Appendix

A

Hybrid Parameters—Graphical Determinations and Conversion Equations (Exact and Approximate)

A.1 GRAPHICAL DETERMINATION OF THE *h*-PARAMETERS

Using partial derivatives (calculus), it can be shown that the magnitude of the *h*-parameters for the small-signal transistor equivalent circuit in the region of operation for the common-emitter configuration can be found using the following equations:*

$$\boxed{h_{ie} = \frac{\partial v_i}{\partial i_i} = \frac{\partial v_{be}}{\partial i_b} \cong \left.\frac{\Delta v_{be}}{\Delta i_b}\right|_{V_{CE}=\text{constant}}} \quad \text{(ohms)} \tag{A.1}$$

$$\boxed{h_{re} = \frac{\partial v_i}{\partial v_o} = \frac{\partial v_{be}}{\partial v_{ce}} \cong \left.\frac{\Delta v_{be}}{\Delta v_{ce}}\right|_{I_B=\text{constant}}} \quad \text{(unitless)} \tag{A.2}$$

$$\boxed{h_{fe} = \frac{\partial i_o}{\partial i_i} = \frac{\partial i_c}{\partial i_b} \cong \left.\frac{\Delta i_c}{\Delta i_b}\right|_{V_{CE}=\text{constant}}} \quad \text{(unitless)} \tag{A.3}$$

$$\boxed{h_{oe} = \frac{\partial i_o}{\partial v_o} = \frac{\partial i_c}{\partial v_{ce}} \cong \left.\frac{\Delta i_c}{\Delta v_{ce}}\right|_{I_B=\text{constant}}} \quad \text{(siemens)} \tag{A.4}$$

In each case, the symbol Δ refers to a small change in that quantity around the quiescent point of operation. In other words, the *h*-parameters are determined in the region of operation for the applied signal so that the equivalent circuit will be the most accurate available. The constant values of V_{CE} and I_B in each case refer to a condition that must be met when the various parameters are determined from the characteristics of the transistor. For the common-base and common-collector configurations, the proper equation can be obtained by simply substituting the proper values of v_i, v_o, i_i, and i_o.

The parameters h_{ie} and h_{re} are determined from the input or base characteristics, whereas the parameters h_{fe} and h_{oe} are obtained from the output or collector characteristics. Since h_{fe} is usually the parameter of greatest interest, we shall discuss the operations involved with equations, such as Eqs. (A.1) through (A.4), for this parameter first. The first step in determining any of the four hybrid parameters is to find the quiescent point of operation as

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*The partial derivative $\partial v_i/\partial i_i$ provides a measure of the instantaneous change in v_i due to an instantaneous change in i_i.

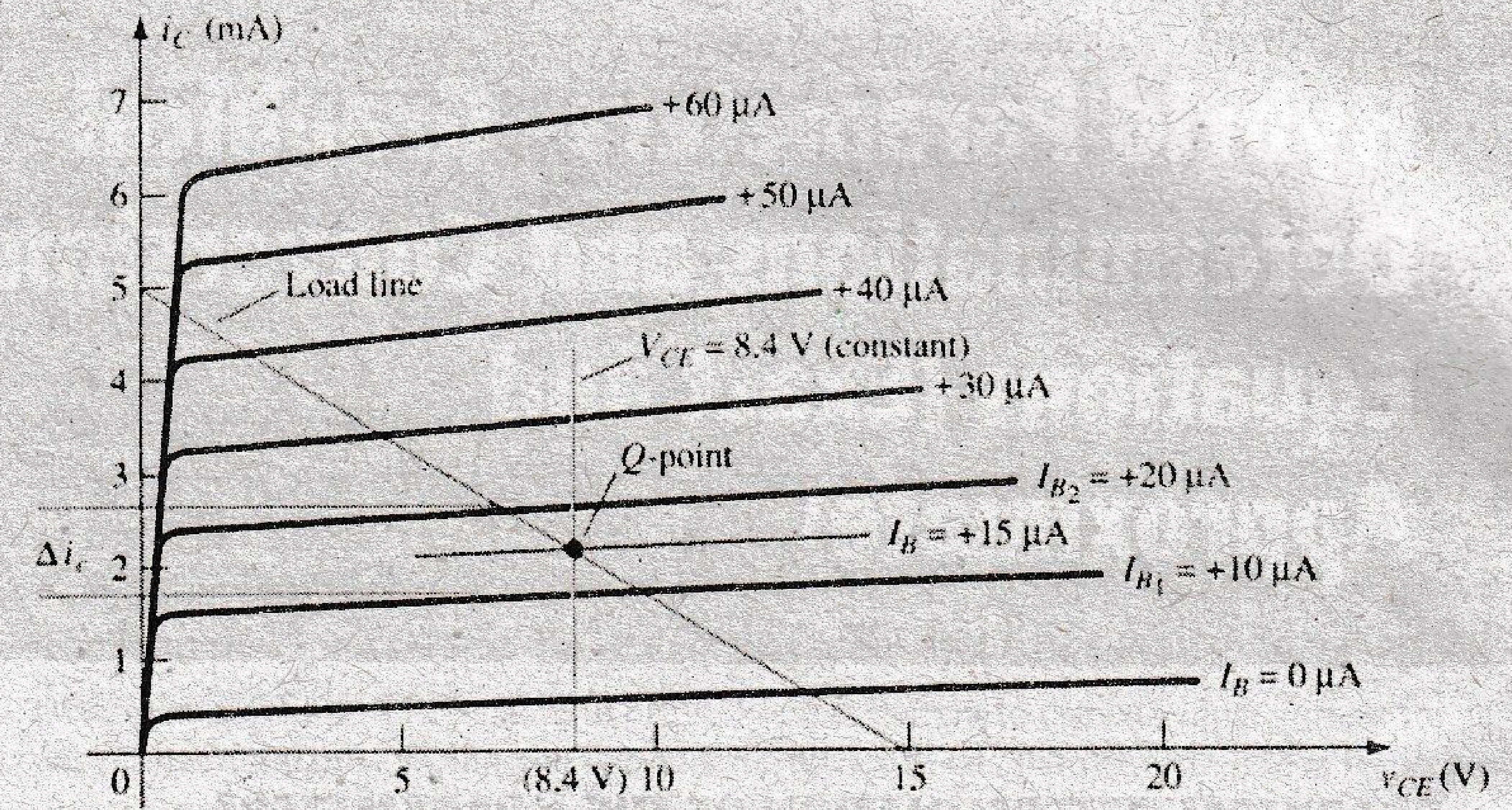


FIG. A.1
h_{fe} *determination.*

indicated in Fig. A.1. In Eq. (A.3) the condition V_{CE} = constant requires that the changes in base current and collector current be taken along a vertical straight line drawn through the Q-point representing a fixed collector-to-emitter voltage. Equation (A.3) then requires that a small change in collector current be divided by the corresponding change in base current. For the greatest accuracy, these changes should be made as small as possible.

In Fig. A.1, the change in i_b is chosen to extend from I_{B_1} to I_{B_2} along the perpendicular straight line at V_{CE}. The corresponding change in i_c is then found by drawing the horizontal lines from the intersections of I_{B_1} and I_{B_2} with V_{CE} = constant to the vertical axis. All that remains is to substitute the resultant changes of i_b and i_c into Eq. (A.3). That is,

$$|h_{fe}| = \left.\frac{\Delta i_c}{\Delta i_b}\right|_{V_{CE}=\text{constant}} = \left.\frac{(2.7 - 1.7)\text{ mA}}{(20 - 10)\ \mu\text{A}}\right|_{V_{CE}=8.4\text{ V}}$$

$$= \frac{10^{-3}}{10 \times 10^{-6}} = \mathbf{100}$$

In Fig. A.2, a straight line is drawn tangent to the curve I_B through the Q-point to establish a line I_B = constant as required by Eq. (A.4) for h_{oe}. A change in v_{CE} was then chosen and the corresponding change in i_C determined by drawing the horizontal lines to the vertical axis at

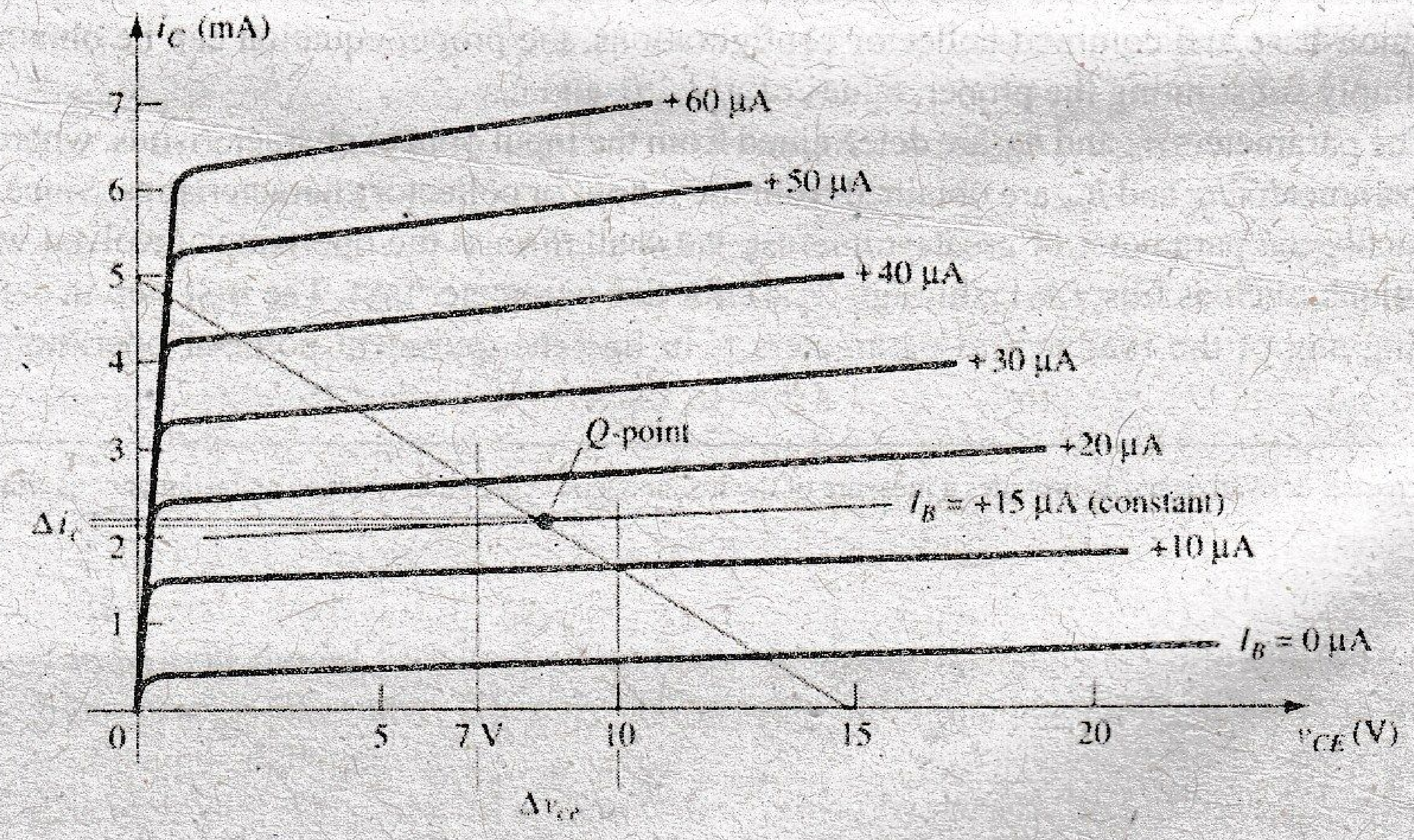


FIG. A.2
h_{oe} *determination.*

the intersections on the I_B = constant line. Substituting into Eq. (A.4), we get

$$|h_{oe}| = \left.\frac{\Delta i_c}{\Delta v_{ce}}\right|_{I_B=\text{constant}} = \left.\frac{(2.2-2.1)\text{ mA}}{(10-7)\ V}\right|_{I_B=+15\ \mu\text{A}}$$

$$= \frac{0.1\times10^{-3}}{3} = \mathbf{33\ \mu A/V = 33\times10^{-6}\ S = 33\ \mu S}$$

To determine the parameters h_{ie} and h_{re} the Q-point must first be found on the input or base characteristics as indicated in Fig. A.3. For h_{ie}, a line is drawn tangent to the curve V_{CE} = 8.4 V through the Q-point to establish a line V_{CE} = constant as required by Eq. (A.1). A small change in v_{be} is then chosen, resulting in a corresponding change in i_b. Substituting into Eq. (A.1), we get

$$|h_{ie}| = \left.\frac{\Delta v_{be}}{\Delta i_b}\right|_{V_{CE}=\text{constant}} = \left.\frac{(733-718)\text{ mV}}{(20-10)\ \mu\text{A}}\right|_{V_{CE}=8.4\text{ V}}$$

$$= \frac{15\times10^{-3}}{10\times10^{-6}} = \mathbf{1.5\ k\Omega}$$

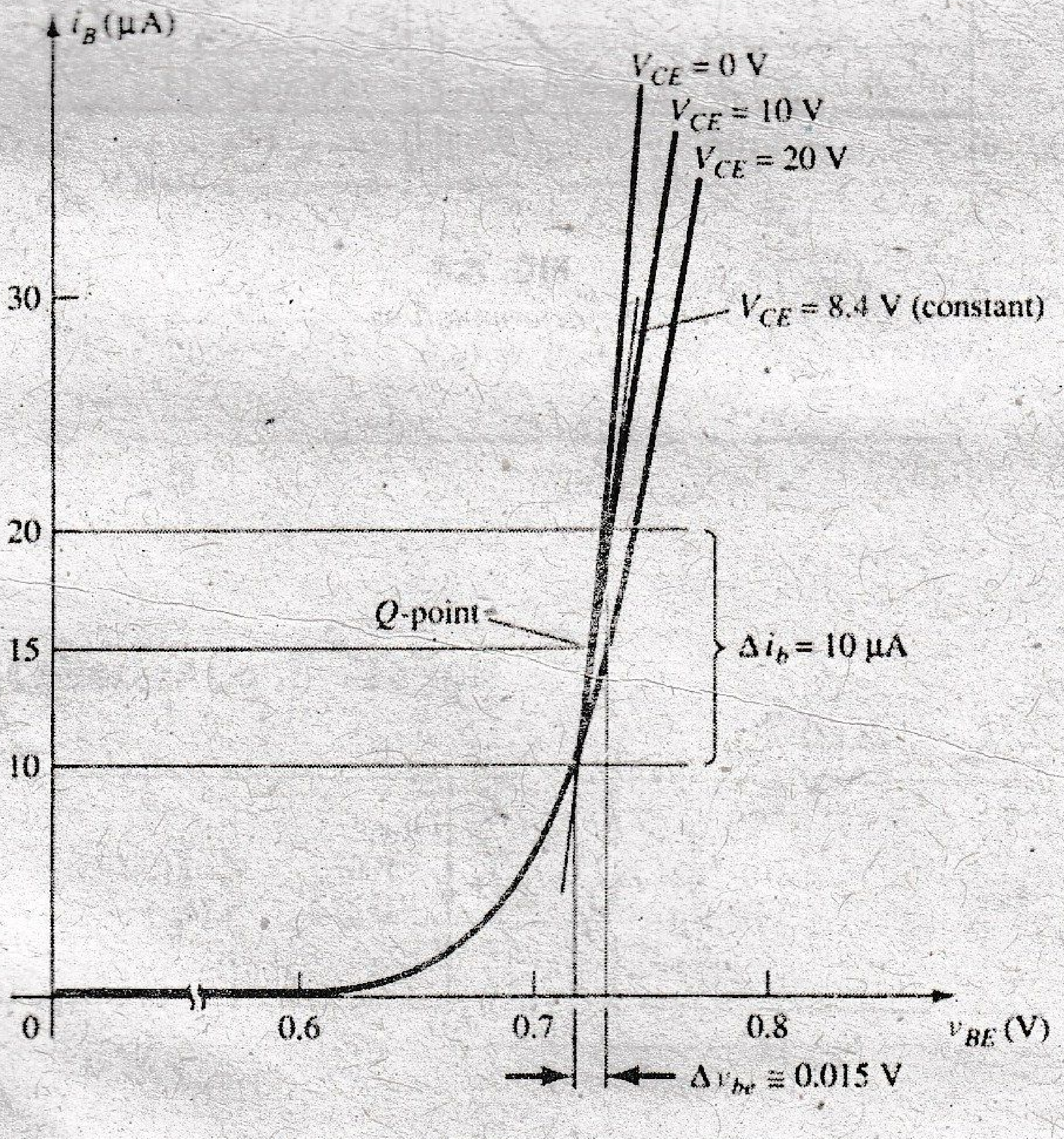


FIG. A.3
h_{ie} determination.

The last parameter, h_{re}, can be found by first drawing a horizontal line through the Q-point at I_B = 15 μA. The natural choice then is to pick a change in v_{CE} and find the resulting change in v_{BE} as shown in Fig. A.4.

Substituting into Eq. (A.2), we get

$$|h_{re}| = \left.\frac{\Delta v_{be}}{\Delta v_{ce}}\right|_{I_B=\text{constant}} = \frac{(733-725)\text{ mV}}{(20-0)\text{ V}} = \frac{8\times10^{-3}}{20} = \mathbf{4\times10^{-4}}$$

For the transistor whose characteristics appear in Figs. A.1 through A.4, the resulting hybrid small-signal equivalent circuit is shown in Fig. A.5.

As mentioned earlier, the hybrid parameters for the common-base and common-collector configurations can be found using the same basic equations with the proper variables and characteristics.

Table A.1 lists typical parameter values in each of the three configurations for the broad range of transistors available. The minus sign indicates that in Eq. (A.3) as one quantity increases in magnitude within the change chosen, the other decreases in magnitude.

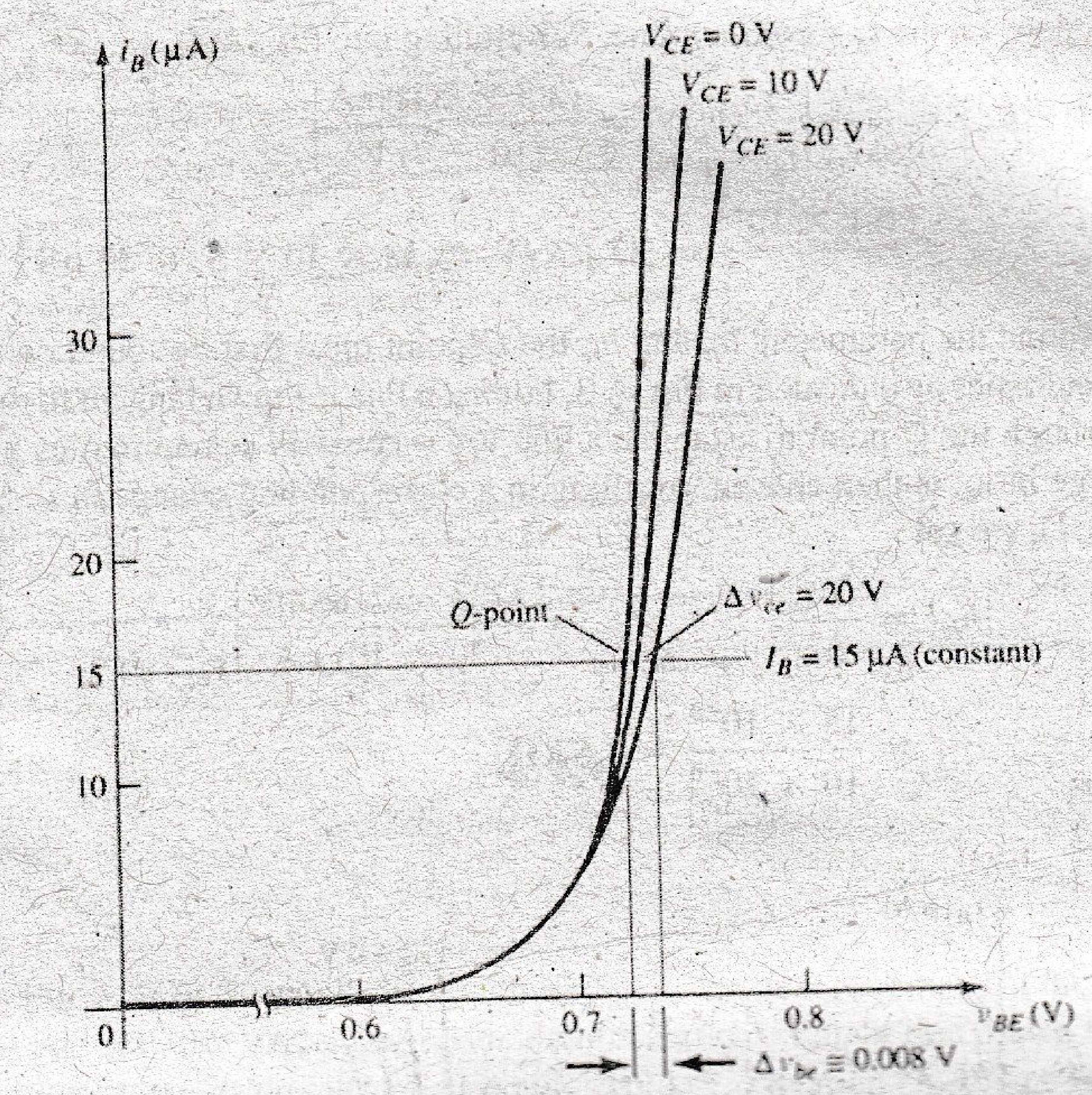


FIG. A.4

h_{re} determination.

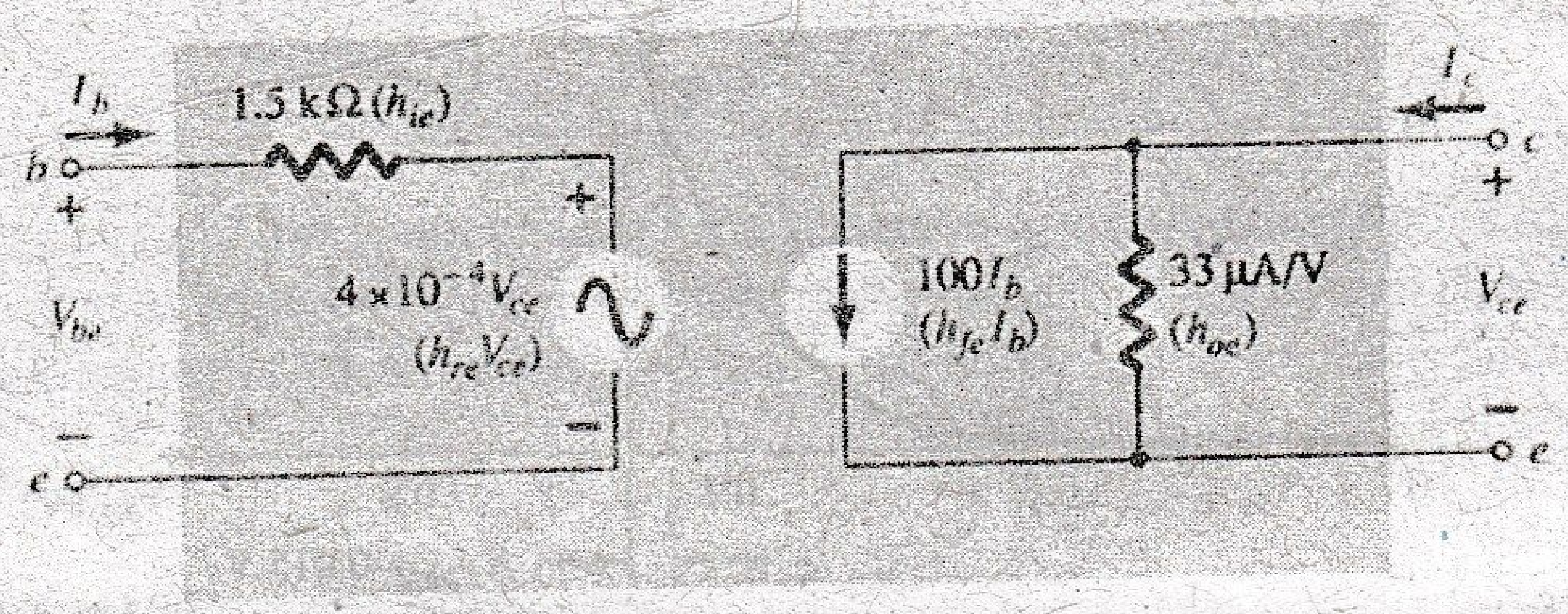


FIG. A.5

Complete hybrid equivalent circuit for a transistor having the characteristics that appear in Figs. A.1 through A.4.

TABLE A.1

Typical Parameter Values for the CE, CC, and CB Transistor Configurations

Parameter	CE	CC	CB
h_i	1 kΩ	1 kΩ	20 Ω
h_r	2.5×10^{-4}	$\cong 1$	3.0×10^{-4}
h_f	50	−50	−0.98
h_o	25 μA/V	25 μA/V	0.5 μA/V
$1/h_o$	40 kΩ	40 kΩ	2 MΩ

A.2 EXACT CONVERSION EQUATIONS

Common-Emitter Configuration

$$h_{ie} = \frac{h_{ib}}{(1 + h_{fb})(1 - h_{rb}) + h_{ob}h_{ib}} = h_{ic}$$

$$h_{re} = \frac{h_{ib}h_{ob} - h_{rb}(1 + h_{fb})}{(1 + h_{fb})(1 - h_{rb}) + h_{ob}h_{ib}} = 1 - h_{rc}$$

$$h_{fe} = \frac{-h_{fb}(1 - h_{rb}) - h_{ob}h_{ib}}{(1 + h_{fb})(1 - h_{rb}) + h_{ob}h_{ib}} = -(1 + h_{fc})$$

$$h_{oe} = \frac{h_{ob}}{(1 + h_{fb})(1 - h_{rb}) + h_{ob}h_{ib}} = h_{oc}$$

Common-Base Configuration

$$h_{ib} = \frac{h_{ie}}{(1 + h_{fe})(1 - h_{re}) + h_{ie}h_{oe}} = \frac{h_{ic}}{h_{ic}h_{oc} - h_{fc}h_{rc}}$$

$$h_{rb} = \frac{h_{ie}h_{oe} - h_{re}(1 + h_{fe})}{(1 + h_{fe})(1 - h_{re}) + h_{ie}h_{oe}} = \frac{h_{fc}(1 - h_{rc}) + h_{ic}h_{oc}}{h_{ic}h_{oc} - h_{fc}h_{rc}}$$

$$h_{fb} = \frac{-h_{fe}(1 - h_{re}) - h_{ie}h_{oe}}{(1 + h_{fe})(1 - h_{re}) + h_{ie}h_{oe}} = \frac{h_{rc}(1 + h_{fc}) - h_{ic}h_{oc}}{h_{ic}h_{oc} - h_{fc}h_{rc}}$$

$$h_{ob} = \frac{h_{oe}}{(1 + h_{fe})(1 - h_{re}) + h_{ie}h_{oe}} = \frac{h_{oc}}{h_{ic}h_{oc} - h_{fc}h_{rc}}$$

Common-Collector Configuration

$$h_{ic} = \frac{h_{ib}}{(1 + h_{fb})(1 - h_{rb}) + h_{ob}h_{ib}} = h_{ie}$$

$$h_{rc} = \frac{1 + h_{fb}}{(1 + h_{fb})(1 - h_{rb}) + h_{ob}h_{ib}} = 1 - h_{re}$$

$$h_{fc} = \frac{h_{rb} - 1}{(1 + h_{fb})(1 - h_{rb}) + h_{ob}h_{ib}} = -(1 + h_{fe})$$

$$h_{oc} = \frac{h_{ob}}{(1 + h_{fb})(1 - h_{rb}) + h_{ob}h_{ib}} = h_{oe}$$

A.3 APPROXIMATE CONVERSION EQUATIONS

Common-Emitter Configuration

$$h_{ie} \cong \frac{h_{ib}}{1 + h_{fb}} \cong \beta r_e$$

$$h_{re} \cong \frac{h_{ib}h_{ob}}{1 + h_{fb}} - h_{rb}$$

$$h_{fe} \cong \frac{-h_{fb}}{1 + h_{fb}} \cong \beta$$

$$h_{oe} \cong \frac{h_{ob}}{1 + h_{fb}}$$

Common-Base Configuration

$$h_{ib} \cong \frac{h_{ie}}{1 + h_{fe}} \cong \frac{-h_{ic}}{h_{fc}} \cong r_e$$

$$h_{rb} \cong \frac{h_{ie}h_{oe}}{1 + h_{fe}} - h_{re} \cong h_{rc} - 1 - \frac{h_{ic}h_{oc}}{h_{fc}}$$

$$h_{fb} \cong \frac{-h_{fe}}{1 + h_{fe}} \cong -\frac{(1 + h_{fc})}{h_{fc}} \cong -\alpha$$

$$h_{ob} \cong \frac{h_{oe}}{1 + h_{fe}} \cong \frac{-h_{oc}}{h_{fc}}$$

Common-Collector Configuration

$$h_{ic} \cong \frac{h_{ib}}{1 + h_{fb}} \cong \beta r_e$$

$$h_{rc} \cong 1$$

$$h_{fc} \cong \frac{-1}{1 + h_{fb}} \cong -\beta$$

$$h_{oc} \cong \frac{h_{ob}}{1 + h_{fb}}$$

Appendix B

Ripple Factor and Voltage Calculations

B.1 RIPPLE FACTOR OF RECTIFIER

The ripple factor of a voltage is defined by

$$r = \frac{\text{rms value of ac component of signal}}{\text{average value of signal}}$$

which can be expressed as

$$r = \frac{V_r(\text{rms})}{V_{\text{dc}}}$$

Since the ac voltage component of a signal containing a dc level is

$$v_{\text{ac}} = v - V_{\text{dc}}$$

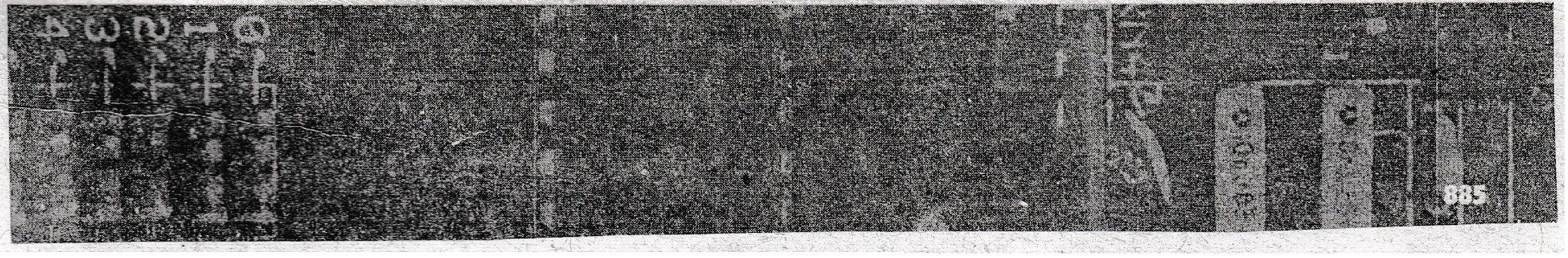
the rms value of the ac component is

$$\begin{aligned} V_r(\text{rms}) &= \left[\frac{1}{2\pi}\int_0^{2\pi} v_{\text{ac}}^2\, d\theta\right] \\ &= \left[\frac{1}{2\pi}\int_0^{2\pi} (v - V_{\text{dc}})^2\, d\theta\right]^{1/2} \\ &= \left[\frac{1}{2\pi}\int_0^{2\pi} (v^2 - 2vV_{\text{dc}} + V_{\text{dc}}^2)\, d\theta\right]^{1/2} \\ &= [V^2(\text{rms}) - 2V_{\text{dc}}^2 + V_{\text{dc}}^2]^{1/2} \\ &= [V^2(\text{rms}) - V_{\text{dc}}^2]^{1/2} \end{aligned}$$

where $V(\text{rms})$ is the rms value of the total voltage. For the half-wave rectified signal,

$$\begin{aligned} V_r(\text{rms}) &= [V^2(\text{rms}) - V_{\text{dc}}^2]^{1/2} \\ &= \left[\left(\frac{V_m}{2}\right)^2 - \left(\frac{V_m}{\pi}\right)^2\right]^{1/2} \\ &= V_m\left[\left(\frac{1}{2}\right)^2 - \left(\frac{1}{\pi}\right)^2\right]^{1/2} \end{aligned}$$

$$\boxed{V_r(\text{rms}) = 0.385V_m \qquad \text{(half-wave)}} \qquad \textbf{(B.1)}$$



For the full-wave rectified signal,

$$V_r(\text{rms}) = [V^2(\text{rms}) - V_{\text{dc}}^2]^{1/2}$$
$$= \left[\left(\frac{V_m}{\sqrt{2}}\right)^2 - \left(\frac{2V_m}{\pi}\right)^2\right]^{1/2}$$
$$= V_m\left(\frac{1}{2} - \frac{4}{\pi^2}\right)^{1/2}$$

$$\boxed{V_r(\text{rms}) = 0.308V_m \qquad \text{(full-wave)}} \tag{B.2}$$

B.2 RIPPLE VOLTAGE OF CAPACITOR FILTER

Assuming a triangular ripple waveform approximation as shown in Fig. B.1, we can write (see Fig. B.2)

$$V_{\text{dc}} = V_m - \frac{V_r(\text{p-p})}{2} \tag{B.3}$$

During capacitor discharge, the voltage change across C is

$$V_r(\text{p-p}) = \frac{I_{\text{dc}}T_2}{C} \tag{B.4}$$

From the triangular waveform in Fig. B.1,

$$V_r(\text{rms}) = \frac{V_r(\text{p-p})}{2\sqrt{3}} \tag{B.5}$$

(obtained by calculations not shown).

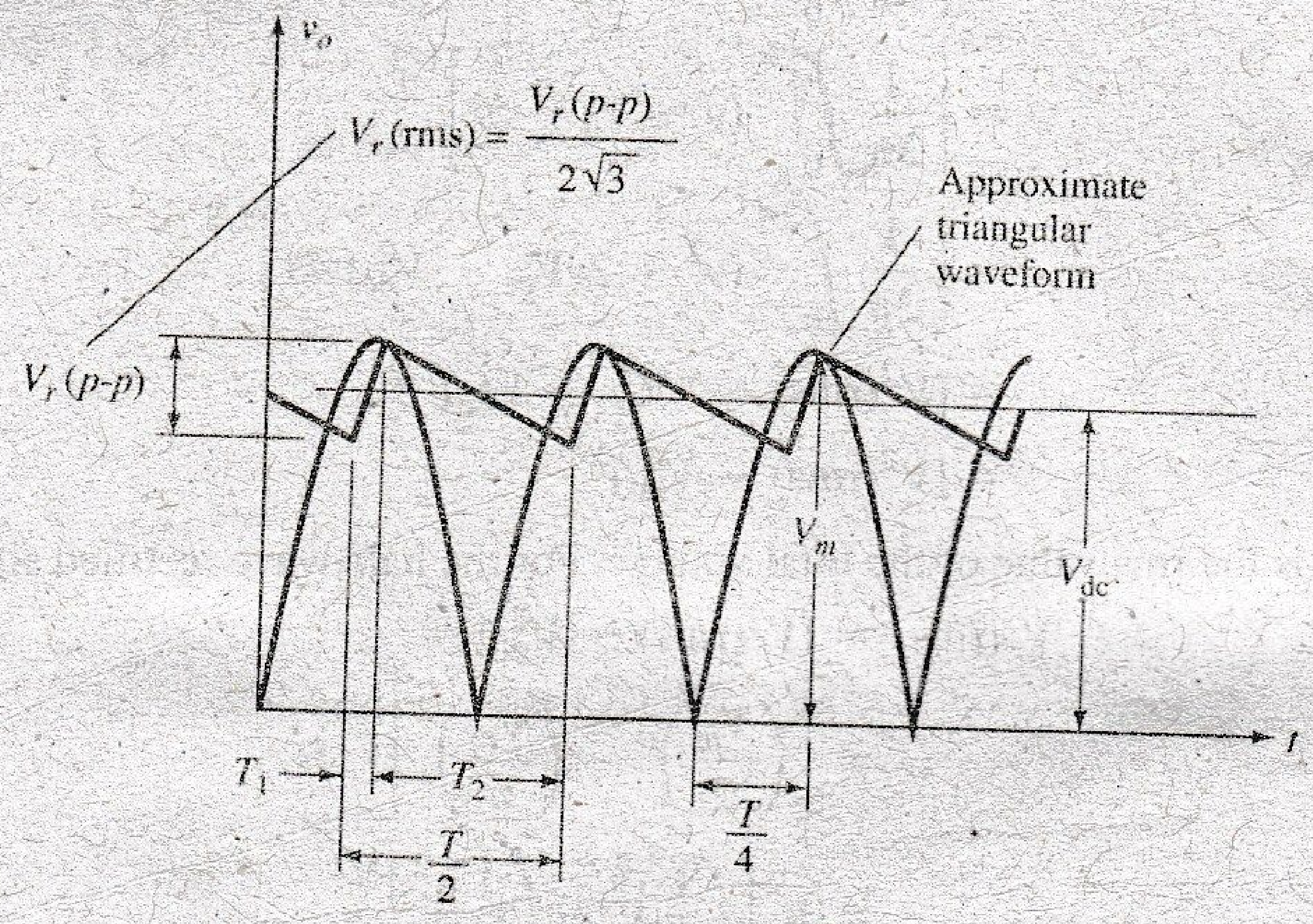


FIG. B.1
Approximate triangular ripple voltage for capacitor filter.

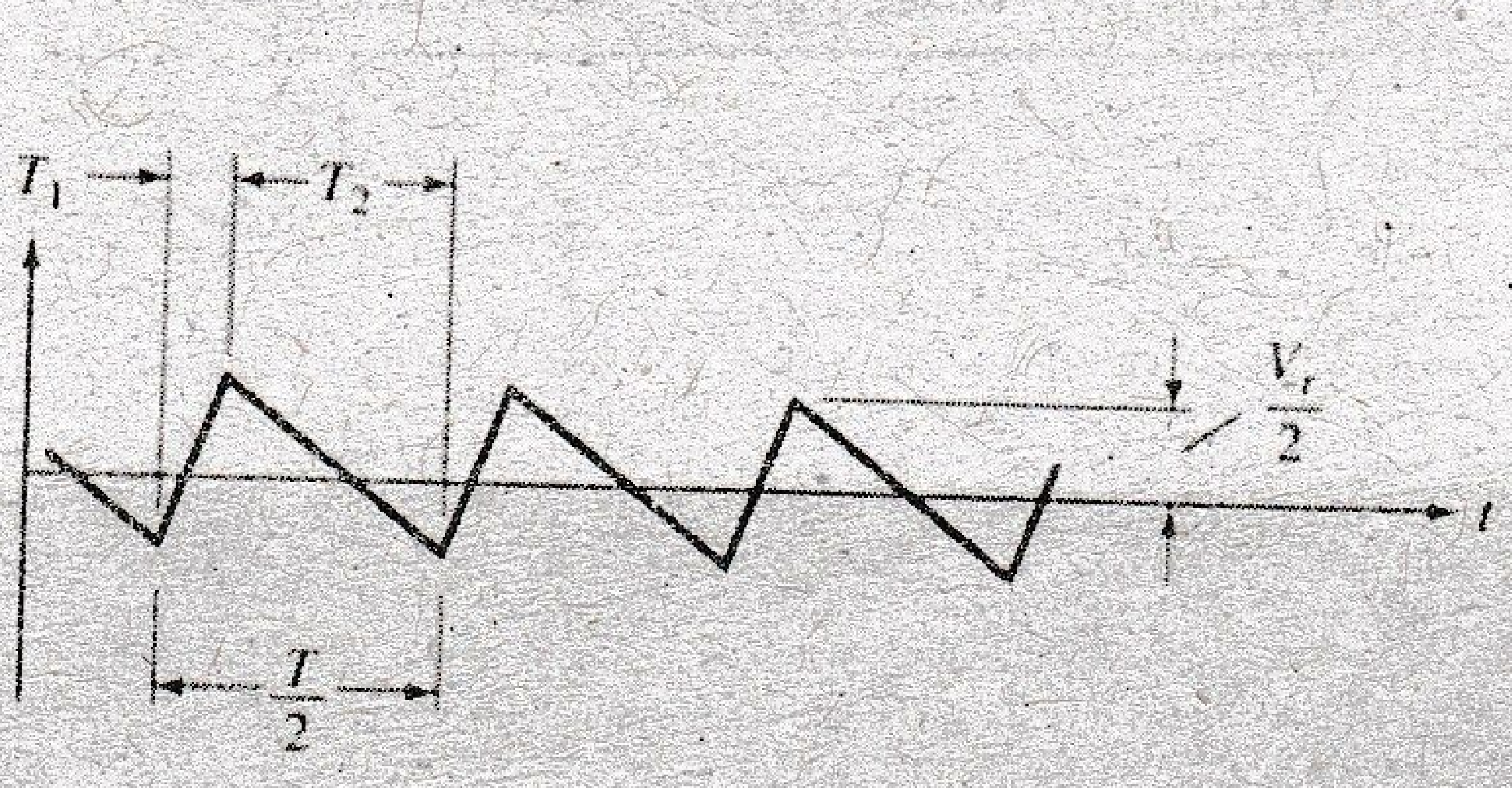


FIG. B.2
Ripple voltage.

Using the waveform details of Fig. B.1 results in

$$\frac{V_r(\text{p-p})}{T_1} = \frac{V_m}{T/4}$$

$$T_1 = \frac{V_r(\text{p-p})(T/4)}{V_m}$$

Also,

$$T_2 = \frac{T}{2} - T_1 = \frac{T}{2} - \frac{V_r(\text{p-p})(T/4)}{V_m} = \frac{2TV_m - V_r(\text{p-p})T}{4V_m}$$

$$T_2 = \frac{2V_m - V_r(\text{p-p})}{V_m}\frac{T}{4} \tag{B.6}$$

Since Eq. (B.3) can be written as

$$V_{\text{dc}} = \frac{2V_m - V_r(\text{p-p})}{2}$$

we can combine the last equation with Eq. (B.6) to obtain

$$T_2 = \frac{V_{\text{dc}}}{V_m}\frac{T}{2}$$

which, inserted into Eq. (B.4), gives

$$V_r(\text{p-p}) = \frac{I_{\text{dc}}}{C}\left(\frac{V_{\text{dc}}}{V_m}\frac{T}{2}\right)$$

$$T = \frac{1}{f}$$

$$V_r(\text{p-p}) = \frac{I_{\text{dc}}}{2fC}\frac{V_{\text{dc}}}{V_m} \tag{B.7}$$

Combining Eqs. (B.5) and (B.7), we solve for V_r (rms):

$$\boxed{V_r(\text{rms}) = \frac{V_r(\text{p-p})}{2\sqrt{3}} = \frac{I_{\text{dc}}}{4\sqrt{3}fC}\frac{V_{\text{dc}}}{V_m}} \tag{B.8}$$

B.3 RELATION OF V_{dc} AND V_m TO RIPPLE r

The dc voltage developed across a filter capacitor from a transformer providing a peak voltage V_m can be related to the ripple as follows:

$$r = \frac{V_r(\text{rms})}{V_{\text{dc}}} = \frac{V_r(\text{p-p})}{2\sqrt{3}V_{\text{dc}}}$$

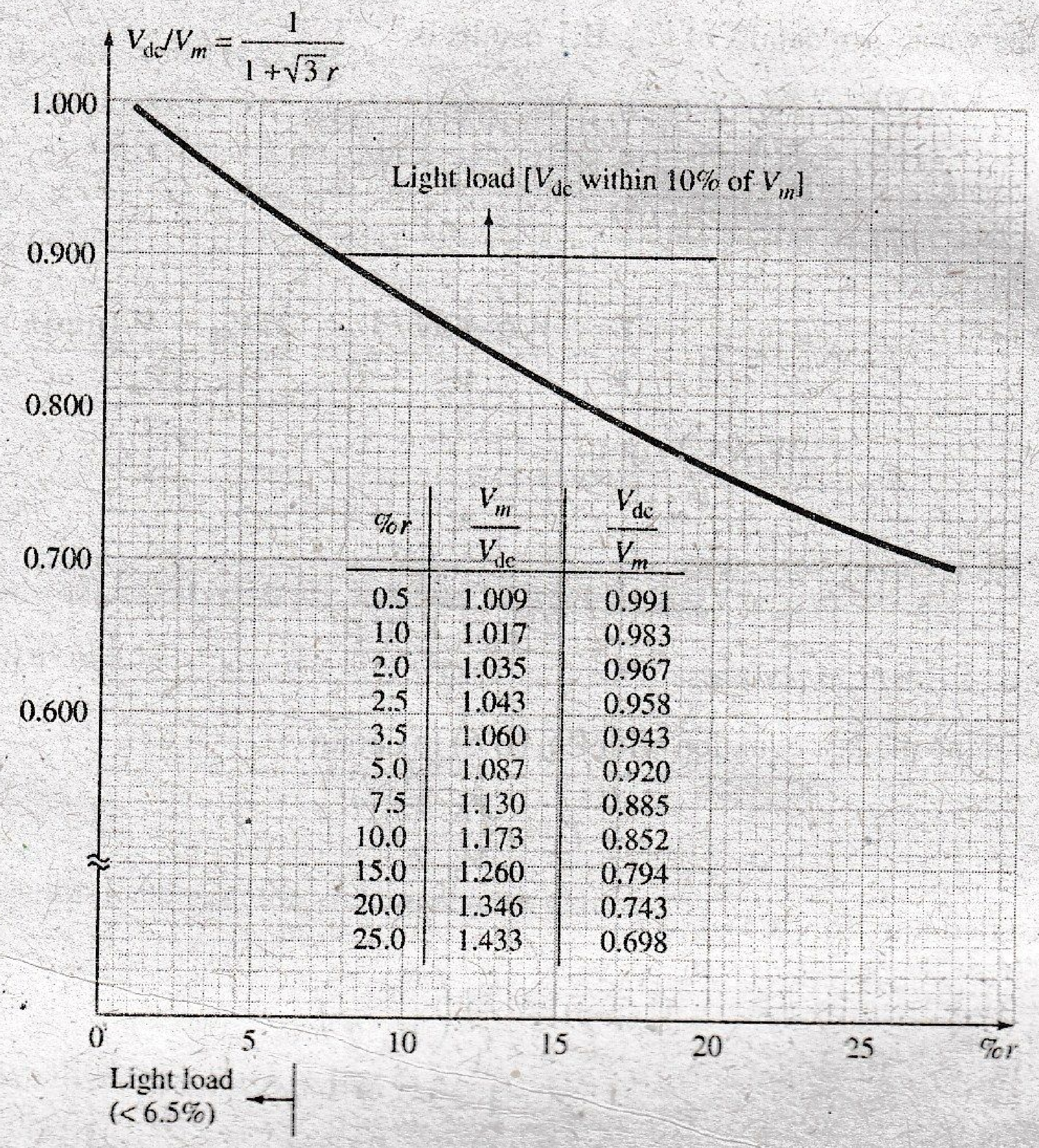
$$V_{\text{dc}} = \frac{V_r(\text{p-p})}{2\sqrt{3}r} = \frac{V_r(\text{p-p})/2}{\sqrt{3}r} = \frac{V_r(\text{p})}{\sqrt{3}r} = \frac{V_m - V_{\text{dc}}}{\sqrt{3}r}$$

$$V_m - V_{\text{dc}} = \sqrt{3}rV_{\text{dc}}$$

$$V_m = (1 + \sqrt{3}r)V_{\text{dc}}$$

$$\boxed{\frac{V_m}{V_{\text{dc}}} = 1 + \sqrt{3}r} \tag{B.9}$$

Equation (B.9) applies to both half-wave and full-wave rectifier-capacitor filter circuits and is plotted in Fig. B.3. As an example, at a ripple of 5% the dc voltage is $V_{\text{dc}} = 0.92V_m$, or within 10% of the peak voltage, whereas at 20% ripple the dc voltage drops to only $0.74V_m$, which is more than 25% less than the peak value. Note that V_{dc} is within 10% of V_m for ripple less than 6.5%. This amount of ripple represents the borderline of the light-load condition.



%r	$\dfrac{V_m}{V_{dc}}$	$\dfrac{V_{dc}}{V_m}$
0.5	1.009	0.991
1.0	1.017	0.983
2.0	1.035	0.967
2.5	1.043	0.958
3.5	1.060	0.943
5.0	1.087	0.920
7.5	1.130	0.885
10.0	1.173	0.852
15.0	1.260	0.794
20.0	1.346	0.743
25.0	1.433	0.698

FIG. B.3
Plot of V_{dc}/V_m as a function of %r.

B.4 RELATION OF V_r(rms) AND V_m TO RIPPLE r

We can also obtain a relation connecting V_r(rms), V_m, and the amount of ripple for both half-wave and full-wave rectifier-capacitor filter circuits as follows:

$$\frac{V_r(\text{p-p})}{2} = V_m - V_{dc}$$

$$\frac{V_r(\text{p-p})/2}{V_m} = \frac{V_m - V_{dc}}{V_m} = 1 - \frac{V_{dc}}{V_m}$$

$$\frac{\sqrt{3}V_r(\text{rms})}{V_m} = 1 - \frac{V_{dc}}{V_m}$$

Using Eq. (B.9), we get

$$\frac{\sqrt{3}V_r(\text{rms})}{V_m} = 1 - \frac{1}{1+\sqrt{3}r}$$

$$\frac{V_r(\text{rms})}{V_m} = \frac{1}{\sqrt{3}}\left(1 - \frac{1}{1+\sqrt{3}r}\right) = \frac{1}{\sqrt{3}}\left(\frac{1+\sqrt{3}r-1}{1+\sqrt{3}r}\right)$$

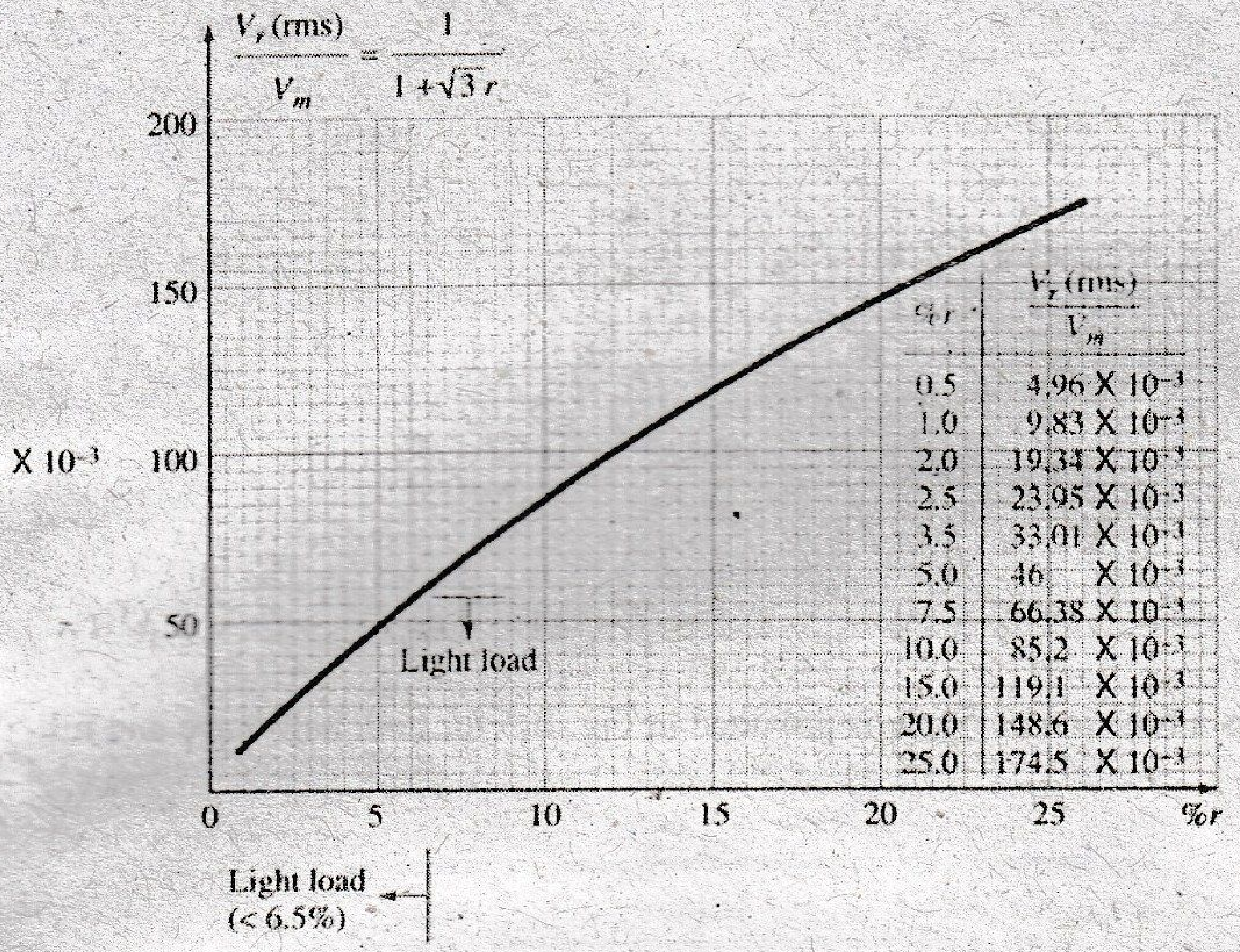
$$\boxed{\frac{V_r(\text{rms})}{V_m} = \frac{r}{1+\sqrt{3}r}} \qquad \textbf{(B.10)}$$

Equation (B.10) is plotted in Fig. B.4.

Since V_{dc} is within 10% of V_m for ripple $\leq 6.5\%$,

$$\frac{V_r(\text{rms})}{V_m} \cong \frac{V_r(\text{rms})}{V_{dc}} = r \qquad \text{(light load)}$$

and we can use $V_r(\text{rms})/V_m = r$ for ripple $\leq 6.5\%$.



%r	$\frac{V_r\text{(rms)}}{V_m}$
0.5	4.96×10^{-3}
1.0	9.83×10^{-3}
2.0	19.34×10^{-3}
2.5	23.95×10^{-3}
3.5	33.01×10^{-3}
5.0	46×10^{-3}
7.5	66.38×10^{-3}
10.0	85.2×10^{-3}
15.0	119.1×10^{-3}
20.0	148.6×10^{-3}
25.0	174.5×10^{-3}

FIG. B.4

Plot of $V_r\text{(rms)}/V_m$ *as a function of %r.*

B.5 RELATION CONNECTING CONDUCTION ANGLE, PERCENTAGE RIPPLE, AND $I_{\text{peak}}/I_{\text{dc}}$ FOR RECTIFIER-CAPACITOR FILTER CIRCUITS

Using Fig. B.1, we can determine the angle θ_1 at which the diode starts to conduct as follows: Since

$$v = V_m \sin\theta = V_m - V_r\text{(p-p)} \qquad \text{at} \qquad \theta = \theta_1$$

we have

$$\theta_1 = \sin^{-1}\left[1 - \frac{V_r\text{(p-p)}}{V_m}\right]$$

Using Eq. (B.10) and $V_r\text{(rms)} = V_r\text{(p-p)}/2\sqrt{3}$ gives

$$\frac{V_r\text{(p-p)}}{V_m} = \frac{2\sqrt{3}V_r\text{(rms)}}{V_m}$$

so that

$$1 - \frac{V_r\text{(p-p)}}{V_m} = 1 - \frac{2\sqrt{3}V_r\text{(rms)}}{V_m} = 1 - 2\sqrt{3}\left(\frac{r}{1+\sqrt{3}r}\right)$$

$$= \frac{1-\sqrt{3}r}{1+\sqrt{3}r}$$

and

$$\boxed{\theta_1 = \sin^{-1}\frac{1-\sqrt{3}r}{1+\sqrt{3}r}} \qquad \textbf{(B.11)}$$

where θ_1 is the angle at which conduction starts.

When the current becomes zero after charging the parallel impedances R_L and C, we can determine that

$$\theta_2 = \pi - \tan^{-1}\omega R_L C$$

An expression for $\omega R_L C$ can be obtained as follows:

$$r = \frac{V_r\text{(rms)}}{V_{\text{dc}}} = \frac{(I_{\text{dc}}/4\sqrt{3}fC)(V_{\text{dc}}/V_m)}{V_{\text{dc}}} = \frac{V_{\text{dc}}/R_L}{4\sqrt{3}fC}\frac{1}{V_m}$$

$$= \frac{V_{\text{dc}}/V_m}{4\sqrt{3}fCR} = \frac{2\pi\left(\frac{1}{1+\sqrt{3}r}\right)}{4\sqrt{3}\omega CR_L}$$

so that
$$\omega R_L C = \frac{2\pi}{4\sqrt{3}\,(1 + \sqrt{3}r)r} = \frac{0.907}{r(1 + \sqrt{3}r)}$$

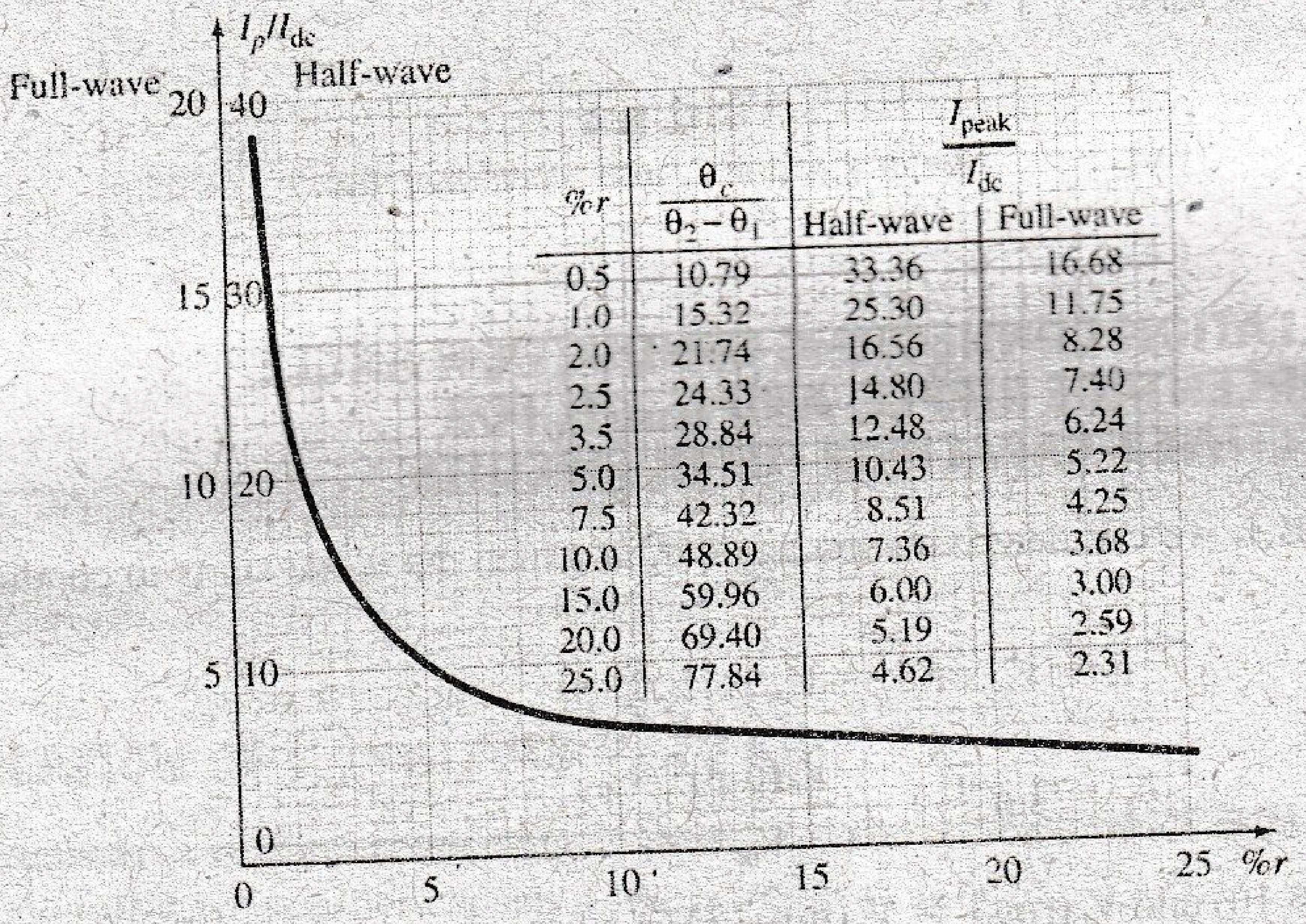
Thus conduction stops at an angle

$$\boxed{\theta_2 = \pi - \tan^{-1}\frac{0.907}{(1 + \sqrt{3}r)r}} \tag{B.12}$$

From Eq. (15.10b), we can write

$$\frac{I_{\text{peak}}}{I_{\text{dc}}} = \frac{I_p}{I_{\text{dc}}} = \frac{T}{T_1} = \frac{180°}{\theta} \quad \text{(full-wave)}$$
$$= \frac{360°}{\theta} \quad \text{(half-wave)} \tag{B.13}$$

A plot of I_p/I_{dc} as a function of ripple is provided in Fig. B.5 for both half-wave and full-wave operation.



%r	$\frac{\theta_c}{\theta_2-\theta_1}$	$\frac{I_{\text{peak}}}{I_{\text{dc}}}$ Half-wave	Full-wave
0.5	10.79	33.36	16.68
1.0	15.32	25.30	11.75
2.0	21.74	16.56	8.28
2.5	24.33	14.80	7.40
3.5	28.84	12.48	6.24
5.0	34.51	10.43	5.22
7.5	42.32	8.51	4.25
10.0	48.89	7.36	3.68
15.0	59.96	6.00	3.00
20.0	69.40	5.19	2.59
25.0	77.84	4.62	2.31

$$\theta_1 = \sin^{-1}\left(\frac{1-\sqrt{3}\,r}{1+\sqrt{3}\,r}\right) \qquad \theta_2 = \pi - \tan^{-1}\left[\frac{0.907}{r\,(1+\sqrt{3}\,r)}\right] \qquad \theta_c = \theta_2 - \theta_1$$

FIG. B.5

Plot of I_p/I_{dc} versus %r for half-wave and full-wave operation.

Appendix C

Charts and Tables

TABLE C.1
Greek Alphabet

Name	Capital	Lowercase
alpha	Α	α
beta	Β	β
gamma	Γ	γ
delta	Δ	δ
epsilon	Ε	ε
zeta	Ζ	ζ
eta	Η	η
theta	Θ	θ
iota	Ι	ι
kappa	Κ	κ
lambda	Λ	λ
mu	Μ	μ
nu	Ν	ν
xi	Ξ	ξ
omicron	Ο	o
pi	Π	π
rho	Ρ	ρ
sigma	Σ	σ
tau	Τ	τ
upsilon	Υ	υ
phi	Φ	ϕ
chi	Χ	χ
psi	Ψ	ψ
omega	Ω	ω

TABLE C.2

Standard Values of Commercially Available Resistors

Ohms (Ω)					Kilohms (kΩ)		Megohms (MΩ)	
0.10	**1.0**	**10**	**100**	**1000**	**10**	**100**	**1.0**	**10.0**
0.11	1.1	11	110	1100	11	110	1.1	11.0
0.12	**1.2**	**12**	**120**	**1200**	**12**	**120**	**1.2**	**12.0**
0.13	1.3	13	130	1300	13	130	1.3	13.0
0.15	**1.5**	**15**	**150**	**1500**	**15**	**150**	**1.5**	**15.0**
0.16	1.6	16	160	1600	16	160	1.6	16.0
0.18	**1.8**	**18**	**180**	**1800**	**18**	**180**	**1.8**	**18.0**
0.20	2.0	20	200	2000	20	200	2.0	20.0
0.22	**2.2**	**22**	**220**	**2200**	**22**	**220**	**2.2**	**22.0**
0.24	2.4	24	240	2400	24	240	2.4	
0.27	**2.7**	**27**	**270**	**2700**	**27**	**270**	**2.7**	
0.30	3.0	30	300	3000	30	300	3.0	
0.33	**3.3**	**33**	**330**	**3300**	**33**	**330**	**3.3**	
0.36	3.6	36	360	3600	36	360	3.6	
0.39	**3.9**	**39**	**390**	**3900**	**39**	**390**	**3.9**	
0.43	4.3	43	430	4300	43	430	4.3	
0.47	**4.7**	**47**	**470**	**4700**	**47**	**470**	**4.7**	
0.51	5.1	51	510	5100	51	510	5.1	
0.56	**5.6**	**56**	**560**	**5600**	**56**	**560**	**5.6**	
0.62	6.2	62	620	6200	62	620	6.2	
0.68	**6.8**	**68**	**680**	**6800**	**68**	**680**	**6.8**	
0.75	7.5	75	750	7500	75	750	7.5	
0.82	**8.2**	**82**	**820**	**8200**	**82**	**820**	**8.2**	
0.91	9.1	91	910	9100	91	910	9.1	

TABLE C.3

Typical Capacitor Component Values

pF				μF				
10	100	1000	10,000	0.10	1.0	10	100	1000
12	120	1200						
15	150	1500	15,000	0.15	1.5	18	180	1800
22	220	2200	22,000	0.22	2.2	22	220	2200
27	270	2700						
33	330	3300	33,000	0.33	3.3	33	330	3300
39	390	3900						
47	470	4700	47,000	0.47	4.7	47	470	4700
56	560	5600						
68	680	6800	68,000	0.68	6.8			
82	820	8200						

Appendix D

Solutions to Selected Odd-Numbered Problems

Chapter 1

5. 2.4×10^{-18} C
15. **(a)** 25.27 mV **(b)** 11.84 mA
17. **(a)** 25.27 mV **(b)** 0.1 μA
19. 0.41 V
21. 1.6 μA
23. -75°C: 1.1 V, 0.01 pA; 25°C: 0.85 V, 1 pA; 125°C: 1.1 V, 105 μA
27. 175 Ω
29. -10 V: 100 MΩ; -30 V: 300 MΩ
31. **(a)** 3 Ω **(b)** 2.6 Ω **(c)** quite close
33. 1 mA: 52 Ω, 15 mA: 1.73 Ω
35. 22.5 Ω
37. $r_d = 4\ \Omega$
39. **(a)** -25 V: 0.75 pF; -10 V: 1.25 pF; $\Delta C_T/\Delta V_R = 0.033$ pF/V
43. 2.81 pF
45. $t_s = 3$ ns, $t_t = 6$ ns
47. **(b)** 6 pF **(c)** 0.58
49. 25°C: 0.5 nA; 100°C: 60 nA; 60 nA: 0.5 nA = 120:1
51. 25°C: 500 mW; 100°C: 260 mW; 25°C: 714.29 mA; 100°C: 371.43 mA
55. 0.053%/°C
57. 13 Ω
59. 2 V
61. 2.3 V
63. **(a)** 75° **(b)** 40°

Chapter 2

1. **(a)** $I_{D_Q} \cong 15$ mA, $V_{D_Q} \cong 0.85$ V, $V_R = 11.15$ V **(b)** $I_{D_Q} \cong 15$ mA, $V_{D_Q} = 0.71$ V, $V_R = 11.3$ V **(c)** $I_{D_Q} = 16$ mA, $V_{D_Q} = 0$ V, $V_R = 12$ V
3. $R = 0.62$ kΩ
5. **(a)** $I = 0$ mA **(b)** $I = 2.895$ A **(c)** $I = 1$ A
7. **(a)** $V_o = 9.17$ V **(b)** $V_o = 10$ V
9. **(a)** $V_{o_1} = 11.3$ V, $V_{o_2} = 1.2$ V **(b)** $V_{o_1} = 0$ V, $V_{o_2} = 0$ V
11. **(a)** $V_o = 0.3$ V, $I = 0.3$ mA **(b)** $V_o = 14.6$ V, $I = 3.96$ mA
13. $V_o = 6.03$ V, $I_D = 1.635$ mA
15. $V_o = 9.3$ V

17. $V_o = 10$ V
19. $V_o = -0.7$ V
21. $V_o = 4.7$ V
23. v_i: $V_m = 6.98$ V: r_d: pos. max = 0.7 V, neg. peak = −6.98 V: i_d: pos. pulse of 3.14 mA
25. Pos. pulse, peak = 169.68 V, $V_{dc} = 5.396$ V
27. **(a)** $I_{D_{max}} = 20$ mA **(b)** $I_{max} = 40$ mA **(c)** $I_D = 18.1$ mA
(d) $I_D = 36.2 \text{ mA} > I_{D_{max}} = 20$ mA
29. Full rectified waveform, peak = −100 V; PIV = 100 V, $I_{max} = 45.45$ mA
31. Full rectified waveform, peak = 56.67 V; $V_{dc} = 36.04$ V
33. **(a)** Pos. pulse of 5.09 V **(b)** Pos. pulse of 15.3 V
35. **(a)** Clipped at 4.7 V **(b)** Pos. clip at 0.7 V, neg. peak = −11 V
37. **(a)** 0 V to 40 V swing **(b)** −5 V to 35 V swing
39. **(a)** 28 ms **(b)** 56:1 **(c)** −1.3 V to −25.3 V swing
41. Network of Fig. 2.179 with battery reversed
43. **(a)** $R_s = 20\ \Omega$, $V_Z = 12$ V **(b)** $P_{Z_{max}} = 2.4$ W
45. $R_s = 0.5\ \text{k}\Omega$, $I_{ZM} = 40$ mA
47. $V_o = 339.36$ V

Chapter 3

3. Forward- and reverse-biased
9. $I_C = 7.921$ mA, $I_B = 79.21\ \mu$A
11. $V_{CB} = 1$ V: $V_{BE} = 800$ mV
$V_{CB} = 10$ V: $V_{BE} = 770$ mV
$V_{CB} = 20$ V: $V_{BE} = 750$ mV
Only slight
13. **(a)** $I_C \cong 3.5$ mA **(b)** $I_C \cong 3.5$ mA **(c)** Negligible **(d)** $I_C = I_E$
15. **(a)** $I_C = 3.992$ mA **(b)** $\alpha = 0.946$
19. **(a)** $\beta_{dc} = 111.11$ **(b)** $\alpha_{dc} = 0.991$ **(c)** $I_{CEO} = 0.3$ mA **(d)** $I_{CBO} = 2.7$ mA
21. **(a)** $\beta_{dc} = 87.5$ **(b)** $\beta_{dc} = 108.3$ **(c)** $\beta_{dc} = 135$
23. $\beta_{dc} = 116$, $\alpha_{dc} = 0.991$, $I_E = 2.93$ mA
29. $I_C = I_{C_{max}}$, $V_{CB} = 6$ V
$V_{CB} = V_{CB_{max}}$, $I_C = 2.1$ mA
$I_C = 4$ mA, $V_{CB} = 10.5$ V
$V_{CB} = 10$ V, $I_C = 4.2$ mA
31. $I_C = I_{C_{max}}$, $V_{CE} = 3.125$ V
$V_{CE} = V_{CE_{max}}$, $I_C = 20.83$ mA
$I_C = 100$ mA, $V_{CE} = 6.25$ mA
$V_{CE} = 20$ V, $I_C = 31.25$ mA
33. h_{FE}: $I_C = 0.1$ mA, $h_{FE} \cong 43$
$I_C = 10$ mA, $h_{FE} \cong 98$
h_{fe}: $I_C = 0.1$ mA, $h_{fe} \cong 72$
$I_C = 10$ mA, $h_{fe} \cong 160$
35. $I_C = 1$ mA, $h_{fe} \cong 120$
$I_C = 10$ mA, $h_{fe} \cong 160$
37. **(a)** $\beta_{ac} = 190$ **(b)** $\beta_{dc} = 201.7$ **(c)** $\beta_{ac} = 200$ **(d)** $\beta_{dc} = 230.77$ **(f)** Yes

Chapter 4

1. **(a)** $I_{B_Q} = 30\ \mu$A **(b)** $I_{CQ} = 3.6$ mA **(c)** $V_{CE_Q} = 9.52$ V **(d)** $V_C = 9.52$ V
(e) $V_B = 0.7$ V **(f)** $V_E = 0$ V
3. **(a)** $I_C = 3.98$ mA **(b)** $V_{CC} = 15.96$ V **(c)** $\beta = 199$ **(d)** $R_B = 763\ \text{k}\Omega$
5. **(b)** $R_B = 812\ \text{k}\Omega$ **(c)** $I_{C_Q} = 3.4$ mA, $V_{CE_Q} = 10.75$ V **(d)** $\beta_{dc} = 136$ **(e)** $\alpha = 0.992$
(f) $I_{C_{sat}} = 7$ mA **(h)** $P_D = 36.55$ mW **(i)** $P_s = 71.92$ mW **(j)** $P_R = 35.37$ mW
7. $I_{C_Q} = 2.4$ mA, $V_{CE_Q} = 11.5$ V
9. **(b)** $I_{C_Q} = 4.7$ mA, $V_{CE_Q} = 7.5$ V **(c)** 133.25 **(d)** reasonably close
11. **(a)** 154.5 **(b)** 17.74 V **(c)** 747 kΩ
13. **(a)** 2.33 kΩ **(b)** 133.33 **(c)** 616.67 kΩ **(d)** 40 mW **(e)** 37.28 mW
15. **(a)** 21.42 μA **(b)** 1.71 mA **(c)** 8.17 V **(d)** 9.33 V **(e)** 1.16 V **(f)** 1.86 V

17. **(a)** $I_C = 1.28$ mA **(b)** $V_E = 1.54$ V **(c)** $V_B = 2.24$ V **(d)** $R_1 = 39.4$ kΩ
19. $I_{C_{\text{sat}}} = 3.49$ mA
21. **(a)** 2.43 mA **(b)** 7.55 V **(c)** 20.25 μA **(d)** 2.43 V **(e)** 3.13 V
23. **(a)** 1.99 mA **(b)** $I_{C_Q} = 1.71$ mA, $V_{CE_Q} = 8.17$ V, $I_{B_Q} = 21.42$ μA
25. **(a)** $I_C = 1.71$ mA, $V_{CE} = 8.17$ V **(b)** $I_C = 1.8$ mA, $V_{CE} = 7.76$ V **(c)** % $\Delta I_C = 5.26$. % $\Delta V_{CE} = 5.02$ **(e)** Voltage-divider
27. **(a)** 18.09 μA **(b)** 2.17 mA **(c)** 8.19 V
29. **(a)** 2.24 mA **(b)** 11.63 V **(c)** 4.03 V **(d)** 7.6 V
31. **(a)** $I_C = 0.91$ mA, $V_{CE} = 5.44$ V **(b)** $I_C = 0.983$ mA, $V_{CE} = 4.11$ V **(c)** % $\Delta I_C = 8.02$, % $\Delta V_{CE} = 24.45$ **(d)** Voltage-divider
33. **(a)** 3.3 V **(b)** 2.75 mA **(c)** 11.95 V **(d)** 8.65 V **(e)** 24.09 μA **(f)**114.16
35. **(a)** $I_B = 65.77$ μA, $I_C = 7.23$ mA, $I_E = 7.3$ mA **(b)** $V_B = 9.46$ V, $V_C = 12$ V, $V_E = 8.76$ V **(c)** $V_{BC} = -2.54$ V, $V_{CE} = 3.24$ V
37. **(a)** $I_E = 3.32$ mA, $V_C = 4.02$ V, $V_{CE} = 4.72$ V
39. **(a)** $R_{\text{Th}} = 255$ kΩ, $E_{\text{Th}} = 0$ V, $I_B = 13.95$ μA **(b)** $I_C = 1.81$ mA **(c)** $V_E = -4.42$ V **(d)** $V_{CE} = 5.95$ V
41. $R_B = 361.6$ kΩ, $R_C = 2.4$ kΩ
Standard values: $R_B = 360$ kΩ, $R_C = 2.4$ kΩ
43. $R_E = 0.75$ kΩ, $R_C = 3.25$ kΩ, $R_2 = 7.5$ kΩ, $R_1 = 41.15$ kΩ, Standard values: $R_E = 0.75$ kΩ, $R_C = 3.3$ kΩ, $R_2 = 8.2$ kΩ, $R_1 = 43$ kΩ
45. **(a)** $V_{B_1} = 4.14$ V, $V_{E_1} = 3.44$ V, $I_{C_1} = I_{E_1} = 3.44$ mA, $V_{C_1} = 12.43$ V, $V_{B_2} = 2.61$ V, $V_{E_2} = 1.91$ V, $I_{E_2} = I_{C_2} = 1.59$ mA, $V_{C_2} = 16.5$ V
(b) $I_{B_1} = 21.5$ μA, $I_{C_1} \cong I_{E_1} = 3.44$ mA, $I_{B_2} = 17.67$ μA, $I_{C_2} \cong I_{E_2} = 1.59$ mA
47. **(a)** $I_{B_1} = 57.33$ μA, $I_{C_1} = 3.44$ mA, $I_{B_2} = 28.67$ μA, $I_{C_2} = 3.44$ mA
(b) $V_{B_1} = 4.48$ V, $V_{B_2} = 10.86$ V, $V_{E_1} = 3.78$ V, $V_{C_1} = 10.16$ V, $V_{E_2} = 10.16$ V, $V_{C_2} = 14.43$ V
49. $I = 8.65$ mA
51. $I = 2.59$ mA
53. $I_E = 3.67$ μA
55. $I_B = 17.5$ μA, $V_C = -13.53$ V
57. $I_{C_{sat}} = 4.167$ mA, $V_o = 9.76$ V
59. **(a)** $t_{on} = 168$ ns, $t_{off} = 148$ ns **(b)** $t_{on} = 37$ ns, $t_{off} = 132$ ns
63. **(a)** $V_C\downarrow$ **(b)** $V_{CE}\downarrow$ **(c)** $I_C\downarrow$ **(d)** $V_{CE} \cong 20$ V **(e)** $V_{CE} \cong 20$ V
65. **(a)** $S(I_{CO}) = 120$ **(b)** $S(V_{\beta E}) = -235 \times 10^{-6}$S **(c)** $S(\beta) = 30 \times 10^{-6}$ A **(d)** $\Delta I_C \cong 2.12$ mA
67. **(a)** $S(I_{CO}) = 11.06$ **(b)** $S(V_{BE}) = -1280 \times 10^{-6}$ S **(c)** $S(\beta) = 2.43 \times 10^{-6}$ A **(d)** $\Delta I_C = 0.313$ mA

Chapter 5

1. **(c)** 80.4%
7. **(a)** 20 Ω **(b)** 0.588 V **(c)** 58.8 **(d)** ∞ Ω **(e)** 0.98 **(f)** 10 μA
9. 8.57 Ω **(b)** 25 μA **(c)** 3.5 mA **(d)** 132.84 **(e)** −298.89
11. **(a)** $Z_i = 497.47$ Ω, $Z_o = 2.2$ kΩ **(b)** −264.74 **(c)** $Z_i = 497.47$ Ω, $Z_o = 1.98$ kΩ, $A_v = -238.27$
13. **(a)** $I_B = 18.72$ μA, $I_C = 1.87$ mA, $r_e = 13.76$ Ω **(b)** $Z_i = 1.38$ kΩ, $Z_o = 5.6$ kΩ **(c)** −406.98 **(d)** −343.03
15. **(a)** 30.56 Ω **(b)** $Z_i = 1.77$ kΩ, $Z_o = 3.9$ kΩ **(c)** −127.6 **(d)** $Z_i = 1.77$ kΩ, $Z_o = 3.37$ kΩ, $A_v = -110.28$
17. **(a)** 18.95 Ω **(b)** $V_B = 3.72$ V, $V_C = 13.59$ V **(c)** $Z_i = 3.17$ kΩ, $A_v = -298.15$
19. **(a)** 5.34 Ω **(b)** $Z_i = 118.37$ kΩ, $Z_o = 2.2$ kΩ **(c)** −1.81 **(d)** $Z_i = 105.95$ kΩ, $Z_o = 2.2$ kΩ, $A_v = -1.81$
21. $R_E = 0.82$ kΩ, $R_B = 242.09$ kΩ
23. **(a)** 15.53 Ω **(b)** $V_B = 2.71$ V, $V_{CE} = 6.14$ V, $V_{CB} = 5.44$ V **(c)** $Z_i = 67.45$ kΩ, $Z_o = 4.7$ kΩ **(d)** −3.92 **(e)** 56.26
25. **(a)** $Z_i = 236.1$ kΩ, $Z_o = 31.2$ Ω **(b)** 0.994 **(c)** 0.994 mV
27. **(a)** 33.38 Ω **(b)** $Z_i = 33.22$ Ω, $Z_o = 4.7$ kΩ **(c)** 140.52
29. **(a)** 13.08 Ω **(b)** $Z_i = 501.98$ Ω, $Z_o = 3.83$ kΩ **(c)** −298
31. **(c)** $A_v = -1.83$, $Z_i = 40.8$ kΩ, $Z_o = 2.16$ kΩ

33. **(a)** $Z_i = 12.79\text{ k}\Omega$, $Z_o = 1.75\text{ k}\Omega$, $A_v = -2.65$

35. **(a)** $R_L = 4.7\text{ k}\Omega$, $A_{v_L} = -191.65$; $R_L = 2.2\text{ k}\Omega$, $A_{v_L} = -130.49$; $R_L = 0.5\text{ k}\Omega$, $A_{v_L} = -42.92$ **(b)** No change

37. **(a)** $A_{v_{NL}} = -557.36$, $Z_i = 616.52\ \Omega$, $Z_o = 4.3\text{ k}\Omega$ **(c)** $A_{v_L} = -214.98$, $A_{v_s} = -81.91$ **(d)** 49.04 **(e)** -120.12 **(f)** A_{v_s} the same **(g)** No change

39. **(a)** $R_L = 4.7\text{ k}\Omega$, $A_{v_L} = -154.2$; $R_L = 2.2\text{ k}\Omega$, $A_{v_L} = -113.2$; $R_L = 0.5\text{ k}\Omega$, $A_{v_L} = -41.93$ **(b)** No change

41. **(a)** $A_{v_{NL}} = 0.983$, $Z_i = 9.89\text{ k}\Omega$, $Z_o = 20.19\ \Omega$ **(c)** $A_{v_L} = 0.976$, $A_{v_s} = 0.92$ **(d)** $A_{v_L} = 0.976$, $A_{v_s} = 0.886$ **(e)** No change **(f)** $A_{v_L} = 0.979$, $A_{v_s} = 0.923$ **(g)** $A_i = 3.59$

43. **(a)** $A_{v_1} = -97.67$, $A_{v_2} = -189$ **(b)** $A_{v_L} = 18.46 \times 10^3$, $A_{v_s} = 11.54 \times 10^3$ **(c)** $A_{i_1} = 97.67$, $A_{i_2} = 70$ **(d)** $A_{i_L} = 6.84 \times 10^3$ **(e)** No effect **(f)** No effect **(g)** In phase

45. $V_B = 3.08$ V, $V_E = 2.38$ V, $I_E \cong I_C = 1.59$ mA, $V_C = 6.89$ V

47. $V_{B_1} = 4.4$ V, $V_{B_2} = 11.48$ V, $V_{E_1} = 3.7$ V, $I_{C_1} \cong I_{E_1} = 3.7\text{ mA} \cong I_{E_2} \cong I_{C_2}$, $V_{C_2} = 14.45$ V, $V_{C_1} = 10.78$ V

49. -1.86 V

51. **(a)** $V_{B_1} = 9.59$ V, $V_{C_1} = 16$ V, $V_{E_2} = 8.17$ V, $V_{CB_1} = 6.41$ V, $V_{CE_2} = 7.83$ V **(b)** $I_{B_1} = 2.67\ \mu$A, $I_{B_2} = 133.5\ \mu$A, $I_{E_2} = 16.02$ mA **(c)** $Z_i = 1.13\text{ M}\Omega$, $Z_o = 3.21\ \Omega$ **(d)** $A_v \cong 1$, $A_i = 3.16 \times 10^3$

53. **(a)** $V_{B_1} = 8.22$ V, $V_{E_2} = 6.61$ V, $V_{CE_2} \doteq 3.3$ V, $V_{CB_1} = 1.69$ V **(b)** $Z_i \cong 8\text{ k}\Omega$, $Z_o = 470\ \Omega$ **(d)** -235 **(e)** 4×10^3

55. **(a)** $V_{B_1} = 6.24$ V, $V_{B_2} = 3.63$ V, $V_{C_1} = 3.63$ V, $V_{C_2} = 6.95$ V, $V_{E_1} = 6.95$ V, $V_{E_2} = 2.93$ V **(b)** $I_{B_1} = 4.16\ \mu$A, $I_{C_1} = 0.666$ mA, $I_{B_2} = 0.666$ mA, $I_{C_2} = 133.12$ mA, $I_{E_2} = 135.12$ mA **(c)** $Z_i = 0.887\text{ M}\Omega$, $Z_o = 68\ \Omega$ **(d)** $\cong 1$ **(e)** -13.06×10^3

57. $r_e = 21.67\ \Omega$, $\beta r_e = 2.6\text{ k}\Omega$

63. % difference = 4.2, ignore effects

65. % difference = 4.8, ignore effects

67. **(a)** 8.31 Ω **(b)** $h_{fe} = 60$, $h_{ie} = 498.6\ \Omega$ **(c)** $Z_i = 497.47\ \Omega$, $Z_o = 2.2\text{ k}\Omega$ **(d)** $A_v = -264.74$, $A_i \cong 60$ **(e)** $Z_i = 497.47\ \Omega$, $Z_o = 2.09\text{ k}\Omega$ **(f)** $A_v = -250.90$, $A_i = 56.73$

69. **(a)** $Z_i = 9.38\ \Omega$, $Z_o = 2.7\text{ k}\Omega$ **(b)** $A_v = 284.43$, $A_i \cong -1$ **(c)** $\alpha = 0.992$, $\beta = 124$, $r_e = 9.45\ \Omega$, $r_o = 1\text{ M}\Omega$

71. **(a)** 814.8 Ω **(b)** -357.68 **(c)** 132.43 **(d)** 72.9 kΩ

75. **(a)** 75% **(b)** 70%

77. **(a)** 200 μS **(b)** 5 kΩ versus 8.6 kΩ, not a good approximation

79. **(a)** h_{fe} **(b)** h_{oe} **(c)** 30 μS to 0.1 μS **(d)** Mid-region

81. **(a)** Yes **(b)** R_2 not connected as base.

Chapter 6

5. **(a)** 3.5 mA **(b)** 2.5 mA **(c)** 1.5 mA **(d)** 0.5 mA **(e)** As $V_{GS}\downarrow$, $\Delta I_D\downarrow$ **(f)** Nonlinear

15. **(a)** 1.852 mA **(b)** -1.318 V

19. 525 mW

21. 5.5 mA

23. -3 V

25. **(a)** 175 Ω **(b)** 233 Ω **(c)** 252 Ω

29. $V_{GS} = 0$ V, $I_D = 6$ mA; $V_{GS} = -1$ V, $I_D = 2.66$ mA; $V_{GS} = +1$ V, $I_D = 10.67$ mA, $V_{GS} = 2$ V, $I_D = 16.61$ mA; $\Delta I_D = 3.34$ mA versus 6 mA

31. -4.67 V

33. 8.13 V

37. **(a)** $k = 1\text{ mA/V}^2$, $I_D = 1 \times 10^{-3}(V_{GS} - 4\text{ V})^2$ **(c)** $V_{GS} = 2$ V, $I_D = 0$ mA; $V_{GS} = 5$ V, $I_D = 1$ mA; $V_{GS} = 10$ V, $I_D = 36$ mA

39. 1.261

41. $dI_D/dV_{GS} = 2k\,(V_{GS} - V_T)$

Chapter 7

1. **(c)** $I_{D_Q} \cong 4.7$ mA, $V_{DS_Q} \cong 5.54$ V
(d) $I_{D_Q} = 4.69$ mA, $V_{DS_Q} = 5.56$ V

3. (a) $I_D = 2.727$ mA (b) $V_{DS} = 6$ V (c) $V_{GG} = 1.66$ V
5. $V_D = 18$ V, $V_{GS} = -4$ V
7. $I_{D_Q} = 2.6$ mA
9. (a) $I_{D_Q} = 3.33$ mA (b) $V_{GS_Q} \cong -1.7$ V (c) $I_{DSS} = 10.06$ mA (d) $V_D = 11.34$ V (e) $V_{DS} = 9.64$ V
11. $V_S = 1.4$ V
13. (a) $V_G = 2.16$ V $I_{D_Q} \cong 5.8$ mA, $V_{GS_Q} \cong -0.85$ V $V_D = 7.24$ V, $V_S = 6.38$ V $V_{DS_Q} = 0.86$ V (b) $V_{GS} = 0$ V, $V_G = I_D R_S = I_{DSS} R_S$ and $R_S = 216\ \Omega$
15. $R_S = 2.67\ \text{k}\Omega$
17. (a) $I_D = 3.33$ mA (b) $V_D = 10$ V, $V_S = 6$ V (c) $V_{GS} = -6$ V
19. $V_D = 8.8$ V, $V_{GS} = 0$ V
21. (a) $I_{D_Q} \cong 9$ mA, $V_{GS_Q} \cong 0.5$ V (b) $V_{DS} = 7.69$ V, $V_S = -0.5$ V
23. (a) $I_{D_Q} \cong 5$ mA, $V_{GS_Q} \cong 6$ V
25. (a) $V_B = V_G = 3.2$ V (b) $V_E = 2.5$ V (c) $I_E = 2.08$ mA, $I_C = 2.08$ mA, $I_D = 2.08$ mA (d) $I_B = 20.8\ \mu$A (e) $V_C = 5.67$ V, $V_S = 5.67$ V, $V_D = 11.42$ V (f) $V_{CE} = 3.17$ V (g) $V_{DS} = 5.75$ V
27. $V_{GS} = -2$ V, $R_S = 2.4\ \text{k}\Omega$, $R_D = 6.2\ \text{k}\Omega$, $R_2 = 4.3\ \text{M}\Omega$
29. (a) JFET in saturation (b) JFET nonconducting (c) Short from gate to drain (JFET or circuit)
31. JFET in saturation, open circuit between gate and voltage-divider network
33. (a) $I_{D_Q} \cong 4.4$ mA, $V_{GS_Q} \cong -7.25$ V (b) $V_{DS} = -7.25$ V (c) $V_D = -7.25$ V
35. (a) $V_{GS_Q} = -1.96$ V, $I_{D_Q} = 2.7$ mA (b) $V_{DS} = 11.93$ V, $V_D = 13.95$ V, $V_G = 0$ V, $V_S = 2.03$ V
37. (a) $I_{D_Q} = 2.76$ mA, $V_{GS_Q} = -2.04$ V (b) $V_{DS} = 7.86$ V, $V_S = 2.07$ V

Chapter 8

1. 6 mS
3. 10 mA
5. 12.5 mA
7. 2.4 mS
9. $Z_o = 40\ \text{k}\Omega$, $A_v = -180$
11. (a) 4 mS (b) 3.64 mS (c) 3.6 mS (d) 3 mS (e) 3.2 mS
13. (a) 0.75 mS (b) 100 kΩ
15. $g_m = 5.6$ mS, $r_d = 66.67\ \text{k}\Omega$
17. $Z_i = 1\ \text{M}\Omega$, $Z_o = 1.72\ \text{k}\Omega$, $A_v = -4.8$
19. (a) $Z_i = 2\ \text{M}\Omega$, $Z_o = 3.81\ \text{k}\Omega$, $A_v = -7.14$ (b) $Z_i = 2\ \text{M}\Omega$, $Z_o = 4.21\ \text{k}\Omega$, (increased), $A_v = -7.89$ (increased)
21. $Z_i = 10\ \text{M}\Omega$, $Z_o = 730\ \Omega$, $A_v = -2.19$
23. (a) 3.83 kΩ, (b) 3.41 kΩ
25. $Z_i = 9.7\ \text{M}\Omega$, $Z_o = 1.92\ \text{k}\Omega$, $V_o = -210$ mV
27. $Z_i = 9.7\ \text{M}\Omega$, $Z_o = 1.82\ \text{k}\Omega$, $V_o = -198.8$ mV
29. $Z_i = 356.3\ \Omega$, $Z_o = 3.3\ \text{k}\Omega$, $V_o = 28.24$ mV
31. $Z_i = 275.5\ \Omega$, $Z_o = 2.2\ \text{k}\Omega$, $A_v = 5.79$
33. $Z_i = 10\ \text{M}\Omega$, $Z_o = 506.4\ \Omega$, $A_v = 0.745$
35. 11.73 mV
37. $Z_i = 10\ \text{M}\Omega$, $Z_o = 1.68\ \text{k}\Omega$, $A_v = -9.07$
39. $Z_i = 9\ \text{M}\Omega$, $Z_o = 197.6\ \Omega$, $A_v = 0.816$
41. $Z_i = 1.73\ \text{M}\Omega$, $Z_o = 2.15\ \text{k}\Omega$, $A_v = -4.77$
43. −203 mV
45. −3.51 mV
47. $R_S = 180\ \Omega$, $R_D = 2\ \text{k}\Omega$ (standard values)
49. (a) $Z_i = 2\ \text{M}\Omega$, $Z_o = 0.72\ \text{k}\Omega$, $A_{v_{NL}} = 0.733$ (c) $A_{v_L} = 0.552$, $A_{v_s} = 0.552$ (d) $A_{v_L} = 0.670$, A_{v_s} the same (e) A_{v_L} the same, $A_{v_s} = 0.546$ (f) Z_i and Z_o the same
51. From graph $V_{GS_Q} \cong -1.45$ V, $I_{D_Q} \cong 3.7$ mA, $V_D = 9.86$ V, $V_S = 1.44$ V, $V_{DS} = 8.42$ V, $V_G = 0$ V
53. From graph $V_{GS_Q} \cong -1.4$ V, $I_{D_Q} \cong 3.6$ mA, $V_D = 10.08$ V, $V_S = 1.4$ V, $V_{DS} = 8.68$ V, $V_G = 0$ V

55. $Z_i = 10\ \text{M}\Omega$, $Z_o = 2.7\ \text{k}\Omega$
57. $A_{v_1} = -3.77$, $A_{v_2} = -87.2$, $A_{v_T} = 328.74$

Chapter 9

1. **(a)** 3,1.699, -1.151 **(b)** 6.908, 3.912, -0.347 **(c)** Results differ by 2.3
3. **(a)** Same 22.92 **(b)** Same 23.98 **(c)** Same 0.903
5. $G_{dBm} = 43.98$ dBm
7. $G_{dB} = 67.96$ dB
9. **(a)** $G_{dB} = 69.83$ dB **(b)** $G_v = 82.83$ dB **(c)** $R_i = 2\ \text{k}\Omega$ **(d)** $P_o = 1385.64$ V
11. **(a)** $f_L = 1/\sqrt{1 + (1950.43\ \text{Hz}/f)^2}$ **(b)** 100 Hz: $|A_v| = 0.051$; 1k Hz: $|A_v| = 0.456$; 2k Hz: $|A_v| = 0.716$; 5k Hz: $|A_v| = 0.932$; 10k Hz: $|A_v| = 0.982$
(c) $f_L \cong 1950$ Hz
13. **(a)** 10k Hz **(b)** 1k Hz **(c)** 5k Hz **(d)** 100k Hz
15. **(a)** $r_e = 28.48\ \Omega$ **(b)** $A_{v_{\text{mid}}} = -72.91$ **(c)** $Z_i = 2.455\ \text{k}\Omega$ **(d)** $f_{L_s} = 137.93$ Hz, $f_{L_C} = 38.05$ Hz, $f_{L_E} = 85.30$ Hz **(e)** $f_L = f_{L_s} = 137.93$ Hz
17. **(a)** $r_e = 30.23\ \Omega$ **(b)** $A_{v_{\text{mid}}} = 0.983$ **(c)** $Z_i = 21.13\ \text{k}\Omega$ **(d)** $f_{L_s} = 75.32$ Hz, $f_{L_C} = 188.57$ Hz **(e)** $f_L = f_{L_C} = 188.57$ Hz
19. **(a)** $r_e = 28.48\ \Omega$ **(b)** $A_{v_{\text{mid}}} = -72.91$ **(c)** $Z_i = 2.455\ \text{k}\Omega$ **(d)** $f_{L_s} = 103.4$ Hz, $f_{L_C} = 38.05$ Hz, $f_{L_E} = 235.79$ Hz **(e)** $f_L = f_{L_E} = 235.79$ Hz
21. **(a)** $r_e = 30.23\Omega$ **(b)** $A_{v_{\text{mid}}} = 0.983$ **(c)** $Z_i = 21.13\ \text{k}\Omega$ **(d)** $f_{L_s} = 71.92$ Hz, $f_{L_C} = 193.16$ Hz **(e)** $f_L = f_{L_C} = 193.16$ Hz
23. **(a)** $V_{GS_Q} = -2.45$ V, $I_{D_Q} = 2.1$ mA **(b)** $g_m = 1.18$ mS **(c)** $A_{v_{\text{mid}}} = -2$
(d) $Z_i = 1\ \text{M}\Omega$ **(e)** $A_{v_s} = -2$ **(f)** $f_{L_G} = 1.59$ Hz, $f_{L_C} = 4.91$ Hz, $f_{L_S} = 32.04$ Hz
(g) $f_L = f_{L_S} = 32$ Hz
25. **(a)** $V_{GS_Q} = -2.55$ V, $I_{D_Q} = 3.3$ mA **(b)** $g_m = 1.91$ mS **(c)** $A_{v_{\text{mid}}} = -4.39$
(d) $Z_i = 51.94\ \text{k}\Omega$ **(e)** $A_{v_s} = -4.27$ **(f)** $f_{L_G} = 2.98$ Hz, $f_{L_C} = 2.46$ Hz, $f_{L_S} = 41$ Hz
(g) $f_L = f_{L_S} = 41$ Hz
27. **(a)** $f_{H_i} = 277.89$ kHz, $f_{H_o} = 2.73$ mHz **(b)** $f_\beta = 895.56$ kHz, $f_T = 107.47$ MHz
(d) GBP = 18.23 MHz
29. **(a)** $f_{H_i} = 2.87$ MHz, $f_{H_o} = 127.72$ mHz **(b)** $f_\beta = 1.05$ MHz, $f_T = 105$ MHz
(d) GBP = 786.4 kHz
31. **(a)** $g_{m0} = 2$ mS, $g_m = 1.18$ mS **(b)** $A_{v_{\text{mid}}} = A_{v_s} = -2$ **(c)** $f_{H_i} = 7.59$ MHz, $f_{H_o} = 7.82$ MHz **(e)** GBP = 12 MHz
33. $A_{v_T} = 16 \times 10^4$
35. $f'_L = 91.96$ Hz

Chapter 10

1. $V_o = -18.75$ V
3. $V_1 = -40$ mV
5. $V_o = -9.3$ V
7. V_o ranges from 5.5 V to 10.5 V
9. $V_o = -3.39$ V
11. $V_o = 0.5$ V
13. $V_2 = -2$V, $V_1 = 4.2$ V
15. $V_o = 6.4$ V
17. $I_{\text{IB}} = 22$ nA, $I_{\text{IB}} = 18$ nA
19. $A_{\text{CL}} = 80$
21. V_o (offset) = 105 mV
23. CMRR = 75.56 dB

Chapter 11

1. $V_o = -175$ mV, rms
3. $V_o = 412$ mV
7. $V_o = -2.5$ V
11. $I_L = 6$ mA
13. $I_o = 0.5$ mA

13. $I_o = 0.5$ mA
15. $f_{OH} = 1.45$ kHz
17. $f_{OL} = 318.3$ Hz, $f_{OH} = 397.9$ Hz

Chapter 12

1. $P_o = 10.4$ W, $P_o = 640$ mW
3. $P_o = 2.1$ W
5. $R(\text{eff}) = 2.5\ \text{k}\Omega$
7. $a = 44.7$
9. $\%\eta = 37\%$
13. **(a)** Maximum $P_i = 49.7$ W **(b)** Maximum $P_o = 39.06$ W **(c)** Maximum $\%\eta = 78.5\%$
17. **(a)** $P_o = 27$ W **(b)** $P_o = 8$ W **(c)** $\%\eta = 29.6\%$ **(d)** $P_{2Q} = 19$ W
19. $\%D_2 = 14.3\%$, $\%D_3 = 4.8\%$, $\%D_4 = 2.4\%$
21. $\%D_2 = 6.8\%$
23. $P_D = 25$ W
25. $P_D = 3$ W

Chapter 13

9. $V_o = 13$ V
13. Period = 204.8 μs
17. $f_o = 60$ kHz
19. $C = 133$ pF
21. $C_1 = 300$ pF

Chapter 14

1. $A_f = -9.95$
3. $A_f = -14.3$, $R_{of} = 31.5\ \text{k}\Omega$, $R_{of} = 2.4\ \text{k}\Omega$
5. Without feedback: $A_i = -303.2$, $Z_i = 1.18\ \text{k}\Omega$, $Z_o = 4.7\ \text{k}\Omega$
With feedback: $A_{of} = -3.82$, $Z_{of} = 45.8\ \text{k}\Omega$
7. $f_o = 4.2$ kHz
9. $f_o = 1.05$ MHz
11. $f_o = 159.2$ kHz

Chapter 15

1. Ripple factor = 0.028
3. Ripple voltage = 24.2 V
5. $V_r = 1.2$ V
7. $V_r = 0.6$ V rms, $V_{dc} = 17$ V
9. $V_r = 0.12$ V rms
11. $V_m = 13.7$ V
13. $\%r = 7.2\%$
15. $\%r = 8.3\%$, $\%r = 3.1\%$
17. $V_r = 0.325$ V rms
19. $V_o = 7.6$ V, $I_z = 3.66$ mA
21. $V_o = 24.6$ V
25. $I_{dc} = 225$ mA
27. $V_o = 9.9$ V

Chapter 16

3. 33.25 μA
7. $C_D \cong 6.2$ pF, $X_C = 25.67\ \text{k}\Omega$
9. **(a)** -3 V: 40 pF, -12V: 20 pF, $\Delta C = 20$ pF **(b)** -8 V: $\Delta C/\Delta V_R = 2$ pF/V, -2 V: $\Delta C/\Delta V_R = 6.67$ pF/V
11. $C_t \cong 15$ pF, $Q = 354.61$ versus 350 on chart

15. $\cong$ 739.5 kHz
19. **(a)** $\Delta V_{OC}/\Delta f_C = 0.375$ mV/f_C **(b)** 547.5 mV
21. **(a)** 422.8×10^{-21} J **(b)** 305.72×10^{-21} J **(c)** yes
23. 50 V
25. **(a)** $\cong$ 0.9 Ω/fc **(b)** $\cong$ 380 Ω/fc **(c)** $\cong$ 78 kΩ/fc, low-illumination region
27. $V_i = 21$ V
29. As *fc* increases, t_r and t_d decrease exponentially
31. **(a)** $\phi \cong 5$ mW **(b)** 2.27 lm
33. $\phi = 3.44$ mW
37. Lower levels
39. $R = 20$ kΩ
41. R (thermistor) = 90 Ω
43. 1 MHz: 31.83 kΩ; 100 MHz: 318.3 Ω; 1 MHz: $Z_T = -152\ \Omega\angle 0°$; 100 MHz: $Z_T = -137.16\ \Omega\ \angle 26°$; L_S very little effect
45. −62.5 Ω

Chapter 17

5. **(a)** Yes **(b)** No **(c)** No **(d)** Yes, No
9. **(a)** $V_{\text{peak}} = 168.28$ V **(b)** $I_{\text{peak}} = 1.19$ A **(c)** 1.19 A **(d)** 4.17 ms **(e)** 51 ms **(f)** Open **(g)** 23.86 ms **(h)** Turn on **(i)** Forced commutation
13. **(a)** $V_{GK} = -12\text{ V} + \dfrac{R'(24\text{ V})}{R' + R_S}$
(b) 0 V **(c)** 14 kΩ **(d)** 60 mA **(e)** 0.12 mA **(f)** Yes, inductive element in alarm; install protective capacitive element.

15. **(a)** $\cong$ 0.7 MW/cm^2 **(b)** 80.5%
19. 241 pF
21. 153 MΩ $> R_1 >$ 4.875 kΩ
23. **(a)** $R_{B_1} = 5.5$ kΩ, $R_{B_2} = 4.5$ kΩ **(b)** 11.7 V **(c)** OK, 68 kΩ < 166 kΩ
27. **(a)** 1.12 nA/°C
29. **(b)** $\beta_{dc} = 0.4$
31. $\eta = 0.75$, $V_G = 15$ V

INDEX

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