mixing*.

(*i*) Voltage-series Feedback

Fig. 10.2 shows schematically the voltage-series feedback configuration. The emitter follower circuit of Fig. 10.3 is an illustration of *voltage-series negative feedback*. In Fig. 10.3, the output voltage V_0 appearing across the load resistance R_E is being returned to the input. Consequently, the feedback ratio β is unity here. In Fig. 10.3 the emitter-base junction is forward biased through the resistance R_B. The capacitance C_{in} decouples the signal source from the supply V_{CC} and behaves as a short circuit for ac. The output voltage is the sampled signal. The sampled signal being a voltage, the feedback is voltage or shunt feedback. The feedback signal voltage is returned to the input in series with the external input signal voltage, so that we have series mixing. So the feedback in the emitter follower circuit is *voltage-series* or *voltage-voltage* or *shunt-series* feedback.

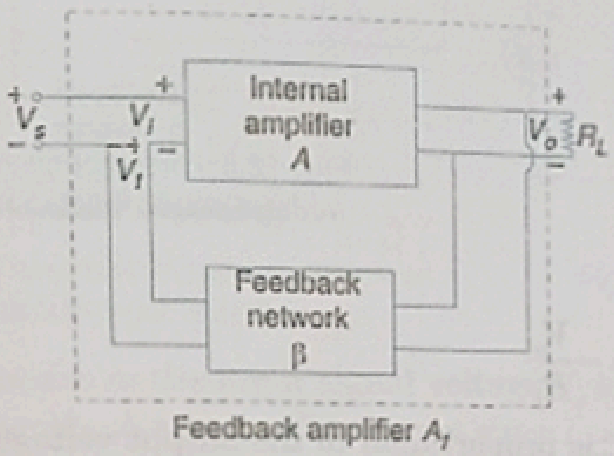

Fig. 10.2 Voltage-series feedback configuration.

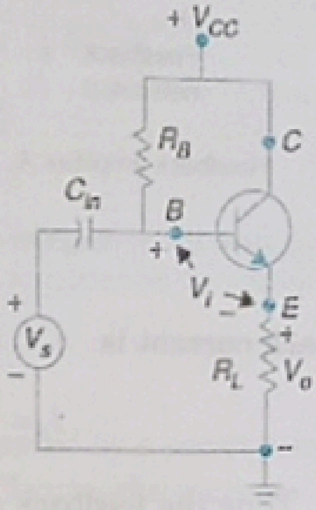

Fig. 10.3 An emitter follower circuit illustrating voltage-series negative feedback

The input signal voltage to the transistor in Fig. 10.3 is $V_i = V_s - V_o$, where V_s is the externally applied input signal voltage. This shows that the feedback is negative. Since for negative feedback $| 1 + A\beta | > 1$, the overall voltage gain is

$$A_f = \frac{A}{1 + A\beta} \tag{10.5}$$

The gain A of the amplifier without feedback can be found by transferring the load resistance R_L from the emitter to the collector leg. Thus

$$A \approx \frac{h_{fe} R_L}{h_{ie}} \tag{10.6}$$

(see Sec 8.9). As $\beta = 1$ here. Eq. (10.5) gives

$$A_f \approx \frac{h_{fe} R_L}{h_{ie} + h_{fe} R_L}. \tag{10.7}$$

Equation (10.7) shows that the voltage gain is less than unity. This expression of the gain, obtained from the concept of feedback, agrees with Eq. (8.79) derived earlier.

(ii) Voltage-shunt Feedback

Fig. 10.4 depicts the block diagram of an amplifier with voltage-shunt feedback. An illustration of this type of feedback is given by the circuit of Fig. 10.5. Here the transistor is in the CE configuration and the resistor R_f provides the feedback from the collector to the base of the transistor. The capacitor C_i isolates the signal source from the supply V_{cc} and acts as a short circuit for ac. The output voltage V_o is much greater than the input voltage V_i and 180° out of phase with it. An increase of the input signal voltage V_s increases the current I_s. Consequently, both I_f and I_i will increase because $I_s = I_i + I_f$. The increase in I_i is less than that of I_s showing that the circuit provides a negative feedback.

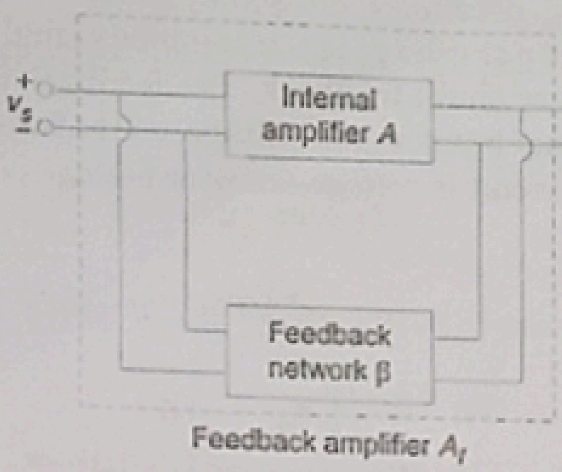

Fig. 10.4 Block diagram of voltage-shunt feedback

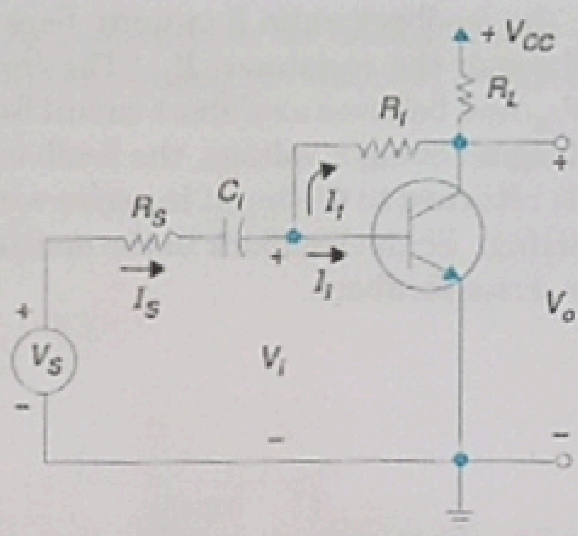

Fig. 10.5 Circuit showing voltage-shunt feedback.

The feedback current is

$$I_f = \frac{V_i - V_o}{R_f} \approx -\frac{V_o}{R_f} \tag{10.8}$$

since $V_o >> V_i$. Thus the feedback current I_f is proportional to the output voltage V_o showing that the feedback is voltage-shunt.

(iii) Current-series Feedback

A current series feedback amplifier is schematically shown in the block diagram of Fig. 10.6.

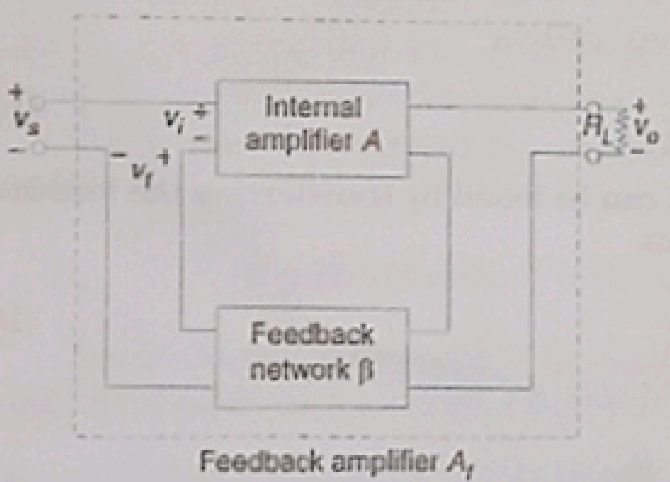

Fig. 10.6 Block diagram of current-series feedback amplifier

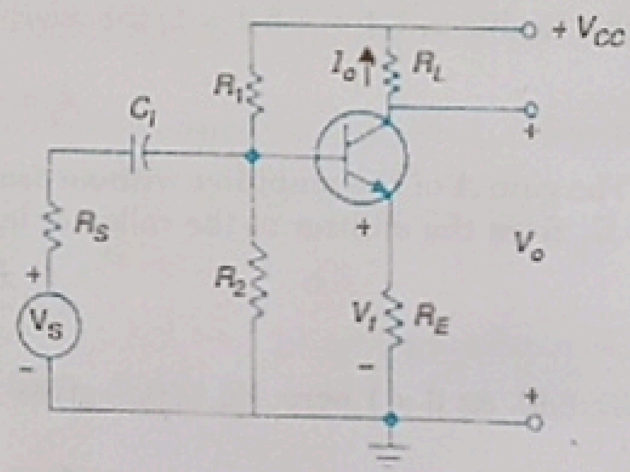

Fig. 10.7 A circuit illustrating current series feedback.

The circuit of such a feedback is shown in Fig. 10.7. Here the feedback voltage is the voltage V_f across the unbypassed emitter resistor R_E. Neglecting the base current, we have $V_f = -R_E I_o$, where I_o is the output collector current. The sampled signal is the current I_o and the feedback signal is the voltage V_f. Hence, the circuit is referred to as the current-series feedback. Following the arguments put forward for an emitter follower, we find that the feedback here is negative.

(iv) Current-shunt Feedback

The block diagram of Fig. 10.8 depicts the current-shunt feedback, an example of which is provided by the circuit of Fig. 10.9. Here two transistors T_1 and T_2 are in cascade. The resistance

R_f connected between the emitter of T_2 and the base of T_1 gives the feedback path. The output voltage V_o' of the first stage is much larger than and 180° out of phase with the input voltage V_i. The voltage V_{e2} across R_{e2} is slightly less than V_o' and is in phase with it. So, V_{e2} is much larger than V_i and 180° out of phase with it.

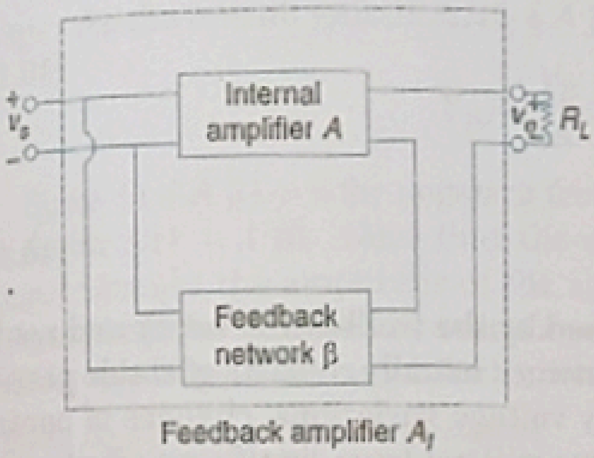

Fig. 10.8 Schematic representation of current-shunt feedback

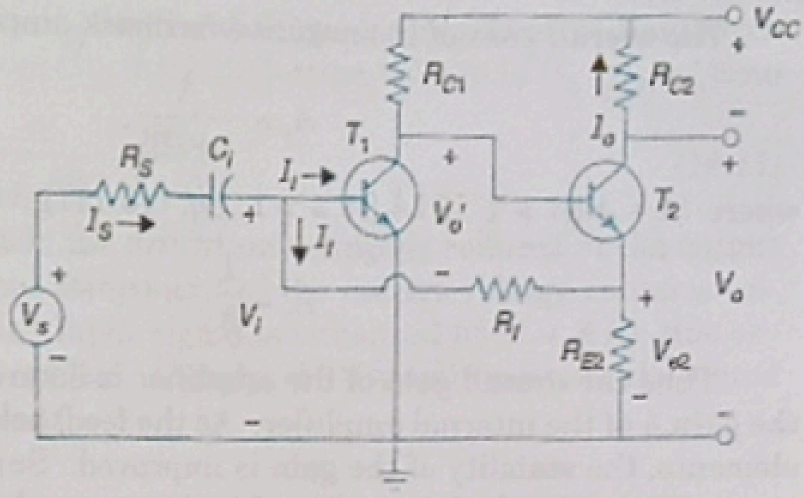

Fig. 10.9 A circuit showing current-shunt feedback

An increase in the input signal voltage V_s is accompanied by a corresponding increase in I_s. Consequently, I_f and I_i will increase since $I_s = I_f + I_i$. Clearly, the increase in I_i is less than that of I_s manifesting negative feedback.

We have for the feedback current

$$I_f = \frac{V_i - V_{e2}}{R_f} \approx -\frac{V_{e2}}{R_f} \tag{10.9}$$

since $V_{e2} >> V_i$. Neglecting the base current of the transistor T_2 compared with its collector current I_o, we have $V_{e2} = (I_f - I_o) R_{E2}$. So, we get from Eq. (10.9)

$$I_f = \frac{(I_o - I_f) R_{E2}}{R_f}$$

Or, $$I_f (R_f + R_{E2}) = I_o R_{E2} \quad \text{or,} \quad I_f = \frac{R_{E2}}{R_f + R_{E2}} I_o \tag{10.10}$$

The feedback current I_f being proportional to the output current I_o, the feedback here is *current-shunt* or *current-current* or *series-shunt*.

10.4 EFFECTS OF NEGATIVE FEEDBACK

Negative feedback introduces the following modifications of the amplifier characteristics:

(*i*) The gain is reduced and stabilized with respect to the variations in transistor parameters like h_{fe}.

(*ii*) The nonlinear distortion is less so that the signal handling capacity of the amplifier increases.

(*iii*) The input impedance can be changed by suitably combining the feedback signal with the externally applied input signal. The output impedance of the amplifier can also be changed by suitably extracting the feedback signal from the output.

(*iv*) The bandwidth of the amplifier increases and the frequency distortion becomes less.

(v) The phase distortion is reduced.

(vi) The noise level is lowered.

These features of negative feedback are discussed below

(i) Stability of Gain

The overall gain of the negative feedback amplifier is

$$A_f = \frac{A}{1 + A\beta}, \tag{10.11}$$

where $|1 + A\beta| > 1$. If $|A\beta| >> 1$, Eq. (10.11) gives

$$A_f \approx \frac{1}{\beta}. \tag{10.12}$$

Thus the overall gain of the amplifier is determined by the feedback network and not by the gain A of the internal amplifier. As the feedback network usually consists of stable passive elements, the stability of the gain is improved. Supply voltage variations, changes of parameters of the active device, aging and temperature changes will not have significant effects on A_f although they can have marked effects on A.

If the loop gain in a negative feedback amplifier is not large, the stability of the gain can be found by differentiating Eq. (10.11) with respect to A. Thus we get

$$\frac{d A_f}{A_f} = \frac{1}{1 + A\beta} \frac{dA}{A}. \tag{10.13}$$

The ratio of the fractional change in the overall gain to the fractional change in the gain of the internal amplifier gives the *sensitivity* S of the transfer gain to changes in the internal amplifier gain. Thus

$$S = \left(\frac{dA_f}{A_f}\right) \Big/ \left(\frac{dA}{A}\right) = \frac{1}{1 + A\beta}. \tag{10.14}$$

The *desensitivity* D is given by

$$D = \frac{1}{S} = 1 + A\beta \tag{10.15}$$

Equations (10.13) and (10.15) give

$$\frac{dA_f}{A_f} = \frac{1}{D}\left(\frac{dA}{A}\right). \tag{10.16}$$

As $|D| > 1$ for negative feedback, the percentage change in A_f is less than that in A. The overall gain stability is thus better.

(ii) Decrease in Nonlinear Distortion

The nonlinearity in the transfer characteristic of the amplifier active device distorts the output signal when a large-amplitude signal is applied to the amplifier input. Let V_{os} and V_D be the signal component of the output voltage and the distortion output voltage, respectively. For simplicity, we assume here that the input signal voltage is sinusoidal and that the distortion voltage is the second harmonic.

If V_s is the applied input signal voltage, we have $V_{os} = AV_s$ in the absence of feedback. The voltage V_D is introduced by the nonlinearity of the active device; it can be assumed to arise from an effective distortion voltage V_D/A applied at the input of a distortionless amplifier of gain A.

In the presence of negative feedback, both V_{os} and V_D will diminish. To keep V_{os} constant at its previous value, the input signal amplitude is increased from V_s to $V_s' = V_s(1 + A\beta)$. As the output voltage remains the same, the input voltage of the internal amplifier is $V_i = V_s$.

When negative feedback is applied, let V_{Df} be the distortion component of the output voltage. As the overall gain is $A/(1 + A\beta)$ and the input distortion voltage is V_D/A, we have

$$V_{Df} = \frac{V_D}{A} \times \frac{A}{1+A\beta} = \frac{V_D}{1+A\beta} \tag{10.17}$$

Since $|1 + A\beta| > 1$ for negative feedback, the distortion voltage is reduced at the output by a factor $1/(1 + A\beta)$. Note that the signal component of the output voltage remains unchanged because the amplitude of the applied input signal is enhanced by $(1 + A\beta)$; this enhancement can be achieved by using a preamplifier. Clearly, the dynamic range or the signal handling capacity of the amplifier is increased.

(iii) Effect on Input and Output Impedances

(a) Input impedance: In the *series-mixing* feedback circuit of Fig. 10.10, the input impedance of the internal amplifier is

$$Z_i = \frac{V_i}{I_i} \tag{10.18}$$

The input impedance of the feedback amplifier is

$$Z_{if} = \frac{V_s}{I_i}. \tag{10.19}$$

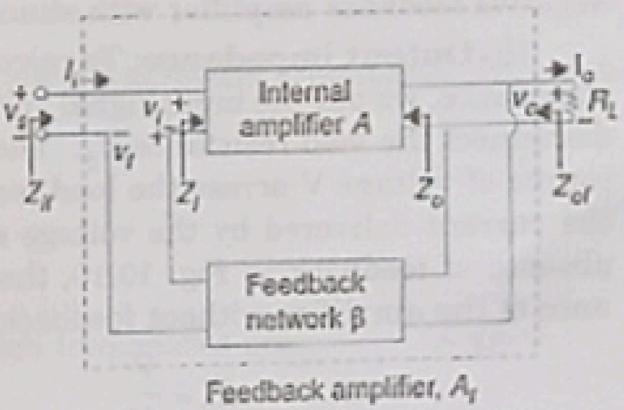

Fig. 10.10 Calculation of impedances for voltage-series feedback.

The externally applied input signal voltage is

$$V_s = V_i + V_f = V_i + \beta V_o = V_i + A\beta V_i \tag{10.20}$$

since $V_o = AV_i$, where A is the voltage gain of the internal amplifier including the load resistance R_L. Equation (10.20) yields

$$V_s = V_i(1 + A\beta) \tag{10.21}$$

So, Eq. (10.19) gives

$$Z_{if} = \frac{V_i(1+A\beta)}{I_i} = Z_i(1 + A\beta) \tag{10.22}$$

using Eq. (10.18). Negative feedback implies $|1 + A\beta| > 1$. Hence, we find from Eq. (10.22) that the input impedance of the amplifier increases for series-mixing negative feedback.

Consider now the *shunt-mixing* feedback of Fig. 10.11. Here, the current gain of the internal amplifier is $A = I_0/I_i$. The input impedance of the internal amplifier is

$$Z_i = \frac{V_s}{I_i} \tag{10.23}$$

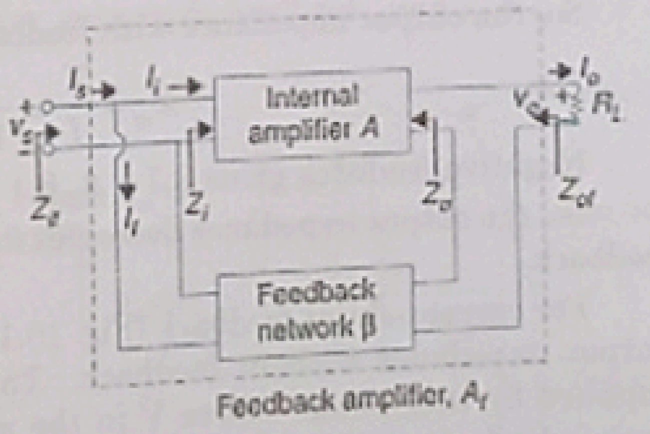

Fig. 10.11 Calculation of impedances for current-shunt feedback.

For the feedback amplifier, the input impedance is

$$Z_{if} = \frac{V_s}{I_s} \tag{10.24}$$

From Kirchhoff's current law, we have

$$I_s = I_i + I_f \tag{10.25}$$

where I_f is the feedback current. If β is the reverse transmission factor,

$$I_f = \beta I_o = A\beta I_i, \tag{10.26}$$

since $I_o = AI_i$, where A is the current gain of the internal amplifier including the load resistance R_L. From Eqs. (10.25) and (10.26), we obtain

$$I_s = I_i(1 + A\beta). \tag{10.27}$$

Equation (10.24) gives

$$Z_{if} = \frac{V_s}{I_i(1+A\beta)} = \frac{Z_i}{1+A\beta}, \tag{10.28}$$

where Eq. (10.23) is used. As $|1 + A\beta| > 1$ for negative feedback, the input impedance of a negative feedback amplifier with shunt mixing is less than that in the absence of feedback.

(*b*) **Output impedance:** To calculate the output impedance, we put the input signal voltage to zero and disconnect the load resistance R_L. Then we connect a source of voltage V across the load terminals. If I' is the current delivered by the voltage source V in the absence of feedback in Fig. 10.10, the output impedance of the amplifier without feedback is

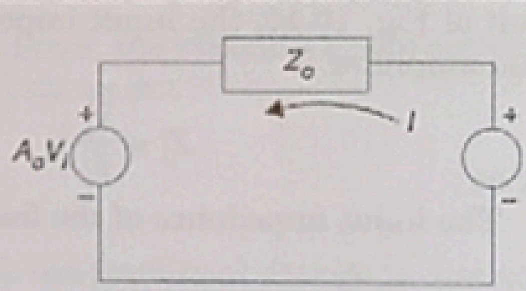

Fig. 10.12 Equivalent output circuit for the calculation of the output impedance for voltage-series feedback.

$$Z_0 = \frac{V}{I'}. \tag{10.29}$$

When feedback is present, the input voltage of the internal amplifier is $V_i = -V_f$, since $V_s = 0$. As $V_f = \beta V$, we have

$$V_i = -\beta V. \tag{10.30}$$

If A_o is the voltage gain of the internal amplifier when the output is an open-circuit, the open-circuit output voltage becomes $A_o V_i = -A_o\beta V$. The equivalent circuit at the output is as shown in Fig. 10.12. The current supplied by the source V is

$$I = \frac{V - A_o V_i}{Z_o} = \frac{V + A_o \beta V}{Z_o}$$

So, the output impedance with feedback is

$$Z_{of} = \frac{V}{I} = \frac{Z_o}{1+A_o\beta} \tag{10.31}$$

Negative feedback gives $|1 + A_o\beta| > 1$.

So, the output impedance decreases for voltage-series feedback.

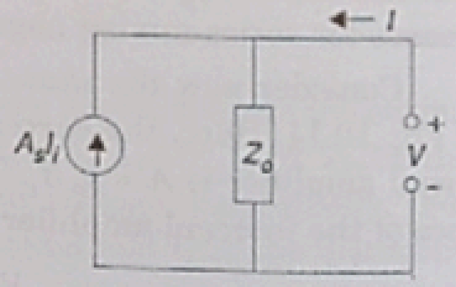

Fig. 10.13 Equivalent output circuit for the calculation of the output impedance for current-shunt feedback.

For current-shunt feedback (Fig. 10.11), let Z_o be the output impedance without feedback. Then the current supplied by the voltage source V in the absence of feedback is V/Z_o. In the presence of feedback, let I be the current delivered by the source V. With $I_s = 0$, $I_i = -I_f = \beta I$, since the feedback current is $I_f = -\beta I$.

If A_s is current gain of the amplifier without feedback when the load terminals are short circuited, the short-circuit output current is $A_s I_i = A_s \beta I$. The equivalent output circuit is then as shown in Fig. 10.13. The current I supplied by the source V is

$$I = \frac{V}{Z_o} - A_s I_i = \frac{V}{Z_o} - A_s \beta I \quad \text{or,} \quad I(1 + A_s \beta) = \frac{V}{Z_o}.$$

So, the output impedance with feedback is

$$Z_{of} = \frac{V}{I} = Z_o (1 + A_s \beta) \tag{10.32}$$

Since $|1 + A_s \beta| > 1$ for negative feedback, the output impedance for current-shunt feedback is greater than that without feedback.

(iv) **Reduction of Frequency Distortion**

In Sec. 9.3, we have found that the low-frequency gain of one stage of an RC-coupled amplifier is

$$A_l = \frac{A_m}{1 - j(f_l / f)}, \tag{10.33}$$

where A_m is the mid-frequency gain and f_l is the lower half-power frequency. The high-frequency gain is

$$A_h = \frac{A_m}{1 + j(f / f_h)}, \tag{10.34}$$

f_h being the upper half-power frequency.

With feedback, the overall gains at low and high frequencies are

$$A_{lf} = \frac{A_l}{1 + A_l \beta} \tag{10.35}$$

and

$$A_{hf} = \frac{A_h}{1 + A_h \beta} \tag{10.36}$$

From Eqs. (10.35) and (10.33), we obtain

$$A_{lf} = \frac{A_m}{1 + A_m \beta - j(f_l / f)} = \frac{A_{mf}}{1 - j(f_{lf} / f)}, \tag{10.37}$$

where $A_{mf} = A_m / (1 + A_m \beta)$ is the mid-frequency gain with feedback, and $f_{lf} = f_l / (1 + A_m \beta)$ is the lower half-power frequency in the presence of feedback. Negative feedback implies $|1 + A_m \beta| > 1$, so that $f_{lf} < f_l$.

In a similar fashion, one can show from Eqs. (10.36) and (10.34)

$$A_{hf} = \frac{A_{mf}}{1 + j(f / f_{hf})} \tag{10.38}$$

where $f_{hf} = f_h (1 + A_m \beta)$ is the upper half-power frequency in the presence of negative feedback. Obviously, $f_{hf} > f_h$.

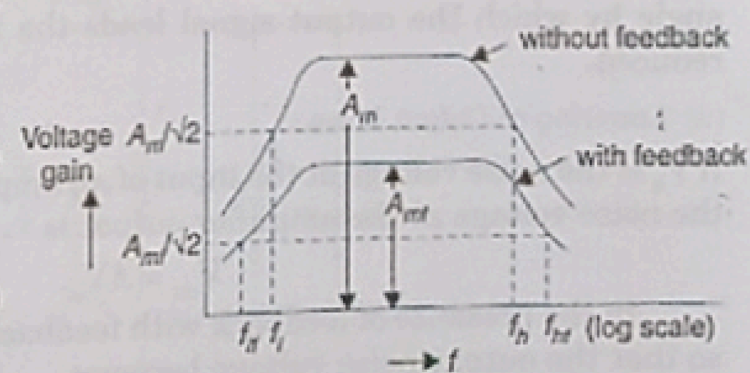

Fig. 10.14 Magnitude of voltage gain versus frequency for one stage of an RC-coupled amplifier with and without feedback.

We thus find that negative feedback decreases the lower half-power frequency and increases the upper half-power frequency. The difference between the two half-power frequencies, *i.e.* the bandwidth of the amplifier is consequently enhanced, and so the frequency distortion is reduced.

The plot of the magnitude of the gain with frequency of an RC-coupled amplifier in the presence and in the absence of feedback is depicted in Fig. 10.14.

(*v*) Decrease of Phase Distortion

When the load or the coupling impedance of an amplifier contains a reactive part, the gain of the amplifier is a complex quantity with a magnitude and a phase angle. So, the gain A of the amplifier without feedback can be written as

$$A = |A| \angle\theta. \tag{10.39}$$

With feedback, the gain is

$$A_f = \frac{A}{1+A\beta}. \tag{10.40}$$

The feedback ratio β can be real or a complex quantity. Taking β to be real for simplicity, we obtain

$$A_f = \frac{|A|\angle\theta}{1+\beta|A|\angle\theta} = \frac{|A|\angle\theta}{1+\beta|A|(\cos\theta + j\sin\theta)}$$

$$= \frac{|A|\angle\theta}{(1+\beta|A|\cos\theta) + j\beta|A|\sin\theta}$$

$$= \frac{|A|\angle\theta}{|B|\angle\phi} \tag{10.41}$$

where $$|B| = \sqrt{(1+\beta|A|\cos\theta)^2 + (\beta|A|\sin\theta)^2} \tag{10.42}$$

and $$\phi = \tan^{-1}\frac{\beta|A|\sin\beta}{1+\beta|A|\cos\theta} \tag{10.43}$$

Writing

$$A_f = |A_f| \angle\theta_f \tag{10.44}$$

we obtain from Eq. (10.41)

$$|A_f| = \frac{|A|}{|B|} \tag{10.45}$$

and $$\theta_f = \theta - \phi. \tag{10.46}$$

Clearly, negative feedback decreases the phase angle of the gain by ϕ. Since the phase angle by which the output signal leads the input signal diminishes, the phase distortion is reduced.

(*vi*) Lowering of Output Noise

If V_n is the noise voltage at the input of an amplifier of voltage gain A in the absence of feedback, the noise voltage at the amplifier output is

$$V_{on} = AV_n. \tag{10.47}$$

In the presence of feedback with feedback fraction β, the gain reduces to $A_f = A/(1+A\beta)$, so that the output noise voltage becomes

$$V_{onf} = \frac{AV_n}{1+A\beta} = \frac{V_{on}}{1+A\beta} \tag{10.48}$$

For negative feedback $|1 + A\beta| > 1$. Therefore, $V_{onf} < V_{on}$. Thus the output noise level is reduced. Note that the signal-to-noise ratio at the amplifier output is not improved since the negative feedback reduces the signal as well as the noise by the same factor.

10.5 REGULATED POWER SUPPLY

A regulated power supply gives a dc output voltage that remains substantially constant even when the ac supply voltage or the dc load current changes. The system contains (*i*) a rectifier with filter, and (*ii*) a voltage regulator, as shown in the block diagram of Fig. 10.15.

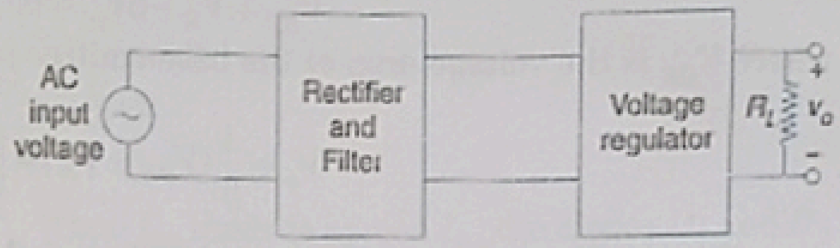

Fig. 10.15 Block diagram of a regulated power supply

The rectifier transforms the input alternating current (or voltage) into a direct current (or voltage). The output of the rectifier contains the fluctuating components of current (or voltage), called the *ripple*. The filter following the rectifier stage smoothens out the ripples. The details of the rectifier and the filter action have been discussed in Secs. 6.3 through 6.6.

The output from the filter can vary with the changes in the ac supply voltage or the load resistance. The voltage regulator tends to eliminate this fluctuation. The principle of a regulator circuit is explained with the help of the diagram of Fig. 10.16, which is known as a *series voltage regulator*. A fraction βV_o of the output voltage V_o of the regulator is compared with a fixed reference voltage V_R appearing across the Zener diode Z. By adjusting the potentiometer P, βV_o is made nearly equal to V_R. The voltage difference $(\beta V_o - V_R)$ is amplified by the amplifier comprising the transistor T_1 and the load resistance R_1. The amplified voltage is applied to the base of the transistor T_2, called the *pass transistor*. If the output voltage V_o exceeds the desired value, βV_0 becomes larger than V_R and drives the base voltage of the transistor T_1 to a more positive value. Consequently, the collector current of T_1 increases, thereby enhancing the voltage drop across R_1. This reduces the forward biasing of the base-emitter junction of T_2. Hence the emitter current I of T_2 decreases. Consequently, the load current and hence the output voltage V_0 decreases. Thus a *negative feedback* occurs: any change in V_o is countered by a change in the current I, causing V_o to remain more or less steady. The capacitor C bypasses the high-frequency components of the output voltage, thus further improving the constancy of the output voltage. The percentage regulation of a regulated power supply, also called the *stabilised power supply*, is much less than that of a simple rectifier. This means that the internal resistance R_o in the equivalent circuit of Fig 6.9 is very small, the system behaving like an ideal voltage source.

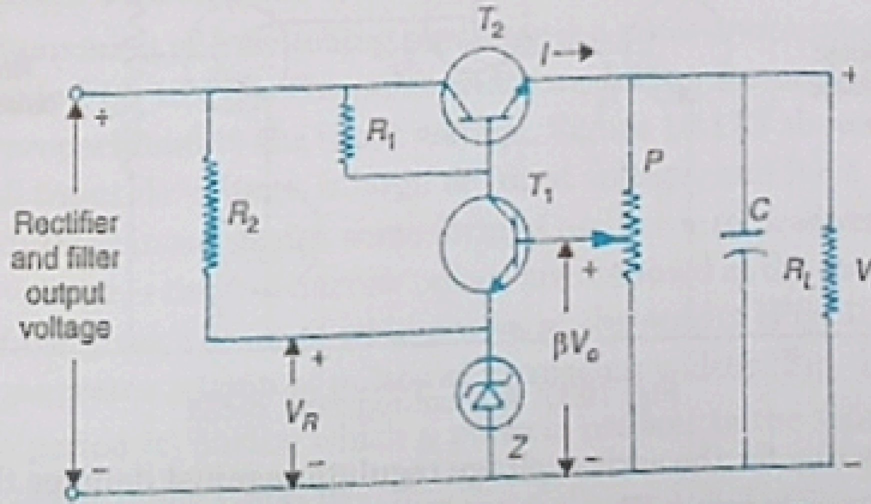

Fig. 10.16 A series voltage regulator using transistors and a Zener diode.