Chapter 10: Power Circuits and Systems

Section 10.9:

Ex. 10.9.2: A class B push-pull amplifier supplies power to a loud speaker of 8 \( \Omega \). The output transformer has a turns ratio \( N_1 : N_2 \) of 4 : 1 and efficiency of 95%. Calculate the following:
1. Maximum power output.
2. Maximum power dissipation in each transistor.
3. Maximum base currents for each transistor.
Assume \( h_{fe} = 15 \) and \( V_{CC} = 24 \) Volts.

Soln.:
Given:
\[ \frac{N_1}{N_2} = 4, \quad \eta \text{ of transformer} = 0.95, \quad V_{CC} = 24 \text{ V}, \quad R_L = 8 \Omega, \quad h_{fe} = 15 \]

To calculate \( P_{ac}(\text{max}) \):

The maximum output power can be obtained by assuming \( V_m = V_{CC} \).

\[ \therefore P_{ac}(\text{max}) = \frac{V_m^2}{2R_L} = \frac{V_{CC}^2}{2R_L} \quad \text{...(1)} \]

But\[ R_L' = \left[ \frac{N_1}{N_2} \right]^2 R_L = (4)^2 \times 8 = 128 \Omega \quad \text{...(2)} \]

\[ \therefore P_{ac}(\text{max}) = \frac{(24)^2}{2 \times 128} = 2.25 \text{ Watt} \quad \text{...(3)} \]

But since the transformer efficiency \( \eta = 0.95 \) the actual output power is given by,

\[ P_o = P_{ac}(\text{max}) \times \eta = 2.25 \times 0.95 = 2.137 \text{ W} \]

\( \ldots \text{Ans.} \)

To calculate the power dissipation:

Maximum power dissipation \[ = \frac{2V_{CC}^2}{\pi R_L' \times \eta} = \frac{2 \times (24)^2}{\pi \times 128} = 0.912 \text{ W.} \]

But this power dissipation corresponds to two transistors. Hence the maximum power dissipation per transistor is given by,

\[ P_{d}(\text{max}) / \text{Transistor} = \frac{0.912}{2} = 0.456 \text{ W} \]

\( \ldots \text{Ans.} \)

To calculate \( I_m \):

We know that,

\[ P_{ac}(\text{max}) = \frac{V_m I_m}{2} = \frac{V_{CC} I_m}{2} \quad \therefore 2.25 = \frac{24 I_m}{2} \]

\[ \therefore I_m = \frac{2.25 \times 2}{24} = 0.1875 \text{ Amp} \]

\( \ldots \text{(4)} \)

To calculate the maximum base current:

\[ I_{b}(\text{max}) = \frac{I_m}{h_{fe}} = \frac{0.1875}{15} = 12.5 \text{ mA} \]

\( \ldots \text{Ans.} \)

Ex. 10.9.3: The maximum ac power supplied to a 4 \( \Omega \) loud speaker by a class B push-pull amplifier is 2 W. Calculate the turns ratio of the transformer if \( V_{CC} = 12 \) V and the transformer is ideal.
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Soln. : 
Given : \( V_{CC} = 12 \text{ V}, \quad P_{ac\ (max)} = 2 \text{ W}, \quad R_L = 4 \Omega \)

We know that the maximum ac power is obtained when \( V_m = V_{CC} \).

\[ P_{ac\ (max)} = \frac{V_m^2}{2R_L} = \frac{V_{CC}^2}{2R_L} \quad \text{∴} \quad R_L' = \frac{V_{CC}^2}{2P_{ac\ (max)}} = \frac{(12)^2}{2 \times 2} = 36 \Omega \quad \text{...(1)} \]

But \( R_L' = \left[ \frac{N_1}{N_2} \right]^2 R_L \)

\[ 36 = \left[ \frac{N_1}{N_2} \right]^2 \times 4 \]

\[ \left[ \frac{N_1}{N_2} \right]^2 = 9 \]

\[ \frac{N_1}{N_2} = 3 \quad \text{...Ans.} \]

Ex. 10.9.4 : For a class B push-pull amplifier operating on a 24 V supply, the collector voltage of each transistor swings from 24 V i.e. \( V_{CC} \) to 4 V, with application of the input signal. Each transistor has the maximum collector dissipation rating of 10 W. Calculate :

1. Output power  
2. DC input power  
3. Collector circuit efficiency. Assume \( \left[ \frac{N_1}{N_2} \right] = 1. \)

Soln. : 
Given : \( V_{CC} = 24 \text{ V}, \quad V_{max} = 24 \text{ V}, \quad V_{min} = 4 \text{ V}, \quad P_{d\ (max)} / \text{transistor} = 10 \text{ W}. \)

To calculate the ac output power and dc power, it is necessary to calculate \( R_L' \).

**Step 1 : Calculate the value of \( R_L' \) :**

\[ P_{d\ (max)} = 2 \times \frac{V_{CC}^2}{\pi^2 R_L'} \]

But, \( P_{d\ (max)} = \frac{2 \times (24)^2}{\pi^2 \times R_L'} \)

\[ \therefore 20 = \frac{2 \times (24)^2}{\pi^2 \times R_L'} \quad \therefore R_L' = 5.84 \Omega \quad \text{...(1)} \]

**Step 2 : Calculate the output power (\( P_{ac} \)) :**

\[ P_{ac} = \frac{V_m^2}{2R_L} = \frac{(V_{max} - V_{min})^2}{2 \times R_L'} = \frac{(24 - 4)^2}{2 \times 5.84} = 34.12 \text{ Watt} \quad \text{...Ans.} \]

**Step 3 : Calculate the dc input power (\( P_{dc} \)) :**

\[ P_{dc} = \frac{V_{CC} \times I_m}{\pi} \]

But, \( I_m = \frac{V_m}{R_L'} = \frac{(24 - 4)}{5.84} = 3.42 \text{ Amp.} \)

\[ \therefore P_{dc} = \frac{24 \times 2 \times 3.42}{\pi} = 52.32 \text{ Watt} \quad \text{...Ans.} \]
Step 4: To calculate the % efficiency:

\[
\% \eta = \frac{P_{ac}}{P_{dc}} \times 100 = \frac{34.12}{52.32} \times 100 = 65.22\% \quad \text{...Ans.}
\]

Ex. 10.9.7: A single transistor operates as an ideal class B amplifier. The dc current drawn by the transistor from the supply is 20 mA. Calculate the amount of ac power delivered to the load if load resistance is 1 kΩ.

Soln.:
Given: \(I_{dc} = 20\) mA, \(R_L = 1\) kΩ

Steps to be followed:

Step 1: Calculate the value of \(I_m\) from \(I_{dc}\) as \(I_{dc} = \frac{I_m}{\pi}\).

Step 2: Then calculate the output power \(P_{ac} = \frac{I_m^2 R_L}{2}\).

\[I_{dc} = \frac{1}{2} \frac{\pi}{2 \pi} \int_0^{\pi} I_m \sin \omega t \, dt = \frac{-I_m}{2 \pi} \left[ \cos \omega t \right]_0^\pi = \frac{-I_m}{2 \pi} \left[ \cos \pi - \cos 0 \right] = \frac{-I_m}{\pi} (-1 - 1) = \frac{I_m}{\pi}\]

\[I_{ac} = I_{dc} \times \pi = 20\, \text{mA} \times \pi = 62.63\, \text{mA}\]

\[P_{ac} = \frac{I_{L_{rms}}^2}{2} R_L\]

- From the current waveform of Fig. P.10.9.7, we can calculate \(I_{L_{rms}}\) as follows:

\[I_{L_{rms}} = \left[ \frac{1}{2 \pi} \int_0^{2 \pi} \left( \frac{1}{4 \pi} I_m^2 \sin^2 \omega t \, dt \right) \right]^{1/2} = \left[ \frac{1}{2 \pi} \int_0^{2 \pi} \frac{1 - \cos 2\omega t}{2} \, dt \right]^{1/2} = \frac{I_m}{2} \left[ \frac{1}{\pi} \left( \pi - 0 \right) \right] = I_m / 2\]
Substitute Equation (4) into (3) to get,
\[
P_{ac} = \left( \frac{I_m}{2} \right)^2 R_L = \frac{I_m^2 R_L}{4}
\]
\[
= \frac{(62.83 \times 10^{-3})^2 \times 1 \times 10^3}{4} = 0.985 \text{ W} \quad \ldots \text{Ans.}
\]

**Ex. 10.9.8:** For an ideal class B push-pull amplifier show that the maximum output power can be as high as five times the maximum power dissipation in each transistor.

**Soln.:** We are expected to prove the following relation:

\[
P_{ac(\max)} = 5 P_{d(\max)} \text{ per transistor}
\]

Referring to Equation (10.9.14) we can write that,

\[
P_{ac(\max)} = \frac{V_{CC}^2}{2 R_L}
\]

Referring to Equation (10.9.15) we can write that,

\[
P_{d(\max)} \text{ per transistor} = \frac{2}{\pi^2} P_{ac(\max)}
\]

\[
\therefore P_{ac(\max)} = \frac{2}{2} P_{d(\max)} \text{ per transistor} = 4.934 P_{d(\max)} \text{ per transistor}
\]

\[
\therefore P_{ac(\max)} \approx 5 P_{d(\max)} \text{ per transistor}
\]

Hence proved.

**Section 10.12:**

**Ex. 10.12.1:** A complementary push-pull amplifier has capacitive coupled load \(R_L = 8\Omega\), supply voltage \(\pm 12\text{ V}\) calculate:
1. \(P_{ac(\max)}\)
2. \(P_D\) of each transistor
3. Efficiency

**Soln.**

**Step 1:** To calculate \(P_{ac(\max)}\):

\[
P_{ac(\max)} = \frac{V_m^2}{2 R_L}
\]

Substitute \(V_m = V_{CC}\) to get,

\[
P_{ac(\max)} = \frac{V_{CC}^2}{2 R_L} = \frac{(12)^2}{2 \times 8} = 9 \text{ Watt} \quad \ldots \text{Ans.}
\]

**Step 2:** To calculate \(I_m\):

\[
I_m = \frac{V_m}{R_L}
\]

\[
\frac{V_{CC}}{R_L} = \frac{12}{8} = 1.5 \text{ Amp}
\]

**Step 3:** To calculate \(P_D\):

\[
P_D = \frac{2 V_{CC} I_m}{\pi}
\]

\[
= \frac{2 \times 12 \times 1.5}{\pi} = 11.46 \text{ W}
\]

**Fig. P. 10.12.1:** Given circuit
Step 4: To calculate efficiency:
\[ \% \eta = \frac{P_{ac}}{P_{dc}} \times 100 = \frac{9}{11.46} \times 100 = 78.5 \% \] ...Ans.

Step 5: To calculate P_d of each transistor:
Total Power dissipation \[ P_d = P_{dc} - P_{ac} \]
\[ = 11.46 - 9 = 2.46 \text{ W} \] ...Ans.
\[ \therefore P_d \text{ per transistor} = \frac{2.46}{2} = 1.23 \text{ W} \] ...Ans.

Ex. 10.12.2: The circuit shown in Fig. P. 10.12.2 operates with a sinusoidal input.
Calculate:
1. Maximum A.C. power output.
2. Power dissipation in each transistor.
3. Conversion efficiency at maximum power output.

Soln.:
As only a single supply is being used, we have to use all the expressions derived for the complementary symmetry with a substitution of \( V_{cc} = V_{cc}/2 \).

Step 1: Maximum A.C. power output \( P_{ac\ (max)} \):
\[ P_{ac} = \frac{V_m^2}{2 R_L} \]
To obtain \( P_{ac\ (max)} \) we substitute \( V_m = V_{cc} \)
But here we will substitute \( V_m = V_{cc}/2 \)
\[ \therefore P_{ac\ (max)} = \frac{(V_{cc}/2)^2}{2 R_L} \]
\[ = \frac{V_{cc}^2}{8 R_L} \times \frac{(20)^2}{8 \times 8} = 6.25 \text{ Watt} \] ...Ans.

Step 2: Power dissipation in each transistor:
We know that,
\[ P_d\ (\text{max}) \text{ per transistor} = \frac{2}{\pi} P_{ac\ (max)} \]
\[ \therefore P_d\ (\text{max}) \text{ per transistor} = \frac{2}{\pi} \times 6.25 = 1.26 \text{ W} \] ...Ans.
\[ \therefore \text{ Total power dissipation} = 1.26 \times 2 = 2.53 \text{ W} \]

Step 3: Efficiency:
\[ \eta = \frac{P_{ac\ (max)}}{P_{ac\ (max)} + P_d} = \frac{6.25}{6.25 + 2.53} = 0.7115 = 71.15\% \] ...Ans.
Ex. 10.12.3: An ideal class B complementary symmetry push pull amplifier operates with $V_{CC} = 12\, \text{V}$ and $R_L = 5\, \Omega$. If the input is sinusoidal, calculate:

1. Maximum power output.
2. Power dissipation in both transistors.
3. Power dissipation in each transistor.
4. Conversion efficiency for maximum output.

Soln.: This example is similar to Ex. 10.12.2.

1. Maximum ac power $P_{ac\, (max)}$:
   \[
P_{ac\, (max)} = \frac{V_{CC}^2}{8R_L} = \frac{(12)^2}{8 \times 5} = 3.6\, \text{W}
   \]
   ...Ans.

2. Maximum power dissipation in both the transistors:
   \[
P_{d\, (max)} = \frac{4}{\pi} P_{ac\, (max)} = \frac{4}{\pi} \times 3.6 = 1.46\, \text{W}
   \]
   ...Ans.

3. Maximum power dissipation per transistor:
   \[
P_{d\, (max)\, /\, \text{transistor}} = 1.46 \div 2 = 0.73\, \text{W}
   \]
   ...Ans.

4. Efficiency:
   \[
   \% \, \eta = \frac{P_{ac\, (max)}}{P_{ac\, (max)} + P_{d\, (max)}} \times 100 = \frac{3.6}{5.06} \times 100 = 71.15\%
   \]
   ...Ans.

Ex. 10.12.4: A series fed class A amplifier shown in Fig. P. 10.12.4, operates from D.C. source and applied sinusoidal input signal generates peak base current 9 mA. Calculate

1. Quiescent current $I_{CQ}$
2. Quiescent voltage $V_{CEQ}$
3. D.C. input power $P_{DC}$
4. A.C. output power $P_{AC}$
5. Efficiency.

Assume $\beta = 50$ and $V_{BE} = 0.7\, \text{V}$.

Soln.:

1. $I_{BQ} = \frac{V_{CC} - V_{BE}}{R_B} = \frac{20 - 0.7}{1.5 \times 10^3} = 12.867\, \text{mA}$
2. $I_{CQ} = \beta \times I_{BQ} = 50 \times 12.867 = 643.33\, \text{mA}$ ...Ans.

Fig. P. 10.12.4: Given circuit

3. $V_{CESQ} = V_{CC} - I_{CQ}R_C = 20 - (0.6433 \times 16) = 9.7 \ldots \text{Ans.}$
4. DC input power \[ P_{DC} = V_{CC} \times I_{CQ} = 20 \times 0.6433 = 12.866 \text{ W} \] ...Ans.

5. AC output power \[ P_{AC} = I_{C_{rms}}^2 \times R_C \]
   \[ I_{b_{peak}} = 9 \text{ mA} = 50 \times 9 = 540 \text{ mA} \]
   \[ \therefore I_{C_{rms}} = \frac{I_{C_{(peak)}}}{\sqrt{2}} = 381.83 \text{ m} \]
   \[ \therefore P_{AC} = (0.3818)^2 \times 16 = 2.3328 \text{ W} \] ...Ans.

6. Efficiency \[ \eta = \frac{P_{AC}}{P_{DC}} = \frac{2.3328}{12.866} = 0.1813 \text{ or } 18.13\% \] ...Ans.

Ex. 10.12.5: A class B push-pull amplifier supplies power to a resistive load of 12 \( \Omega \). The output transformer has a turns ratio of 3 : 1 and efficiency of 78.5\%. Obtain:
1. Maximum power output.
2. Maximum power dissipation in each transistor.
3. Maximum base and collector current for each transistor.
Assume \( h_{fe} = 25 \) and \( V_{CC} = 20 \text{ V} \).

Soln.:
Given:
\[ [N_1 : N_2] = 4, \eta \text{ of transformer } = 0.785 \]
\( V_{CC} = 20 \text{ V}, R_L = 12 \Omega \) and \( h_{fe} = 25 \)

Step 1: Calculate \( P_{ac\ (max)} \):
The maximum output power can be obtained by assuming \( V_{in} = V_{CC} \).
\[ \therefore P_{ac\ (max)} = \frac{V_{in}^2}{2 R_L} = \frac{V_{CC}^2}{2 R_L} \]
But \( R_L' = [N_1 / N_2]^2 R_L = (3)^2 \times 12 = 108 \Omega \)
\[ \therefore P_{ac\ (max)} = \frac{(20)^2}{108} = 3.7 \text{ W} \] ...Ans.

Step 2: Maximum power dissipation:
\[ P_{d\ (max)} = \frac{2 V_{CC}^2}{\pi^2 R_L'} = \frac{2 \times (20)^2}{\pi^2 \times 108} = 0.75 \text{ W} \]
\[ \therefore P_{d\ (max)} \text{ per transistor } = 0.75 / 2 = 0.375 \text{ W} \] ...Ans.

Step 3: Calculate \( I_{in} \):
We know that \[ P_{ac\ (max)} = \frac{V_{in} I_{in}}{2} = \frac{V_{CC} I_{in}}{2} \]
\[ \therefore 3.7 = \frac{20 \times I_{in}}{2} \]
\[ \therefore I_{in} = 0.37 \text{ Amp} \]

Step 4: Calculate the maximum base current:
Ex. 10.12.6: For the transformer coupled class A circuit shown in Fig. P. 10.12.6 calculate the maximum efficiency. Assume 1. the device to be ideal and 2. $R_B$ is adjusted for maximum input swings. 

![Fig. P. 10.12.6]

$I_{b \text{ max}} = \frac{I_m}{h_{fe}} = \frac{0.37}{25} = 14.8 \text{ mA}$  

**Soln.** Please Refer section 10.7.1.

Ex. 10.12.7: In a class B amplifier $V_{CE \text{ (min)}} = 1 \text{ Volt}$ and the supply voltage $V_{CC} = 18 \text{ V}$. Calculate the collector efficiency.

**Soln.** As proved in section 10.9.2,

Efficiency $\eta = \frac{P_{ac}}{P_{dc}} = \frac{\frac{V_m I_m}{2}}{\frac{\pi V_m}{4V_{CC}}} = \frac{\pi V_m}{2 V_{CC} I_m} = \frac{\pi}{4} \frac{V_m}{V_{CC}}$

But $V_m = V_{CC} - V_{CE \text{ (min)}} = 18 - 1 = 17 \text{ V}$

$\therefore \eta = \frac{\pi \times 17}{4 \times 18} = 0.7417 \text{ or } 74.17\%$  

Ex. 10.12.9: A single transistor amplifier with transformer coupled load produces harmonic amplitudes in the output as,

- $B_0 = 1.5 \text{ mA}$
- $B_1 = 120 \text{ mA}$
- $B_2 = 10 \text{ mA}$
- $B_3 = 4 \text{ mA}$
- $B_4 = 2 \text{ mA}$
- $B_5 = 1 \text{ mA}$

1. Determine the percentage total harmonic distortion
2. Assume a second identical transistor is used alongwith a suitable transformer to provide push-pull operation.

Use the above harmonic amplitudes to determine the new total harmonic distortion.

**Soln.**

**Part (i)**

Second harmonic distortion $D_2 = \frac{|B_2|}{|B_1|} = \frac{10}{120} = 0.0833$
Third harmonic distortion

\[ D_3 = \left| \frac{B_3}{B_1} \right| = \frac{4}{120} = 0.0333 \]

Fourth harmonic distortion

\[ D_4 = \left| \frac{B_4}{B_1} \right| = \frac{2}{120} = 0.0166 \]

Fifth harmonic distortion

\[ D_5 = \left| \frac{B_5}{B_1} \right| = \frac{1}{120} = 8.33 \times 10^{-3} \]

Hence percentage total harmonic distortion

\[ D = \sqrt{D_2^2 + D_3^2 + D_4^2 + D_5^2} \times 100 \]

\[ = \sqrt{(0.0833)^2 + (0.0333)^2 + (0.0166)^2 + (8.33 \times 10^{-3})^2} \times 100 \]

\[ = 0.09165 \times 100 = 9.165 \% \]

**Part (ii)**

When a second transistor is used, all the even harmonic components are automatically cancelled out. So the THD is given by,

\[ D = \sqrt{D_3^2 + D_5^2} \times 100 \]

\[ = \sqrt{(0.0333)^2 + (8.33 \times 10^{-3})^2} \times 100 = 3.4326 \% \]

**Ex. 10.12.10:** A transformer coupled class A, AF power amplifier uses an ideal output transformer having a load resistance of 1.5 \( \Omega \) on its secondary side. If the amplifier is to deliver maximum power output of 3 W to the load when the collector supply voltage is 15 V, determine:

1. Turns ratio of output transformer.
2. Power transistor ratings required.
3. DC power input to the amplifier.

**Soln.**:

**Given**:

\[ R_L = 1.5 \Omega, \quad P_{ac} = 3 \text{ W}, \quad V_{CC} = 15 \text{ V}. \]

**Turns ratio of the output transformer**:

The maximum output power is given by,

\[ P_{ac (\text{max})} = \frac{(V_{im})^2}{2 R'_L} \]

where

\[ V_{im} = \text{Maximum primary voltage} = V_{CC} \]

\[ R'_L = \text{Reflected load resistance on the primary side}. \]
\[
P_{ac\ (max)} = \frac{V_{cc}^2}{2R_L'}
\]
\[
R_L' = \frac{(15)^2}{2 \times 3} = 37.5 \ \Omega \quad \text{(1)}
\]

We know that,
\[
\frac{R_L'}{R_L} = \left[ \frac{N_1}{N_2} \right]^2 \quad \therefore \quad \left[ \frac{N_1}{N_2} \right]^2 = \frac{37.5}{15} = 25
\]
\[
\therefore \quad \text{The turns ratio} \quad \frac{N_1}{N_2} = 5 \quad \text{...Ans.}
\]

Power dissipation of the transistor:
\[
P_{d\ (max)} = V_{cc}I_{CQ}
\]
But \( I_{CQ} = \frac{V_{cc}}{R_L'} = 0.4 \)
\[
\therefore \quad P_{d\ (max)} = 15 \times 0.4 = 6.0 \text{ W} \quad \text{...Ans.}
\]

DC input power to the amplifier:
\[
P_{DC} = V_{cc}I_{CQ} = 15 \times 0.4 = 6 \text{ W} \quad \text{...Ans.}
\]

\textbf{Ex. 10.12.11:} A push-pull class B, AF power amplifier uses ideal output transformer whose primary has a total of 160 turns and whose secondary has 40 turns. It must be capable of delivering 40W to 8 \( \Omega \) load under maximum power conditions. What is the minimum possible value \( V_{cc} \)?

\textbf{Soln. :}

\begin{itemize}
  \item \textbf{Given:} \quad \frac{N_1}{N_2} = 4, \quad P_{ac\ (max)} = 40W, \quad R_L = 8 \Omega
\end{itemize}

We know that for a push-pull class B amplifier,
\[
P_{ac\ (max)} = \frac{V_m^2}{2R_L'}
\]
where \( V_m = V_{cc} \) and \( R_L' = \left( \frac{N_1}{N_2} \right)^2 R_L \).
\[
\therefore \quad P_{ac\ (max)} = \frac{V_{cc}^2}{2 \times \left( \frac{N_1}{N_2} \right)^2 R_L}
\]
\[
\therefore \quad V_{cc}^2 = 2 \times (4)^2 \times 8 \times 40 = 10240
\]
\[
\therefore \quad V_{cc} = 101.19 \text{ Volts} \quad \text{...Ans.}
\]

Thus the minimum required \( V_{cc} \) is 101.19 Volts.
Ex. 10.12.12 : Derive the expression for power dissipation rating of a transistor operated as class A and class B amplifier and show that class B can deliver 5 times the output power than class A. A complimentary symmetry amplifier supplies output to a load of 3 \( \Omega \) from supply voltage of 20V. Calculate maximum power output and rating of transistors.

Soln. :

Part I :

1. We know that for a class A amplifier
   \[
   P_{ac \ (max)} = 0.5 \frac{V_{CC}}{2} I_{CQ} \]
   and the maximum power dissipation is given by,
   \[
   P_{d \ (max)} = V_{CC} I_{CQ} \]
   As there are two transistors in a class A push-pull amplifier.
   Maximum power dissipation/transistor = 0.5 \( \frac{V_{CC}}{2} I_{CQ} \) = 0.5 \( P_{d \ (max)} \). Therefore, for a class A amplifier,
   \[
   P_{ac \ (max)} = \text{Maximum power dissipation per transistor} \]
   ...(3)

2. For a class B push pull amplifier
   \[
   P_{d \ (max) \ per \ transistor} = \frac{2}{\pi} P_{ac \ (max)} \]
   \[
   \therefore \ P_{ac \ (max)} = \frac{\pi^2}{2} P_{d \ (max) \ per \ transistor} = 4.934 P_{d \ (max) \ per \ transistor} \]
   \[
   \therefore \ P_{ac \ (max)} \approx 5 P_{d \ (max) \ per \ transistor} \]
   But, from Equation (3), \( P_{d \ (max) \ per \ transistor} = P_{ac \ (max)} \) of class A amplifier hence Equation (4) gets modified as :
   \[
   P_{ac \ (max)} \ of \ class \ B = 5 \times P_{ac \ (max)} \ of \ class \ A \]
   ...Proved.

Part II : Given : A complimentary symmetry amplifier, \( R_L = 3 \ \Omega \), \( V_{CC} = 20 \text{V} \).

Maximum output power :

\[
P_{ac \ (max)} = \frac{V_{CC}^2}{2 R_L} = \frac{(20)^2}{2 \times 3} = 66.66 \text{ W} \]

Maximum power rating of transistor :

\[
I_m = \frac{V_m}{R_L} = \frac{V_{CC}}{R_C} = \frac{20}{3} = 6.66 \text{ Amp.} \]

\[
P_{dc} = \frac{2 V_{CC} I_m}{R_L} = \frac{2 \times 20 \times 6.66}{\pi} = 84.88 \text{ W.} \]

\[
\therefore \ \text{Total power dissipation} = P_{dc} - P_{ac} = 84.88 - 66.66 = 18.22 \text{ W} \]

\[
\therefore \ \text{Power dissipation per transistor} = \frac{18.22}{2} = 9.11 \text{ W} \]
...Ans.
Ex. 10.12.13: The reflected load resistance of a push-pull amplifier is 4Ω. It draws a current of 3.25 Amp from 24 V d.c. power supply with sinusoidal input. Calculate: 1. a.c. power output. 2. Conversion efficiency. 3. Minimum dissipation rating of each transistor.

Soln.: 

Given: \( R'_L = 4 \Omega \), \( I_{dc} = 3.25 \text{ Amp.}, \) \( V_{CC} = 24 \text{ V} \).

AC output power \( P_{ac} \):

\[
P_{ac} = I_{rms}^2 R'_L \quad \text{...(1)}
\]

But \( I_{dc} = \frac{2 I_{lm}}{\pi} \)

:\: Peak primary current \( I_{lm} = \frac{\pi}{2} I_{dc} = \frac{\pi}{2} \times 3.25 = 5.1 \text{ Amp.} \)

\: RMS primary current \( I_{rms} = \frac{I_{lm}}{\sqrt{2}} = 3.6 \text{ Amp.} \)

Substituting this value into Equation (1) we get,

\[
P_{ac} = (3.6)^2 \times 4 = 52.12 \text{ Watts} \quad \text{...Ans.}
\]

Conversion efficiency (\( \eta \)):

DC input power \( P_{DC} = V_{CC} \times I_{dc} = 24 \times 3.25 = 78 \text{ W} \)

Efficiency \( \eta = \frac{P_{ac}}{P_{DC}} = \frac{52.123}{78} = 0.6682 \) or 66.82% \( \text{...Ans.} \)

Minimum dissipation rating of each transistor:

Total power dissipation \( P_d = P_{DC} - P_{ac} = 78 - 52.12 = 25.88 \text{ W} \)

\: Minimum dissipation rating per transistor = \( \frac{25.88}{2} = 12.94 \text{ W} \) \( \text{...Ans.} \)

Ex. 10.12.14: Explain three point method to obtain second harmonic distortion in a power amplifier. A sinusoidal signal \( V_s = 1.75 \sin 600t \) is fed to a power amplifier. The resulting output current is:

\( I_o = 15 \sin 600t + 1.5 \sin 1200t + 1.2 \sin 1800t + 0.5 \sin 2400t \). Calculate percentage increase in power due to distortion. Draw circuit diagram of complementary symmetry power amplifier with a driver circuit using transistors and explain its operation in brief.

Soln.:

1. The output current is given by,

\[
I_o = 15 \sin 600t + 1.5 \sin 1200t + 1.2 \sin 1800t + 0.5 \sin 2400t.
\]

Comparing this expression with the following ,

\[
I_o = A_1 \sin \omega t + A_2 \sin 2\omega t + A_3 \sin 3\omega t + A_4 \sin 4\omega t.
\]
We get the amplitudes of various harmonic components $A_1$, $A_2$, $A_3$ and $A_4$ as:

$A_1 = 15$, $A_2 = 1.5$, $A_3 = 1.2$, $A_4 = 0.5$.

2. The percentage $n^{th}$ harmonic distortion is given by,

$$% \text{n}^{th} \text{harmonic distortion} = % D_n = \left| A_n \right| \left| A_1 \right| \times 100$$

$\therefore$ Second order distortion, $D_2 = \left| A_2 \right| \left| A_1 \right| = \frac{1.5}{15} = 0.1$

Third order distortion, $D_3 = \left| A_3 \right| \left| A_1 \right| = \frac{1.2}{15} = 0.08$

Fourth order distortion, $D_4 = \left| A_4 \right| \left| A_1 \right| = \frac{0.5}{15} = 0.0333$.

3. Let the power delivered to the load without distortion be $P$. Hence the load power when distortion is considered is given by,

$$P' = P (1 + D^2)$$

where $D = \text{Total harmonic distortion}$.

$$D = D_2^2 + D_3^2 + D_4^2 + ......$$

$$\therefore P' = P (1 + D_2^2 + D_3^2 + D_4^2) = P \left[ 1 + (0.1)^2 + (0.08)^2 + (0.0333)^2 \right]$$

$$\therefore P' = \left[ 1.0175 \right] P$$

4. Percent increase in load power $\frac{P' - P}{P} \times 100 = \frac{1.0175 P - P}{P} \times 100 = 1.75\% \hspace{1cm} \text{...Ans.}$

For complementary symmetry power amplifier with a driver circuit refer section 10.9.7.

Ex. 10.12.15: A single stage common-emitter A.F. power amplifier, working in class-A condition, supplies 2 W to 4 kΩ load. The zero signal D.C. collector current is 35 mA and D.C. collector current with signal is 39 mA. Determine the percentage of second harmonic distortion in the output.

Soln.:

Given : $I_{CQ} = 35 \text{ mA} \ldots \text{when the signal is absent}$

1. When the signal is present

$$I_c = I_{CQ} + A_o = 39 \text{ mA}$$

$$\therefore A_o = 39 - 35 = 4 \text{ mA} = A_2 = 4 \text{ mA}$$

2. Now

$$P_{ac} = \left[ \frac{A_1^2}{2} + \frac{A_2^2}{2} \right] R_L = \frac{1}{2} R_L (A_1^2 + A_2^2)$$

$$\therefore 2 = \frac{1}{2} \times 4 \times 10^{-3} \left[ A_1^2 + (4 \times 10^{-3})^2 \right]$$
Let \( A_1 = 0.0313 \text{ Amp or } 31.368 \text{ mA} \).

The second harmonic distortion is given by,
\[
\% D_2 = \left| \frac{A_2}{A_1} \right| \times 100 = \frac{4}{31.368} \times 100 = 12.7\% \quad \text{Ans.}
\]

**Ex. 10.12.16:** For a class A amplifier shown in the Fig. P. 10.12.16(a) transformer turns ratio 8 : 1. The transformer has an efficiency of 90\% and d.c. resistance of 10 \( \Omega \) for the primary. Transistor has \( \beta = 20 \) and \( V_{BE} = 0.5 \text{ V} \). Determine:

(a) Maximum power delivered to the load.
(b) Circuit efficiency.

**Soln. :**

**Step 1 : Draw the Thevenin's equivalent circuit :**

The Thevenin's equivalent circuit is as shown in Fig. P. 10.12.16(b).

\[
V_{TH} = \frac{R_1}{R_1 + R_2} \cdot V_{CC} = \frac{100}{100 + 1000} \cdot 25 = 2.27 \text{ V}
\]

\[
R_B = R_1 \parallel R_2 = 100 \parallel 1000 = 91 \Omega
\]

**Step 2 : Calculate \( I_B \) :**

Applying KVL to the base loop we get,
\[
V_{TH} = I_B R_B + V_{BE} + I_E R_E
\]
\[ V_{TH} = (I_B \times 91) + 0.5 + [ (1 + \beta)I_B \times 10 \Omega] \quad \therefore 2.27 = I_B (91 + 210) + 0.5 \]
\[ \therefore I_B = 5.88 \text{ mA} \quad \ldots(1) \]

**Step 3 : Calculate \( I_E \) and \( V_B \):**

\[ I_E = (1 + \beta)I_B = 21 + 5.88 \text{ mA} = 123.48 \text{ mA or 0.12348 A} \quad \ldots(2) \]

The base voltage \( V_b \) is given by,

\[ V_B = V_{BE} + I_E R_E = 0.5 + (0.12348 \times 10) = 1.7348 \text{ V} \quad \ldots(3) \]

**Step 4 : Calculate current \( I_1 \) through \( R_1 \) and \( I_C \):**

\[ I_1 = \frac{V_{CC} - V_B}{R_1} = \frac{25 - 1.7348}{1 \Omega} = 23.2652 \text{ mA} \quad \ldots(4) \]

and

\[ I_C = \beta I_b = 20 \times 5.88 \text{ mA} = 117.6 \text{ mA} \quad \ldots(5) \]

**Step 5 : Calculate the dc input power :**

Total dc input power \( P_{DC} = (I_C + I_1) \times V_{CC} \)
\[ = (23.2652 + 117.6) \text{ mA} \times 25 = 3.5216 \text{ W} \quad \ldots(6) \]

**Step 6 : Calculate maximum power delivered to the load :**

The reflected load resistance to the primary is

\[ R_L' = \frac{R_L}{n^2} = R_L \times \left( \frac{N_1}{N_2} \right)^2 = 5 \times \left( \frac{8}{1} \right)^2 = 320 \Omega \]

For maximum power delivered to the load, calculate the maximum value of primary voltage.

\[ V_{1m} = V_{CEQ} \]

To calculate \( V_{CEQ} \) apply KVL to the collector loop of Fig. P. 10.12.6(b).

\[ V_{CC} = (I_C \times 10 \Omega) + V_{CEQ} + 10I_E \]

\[ \therefore V_{CEQ} = 25 - (0.1176 \times 10) - (0.12348 \times 10) = 22.59 \text{ volts} \]

\[ \therefore \text{ Maximum primary power} \]

\[ P_{1{(\text{max})}} = \frac{1}{2} \frac{V_{1m}^2}{R_L'} = \frac{1}{2} \times \frac{(22.59)^2}{320} = 0.7974 \text{ W} \]

The maximum load power is given by,

\[ P_{ac{(\text{max})}} = \eta_{\text{Transformer}} \times P_{1{(\text{max})}} = 0.9 \times 0.7974 = 0.7176 \text{ W} \]
Step 7 : Calculate efficiency :
\[
\% \eta = \frac{P_{ac}^{\text{max}}}{P_{dc}} \times 100 = \frac{0.7176}{3.5216} \times 100 = 20.38 \% \quad \text{...Ans.}
\]

Ex. 10.12.17 : The collector characteristics of a power transistor are as follows :

<table>
<thead>
<tr>
<th>( V_{CE} ) (volts)</th>
<th>( I_c ) (Amp)</th>
<th>( I_c ) (Amp)</th>
<th>( I_c ) (Amp)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>for ( I_b = 5 ) mA</td>
<td>for ( I_b = 10 ) mA</td>
<td>for ( I_b = 20 ) mA</td>
</tr>
<tr>
<td>1</td>
<td>0.32</td>
<td>0.62</td>
<td>1.25</td>
</tr>
<tr>
<td>5</td>
<td>0.38</td>
<td>0.70</td>
<td>1.38</td>
</tr>
<tr>
<td>10</td>
<td>0.40</td>
<td>0.75</td>
<td>1.48</td>
</tr>
<tr>
<td>15</td>
<td>0.42</td>
<td>0.82</td>
<td>1.58</td>
</tr>
<tr>
<td>20</td>
<td>0.48</td>
<td>0.90</td>
<td>-</td>
</tr>
</tbody>
</table>

This transistor is used in a transformer coupled class B push-pull amplifier with \( V_{CC} = 20 \) V, reflected load \( R'_L = 15 \) ohms. If a sinusoidal input signal of 20 mA peak is applied to the transistor amplifier calculate :

(a) AC power output 
(b) Collector circuit efficiency. 
(c) % Third harmonic distortion.

Soln. :

Given : \( V_{CC} = 20 \) V, \( R'_L = 15 \) \( \Omega \), input current = 20 mA peak

Type of amplifier : Transformer coupled class B.

Step 1 : Draw the characteristics of power transistor :

- The characteristics of power transistor is shown in Fig. P. 10.12.17.
- The operation is class B, so the co-ordinates of Q point are (20 V, 0 A) and it is on the x-axis.
- The dc load line is a vertical line passing through the Q point. Thus line is parallel to y-axis.
- Draw the ac load line. The ac load line passes through the Q point and its slope is \((-1/R'_L)\). The equation for ac load line is,

\[
I_c = \frac{-1}{R'_L} \times V_{CE} + C \quad \text{...(1)}
\]

At Q point, \( I_c = 0 \) and \( V_{CE} = V_{CC} = 20 \) V, whereas \( R'_L = 15 \) \( \Omega \).

\[
\therefore \quad 0 = \frac{-20}{15} + C \quad \therefore \quad C = 1.33 \quad \text{...(2)}
\]

At \( V_{CE} = 0 \),

\[
I_c = -0 + 1.33 \quad \therefore \quad I_c = 1.33 \text{ mA} \quad \text{...(3)}
\]
So the second point through which the ac load line passes through is \((0, 1.33 \text{ A})\).

The input signal is \(I_b = 20 \text{ mA} \) (peak). The point of intersection of the characteristics for \(I_b = 20 \text{ mA}\) and the ac load line is obtained as point A. Its co-ordinates are \((1.2 \text{ V}, 1.26 \text{ A})\) from the graph.

I\(_C\) corresponding to point A is 1.26 A and V\(_{CE}\) is 2.2 volts.

So as shown in Fig. P. 10.12.17 maximum output voltage is \(V_m = 20 - 1.2 = 18.8 \text{ volts}\) and \(I_m = 1.26 \text{ A}\).

**Fig. P. 10.12.17**

**Step 2 : Calculate the third harmonic distortion :**

- We will use the five point method for calculating the third harmonic distortion.

\[ D_3 = \frac{|B_3|}{|B_1|} \]

- For a class B operation, the even order harmonics \(B_2\) and \(B_4\) are absent and the dc value \(B_0\) and \(I_{CQ}\) is zero.

- Substituting these values we get,
\[ I_{\text{max}} = I_{CQ} + B_0 + B_1 + B_2 + B_3 + B_4 = B_1 + B_3 \quad \ldots(1) \]

and \[ I_{1/2} = I_{CQ} + B_0 + 0.5 B_1 - 0.5 B_2 - B_3 - 0.5 B_4 = 0.5 B_1 - B_3 \quad \ldots(2) \]

- Adding Equations (1) and (2) we get,

\[ I_{\text{max}} + I_{1/2} = 1.5 B_1 \]

\[ \therefore B_1 = \frac{I_{\text{max}} + I_{1/2}}{1.5} = \frac{1.26 + 0.7}{1.5} = 1.3 \]

And from Equation (1)

\[ B_3 = I_{\text{max}} - B_1 = 1.26 - 1.3 = -0.04 \]

So the third harmonic distortion is given by,

\[ D_3 = \left| \frac{B_3}{B_1} \right| = \frac{0.04}{1.3} = 0.03076 \text{ or } 3.076\% \]

**Step 3 : Calculate ac power :**

\[ P_{\text{dc}} = \frac{V_m I_m}{2} = \frac{18.8 \times 1.26}{2} = 11.844 \text{ W} \quad \ldots\text{Ans.} \]

**Step 4 : Calculate dc power and efficiency :**

\[ P_{DC} = V_{CC} \times I_{dc} = V_{CC} \times \frac{2 I_m}{\pi} = 20 \times \frac{2 \times 1.26}{\pi} = 16.042 \text{ W} \quad \ldots\text{Ans.} \]

\[ \eta = \frac{P_{\text{dc}}}{P_{DC}} \times 100 = \frac{11.844}{16.042} \times 100 = 73.83\% \quad \ldots\text{Ans.} \]

**Ex. 10.12.18 :** In the complementary symmetry amplifier shown in Fig. P. 10.12.18, the transistors and diodes are of silicon. Calculate :

(a) Base to ground d.c., voltages of \( Q_1 \) and \( Q_2 \).

(b) Power delivered to load under maximum signal conditions.

(c) Conversion efficiency under maximum signal.

(d) Approximate value of \( C \), if the circuit is used at signal frequency down to 30 Hz.

---

**Fig. P. 10.12.18**
Solution:

Step 1: Calculate the base voltages of the two transistors:
- Assume the base currents of both the transistors to be small and apply KVL to the input loop to get,
  \[ V_{CC} = (1 \, k \times I) + V_{D1} + V_{D2} + (1 \, k \times I) \]
  \[ I = \frac{V_{CC} - V_{D1} - V_{D2}}{2k} = \frac{20 - 14}{2k} = 9.3 \, mA \]
  Base voltage of \( Q_2 \) = \( V_{B2} = I \times 1 \, k = 9.3 \times 1 = 9.3 \, V \) ...Ans.
  Base voltage of \( Q_1 \) = \( V_{B1} = V_{B2} + V_{D1} + V_{D2} = 9.3 + 1.4 = 10.7 \, V \) ...Ans.

Step 2: Calculate maximum load power:
- This circuit operates on a single polarity supply. So the new value of \( V_{CC} \) to be used for amplifier calculations is \( V'_{CC} = V_{CC}/2 = 10 \, V \).
  \[ P_{ac (max)} = \frac{1}{2} \times \left( \frac{V'_{CC}}{R_L} \right)^2 = \frac{1}{2} \times \left( \frac{10}{10} \right)^2 = 5 \, W \] ...Ans.

Step 3: DC power and conversion efficiency:
  \[ P_{DC} = V'_{CC} \times I_{CQ} = \frac{2I_m}{\pi} = V'_{CC} \times \frac{2}{\pi} \]
  \[ \therefore \% \eta = \frac{P_{ac (max)}}{P_{DC}} \times 100 = \frac{5}{6.3661} \times 100 = 78.5398 \% \] ...Ans.

Step 4: Value of C:
  \[ f = \frac{1}{2 \pi R_L C} \]
  \[ C = \frac{1}{2 \pi f \times R_L} = \frac{1}{2 \pi \times 30 \times 10} = 530.5 \, \mu F \] ...Ans.

Example 10.12.19:
A complementary-symmetry class-AB, A. F. power amplifier uses two matched transistors and a dual power supply of ±30 V to feed a common load of 8 Ω. If input voltage of this amplifier is 8 V (rms), calculate:
1. D.C. power input
2. A.C. power output
3. Maximum possible a.c. power output
4. Efficiency
5. Power dissipation of each transistor.
Assume that the two transistors are connected in an ideal C-C configuration.

Solution:
Given:
- \( V_{CC} = \pm 30 \, V \)
- \( R_L = 8 \, \Omega \)
- \( V_{in} = 8 \, V \) (rms)
Type of amplifier: Complementary symmetry class AB.

Step 1: Calculate peak load current \( I_m \):
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For C.C. configuration, voltage gain = 1

\[ V_{o\ (rms)} = V_{in\ (rms)} = 8\ V \]

\[ V_{om} = \sqrt{2} \times V_{o\ (rms)} = \sqrt{2} \times 8 = 11.3137\ V \]

\[ I_m = \frac{V_{om}}{R_L} = \frac{11.3137}{8} = 1.4142\ \text{Amp.} \]

Step 2: Calculate DC input power:

\[ P_{DC} = V_{CC} \times I_{DC} = V_{CC} \times \frac{2I_m}{\pi} = \frac{30 \times 2 \times 1.4142}{\pi} = 27\ W \quad \text{...Ans.} \]

Step 3: AC output power:

\[ P_{o\ (AC)} = \frac{1}{2} V_{om}^2 \frac{1}{R_L} = \frac{1}{2} \times \frac{(11.3137)^2}{8} = 8\ W \quad \text{...Ans.} \]

Step 4: Maximum possible ac output power:

\[ P_{o\ AC\ (max)} = \frac{1}{2} \times \frac{V_{CC}^2}{R_L} = \frac{1}{2} \times \frac{(30)^2}{8} = 56.25\ W \quad \text{...Ans.} \]

Step 5: Efficiency

\[ \eta = \frac{P_{AC}}{P_{DC}} = \frac{8\ W}{27\ W} = 0.2962\ OR\ 29.62\% \quad \text{...Ans.} \]

Step 6: Power dissipation per transistor:

\[ P_D = \frac{P_{DC} - P_{AC}}{2} = \frac{27\ W - 8\ W}{2} = 9.5\ W \quad \text{...Ans.} \]

Ex. 10.12.20: An ideal class B power amplifier is shown in Fig. P. 10.12.20. Assume that the characteristics of the transistors used are linear.

For this circuit, derive the following. Make suitable assumptions if necessary:

1. Power output derived to load (P_{out})
2. DC input power drawn from the supply (P_{CC})
3. Efficiency of the class B amplifier (\eta)
4. Maximum efficiency of the amplifier (\eta_{max})
5. Power dissipated in each transistor.
Soln.:

Let the turns ratio be \( \frac{N_1}{N_2} \)

\[ R'_L = \frac{V_m}{I_m} = \left( \frac{N_1}{N_2} \right)^2 R_L \]

\[ i_{\text{primary}} = i_{c1} - i_{c2} \]

**Step I:** To find power output delivered to load (\( P_{\text{out}} \)):

\[ V_{L \text{rms}} = \frac{V_m}{\sqrt{2}} \quad I_{L \text{rms}} = \frac{I_m}{\sqrt{2}} \]

\[ P_{\text{out}} = V_{L \text{rms}} I_{L \text{rms}} = \frac{V_m I_m}{\sqrt{2} \times \sqrt{2}} = \frac{V_m I_m}{2} \]

**Step II:** To find DC input power drawn from the supply (\( P_{\text{CC}} \)):

The average value of supply current is,

\[ I_{dc} = \frac{2 I_m}{\pi} \]

\[ P_{\text{CC}} = V_{CC} \times I_{dc} = V_{CC} \times \frac{2 I_m}{\pi} = \frac{2 V_{CC} I_m}{\pi} \]

**Step III:** To find efficiency of class B amplifier (\( \eta \)):

\[ \eta = \frac{P_{\text{ac}}}{P_{\text{dc}}} = \frac{P_{\text{out}}}{P_{\text{CC}}} = \frac{V_m I_m}{2} \times \frac{2}{2 V_{CC} I_m} = \frac{\pi}{4} \times \frac{V_m}{V_{CC}} \]

**Step IV:** To find maximum efficiency of the amplifier (\( \eta_{\text{max}} \)):

\[ \% \eta = \frac{\pi}{4} \times \frac{V_m}{V_{CC}} \times 100 \quad \eta = \eta_{\text{max}} \text{ when } V_m = V_{CC} \]

\[ \% \eta_{\text{max}} = \frac{\pi}{4} \times \frac{V_{CC}}{V_{CC}} \times 100 = 78.5 \% \]

**Step V:** To find power dissipated in each transistor:
\[ P_d = P_{dc} - P_{ac} = \frac{2 V_{CC} I_m}{\pi} - \frac{V_m I_m}{2} \]

But \( I_m = \frac{V_m}{R_L} \)
\[ \therefore P_d = \frac{2 V_{CC} V_m}{\pi R_L'} - \frac{V_m^2}{2 R_L'} \]

Ex. 10.12.21: For the circuit shown in Fig. P. 10.12.20 in the previous example show that

1. Power dissipated in the transistor is maximum when load voltage \( V_m = \frac{2 V_{CC}}{\pi} \)
2. Maximum collector power dissipation for both transistors combined as \( 2 \frac{V_{CC}^2}{\pi^2 R_L} \)

Soln.:

Part I: We know that,
\[ P_D = \frac{2 V_m V_{CC}}{\pi R_L} - \frac{V_m^2}{2 R_L} \]
Differentiating w.r.t. \( V_m \)
\[ \frac{d P_D}{d V_m} = \frac{2 V_{CC}}{\pi R_L'} - \frac{2 V_m}{2 R_L'} = 0 \]
\[ \therefore V_m = \frac{2 V_{CC}}{\pi R_L'} \]

Thus, maximum \( P_D \) occurs when \( V_m = \frac{2 V_{CC}}{\pi} \)

Part II: We know that,
\[ P_D = \frac{2 V_m V_{CC}}{\pi R_L'} - \frac{1}{2} \frac{V_m^2}{R_L'} \]

Maximum \( P_D \) occurs when \( V_m = \frac{2 V_{CC}}{\pi} \)
\[ \max P_D = \frac{2 V_{CC}}{\pi} \times \frac{2 V_{CC}}{\pi} - \frac{1}{2} \times \left( \frac{2 V_{CC}}{\pi} \right)^2 \]
\[ \max P_D = \frac{4 V_{CC}^2}{\pi^2 R_L'} - \frac{2 V_{CC}^2}{\pi^2 R_L'} = \frac{V_{CC}^2}{\pi^2 R_L'} [4 - 2] = \frac{2 V_{CC}^2}{\pi^2 R_L'} \]

Ex. 10.12.22: The dynamic transfer characteristic curve for a given transistor is:
\[ i_c \text{ (in mA)} = 50 i_b + 1000 i_b^2 \text{ where } i_b \text{ (in mA)} = 10 \cos 2\pi (100) t \]
Calculate the percent harmonic distortion.

Soln.:
Given: \( G_1 = 50, \quad G_2 = 1000, \quad I_{bas} = 10, \quad \cos \omega t = \cos 2\pi (100) t \)

Step I: To find \( B_b \) and \( B_1 \) :
\[ B_0 = B_2 = G_2 I_{bm} = \frac{1}{2} \times 1000 \times (10)^2 \times 10^{-6} = 0.05 \]
\[ B_1 = G_1 = 50 \]

**Step II : To find % harmonic distortion :**

\[ % D = \left( \frac{B_2}{B_1} \right) \times 100 \% = \left( \frac{0.05}{50} \right) \times 100 = 0.1 \% \quad \ldots \text{Ans.} \]

**Ex. 10.12.23 :** A sinusoidal signal \( V_s = 1.95 \sin 400t \) is applied to a power amplifier. The resulting current is given by

\[ i_o = 12 \sin 400t + 1.2 \sin 800t + 0.9 \sin 1200t + 0.4 \sin 1600t \]

Calculate:
1. Total harmonic distortion
2. Percentage increase in power because of distortion.

**Soln. :**

**Step 1 : Obtain the amplitudes of Fourier components :**

The standard expression for \( i_o \) is as follows:

\[ i_o = B_0 + B_1 \sin \omega t + B_2 \sin 2\omega t + B_3 \sin 3\omega t + B_4 \sin 4\omega t \]

Comparing with the given equation we get,

\[ B_0 = 0, \quad B_1 = 12, \quad B_2 = 1.2, \quad B_3 = 0.9, \quad B_4 = 0.4 \]

**Step 2 : Various distortions and THD :**

Second harmonic distortion \( D_2 = \left( \frac{B_2}{B_1} \right) = \frac{1.2}{12} = 0.1 \)

Third harmonic distortion \( D_3 = \left( \frac{B_3}{B_1} \right) = \frac{0.9}{12} = 0.075 \)

Fourth harmonic distortion \( D_4 = \left( \frac{B_4}{B_1} \right) = \frac{0.4}{12} = 0.0333 \)

Total harmonic distortion. \( \text{THD} = \sqrt{D_2^2 + D_3^2 + D_4^2} \times 100 \)

\[ = \sqrt{(0.1)^2 + (0.075)^2 + (0.0333)^2} \times 100 = 12.9359 \% \quad \ldots \text{Ans.} \]

**Step 3 : Percent increase in power due to distortion :**

Output power including the distortion is

\[ P = (1 + D^2) P_1 \]

where \( D = \text{Total harmonic distortion} \quad P_1 = \text{Fundamental power} \)

\[ \therefore P = \left[ 1 + (0.1294)^2 \right] P_1 = 1.01673 P_1 \]

So % increase \( = (P - P_1) \times 100 = (1.01673 P_1 - P_1) \times 100 = 1.6733 \% \quad \ldots \text{Ans.} \)
Section 10.13:

Ex. 10.13.1: For a regulated dc power supply, the output voltage varies from 12 V to 11.6 V when the load current is varied from 0 to 100 mA which is the maximum value of $I_L$. If the ac line voltage and temperature are constant, calculate the load regulation, % load regulation and output resistance of the power supply.

Soln.:

Given:

$V_{NL} = 12$ V, $V_{FL} = 11.6$ V, $I_{L \text{ max}} = 100$ mA.

1. The load regulation, L.R. = $V_{NL} - V_{FL} = 12 - 11.6 = 0.4$ V

   ... Ans.

2. % load regulation = $\frac{V_{NL} - V_{FL}}{V_{FL}} \times 100 = \frac{0.4}{11.6} \times 100 = 3.45\%$

   ... Ans.

3. Output resistance $R_o = \frac{\Delta V_o}{\Delta I_L} = \frac{0.4}{100 \text{mA}} = 4 \Omega$

   ... Ans.

Ex. 10.13.2: For a regulated dc power supply, the output voltage changes in the range of 12 V ± 0.2 V when the ac line voltage fluctuates in the range of 230V ± 10%. Calculate the source regulation (SR) and percent source regulation.

Soln.:

1. Source regulation, S.R. = $V_{LH} - V_{LL}$

   $V_{LH} = 12 + 0.2 = 12.2$ V and $V_{LL} = 12 - 0.2 = 11.8$ V

   $\therefore$ S.R. = $12.2 - 11.8 = 0.4$ V

   ... Ans.

2. % S.R. = $\frac{S.R.}{V_{Nom}} \times 100$

   Now $V_{Nom} = 12$ V

   $\therefore$ % S.R. = $\frac{0.4}{12} \times 100 = 3.33\%$

Ex. 10.13.3: A DC power supply is known to have a ripple factor of 10%. If the DC output voltage is 10V, what is the rms value of the ripple voltage in the output? Assuming this ripple to be sinusoidal in nature, what is its peak to peak voltage?

Soln.:

R.F. = 0.1, $V_{Ldc} = 10$ V

1. Ripple factor = $\frac{V_{rms}}{V_{Ldc}}$, where $V_{rms}$ = RMS value of ripple voltage.

   $\therefore$ 0.1 = $\frac{V_{rms}}{10}$

   $\therefore$ $V_{rms} = 0.1 \times 10 = 1$ V

   ... Ans.

2. If the ripple is sinusoidal then the peak to peak ripple is given by.

   $V_{P-P} = 2\sqrt{2} \times V_{rms} = 2\sqrt{2} \times 1 = 2.84$ Volts.

   ... Ans.

Ex. 10.13.4: A linear regulator has unregulated supply derived from FWR capacitor filter arrangement. Ripple rejection of regulator is specified to be 60 dB. If input unregulated supply has a ripple of 2 V peak-to-peak, what will be the output RMS ripple? If the regulator has 12 V output with full load current of 1 A, calculate percentage load regulation. Given output resistance of regulator = 200 milliohms.
Soln. :

Given :  
Ripple rejection = 60 dB  
Peak to peak input ripple = 2V,  \( V_o = 12 \) V,  \( I_{FL} = 1 \) A.  
\( R_o = 200 \) m\( \Omega \)

To find :  
Rms ripple in output,  
% load regulation

Step 1 :  
Rms ripple output :

\[
\text{Ripple rejection (dB)} = 20 \log_{10} \left( \frac{V_{\text{ripple (output)}}}{V_{\text{ripple (input)}}} \right) \\
\therefore 60 = 20 \log_{10} \left( \frac{V_{\text{ripple (output)}}}{V_{\text{ripple (input)}}} \right)
\]

\[
\Rightarrow 1 \times 10^{-3} = \frac{V_{\text{ripple (output)}}}{2}
\]

\[
\therefore V_{\text{ripple (output)}} = 2 \times 10^{-3} \text{ volts or } 2 \text{ mV}
\]

Note that this is the peak to peak value of output ripple voltage.

Assuming the output ripple to be sinusoidal we get

\[
\text{Rms } V_{\text{ripple (output)}} = \frac{2 \text{ mV}}{2\sqrt{2}} = 0.707 \text{ mV}
\]

...Ans.

Step 2 :  
Percent load regulation :

Referring to Fig. P. 10.13.4 we get,

\[
V_{o (NL)} = 12 \text{ V}
\]

and \( V_{o (FL)} = 12 - (R_o \times I_L) \)

\[
= 12 - (200 \times 10^{-3} \times 1)
\]

\[
= 11.8 \text{ volts}
\]

\[
\therefore % \text{ load regulation} = \frac{V_{o (NL)} - V_{o (FL)}}{V_{o (FL)}} \times 100 = \frac{12 - 11.8}{11.8} \times 100 = 1.6949 \%
\]

...Ans.

Section 10.15 :

Ex. 10.15.1 :  
For a zener voltage regulator of Fig. P. 10.15.1, if \( I_{Z_{\text{min}}} = 2 \) mA,  \( I_{Z_{\text{max}}} = 20 \) mA and \( V_Z = 5 \) V, determine the range of input voltage over which the output voltage remains constant. Assume \( r_Z = 0 \) \( \Omega \).

Soln. :

Given :  
\( V_Z = 5 \) V,  \( I_{Z_{\text{min}}} = 2 \) mA,  \( I_{Z_{\text{max}}} = 20 \) mA.,  \( R = R_l = 1 \) k\( \Omega \).

Step 1 :  
Calculate load current :

\[
I_L = \frac{V_Z}{R_L} = \frac{5V}{1 \text{ k}\Omega} = 5 \text{ mA}
\]

...(1)
Step 2 : Obtain $V_{in\ (min)}$ :

$V_{in\ (min)}$ is the minimum input voltage which can keep the zener diode in the zener region. So corresponding to $V_{in\ (min)}$, the zener current $I_Z = I_{Z\ (min)}$.

\[ \therefore \text{Source current } I = I_L + I_{Z\ (min)} \]

\[ \therefore I = (5 + 2) = 7 \text{ mA} \quad \ldots (2) \]

\[ \therefore V_{in\ (min)} = V_Z + \text{Minimum voltage drop across } R_S \]

\[ = 5 + IR_S = 5 + (7 \times 10^{-3} \times 1 \times 10^3) = 12 \text{ Volt} \quad \ldots \text{Ans.} \]

Step 3 : Obtain $V_{in\ (max)}$ :

$V_{in\ (max)}$ is the maximum input voltage which will ensure that $I_Z$ is less than or equal to $I_{Z\ (max)}$. So corresponding to $V_{in\ (max)}$, the zener current $I_Z = I_{Z\ (max)}$.

\[ \therefore \text{Source current } I = I_L + I_{Z\ (max)} \]

\[ \therefore I = (5 + 20) = 25 \text{ mA} \quad \ldots (3) \]

\[ \therefore V_{in\ (max)} = V_Z + \text{Maximum voltage drop across } R_S \]

\[ = 5 + IR_S = 5 + (25 \times 10^{-3} \times 1 \times 10^3) = 30 \text{ Volt} \quad \ldots \text{Ans.} \]

Thus the range of input voltage to have a constant output voltage is 12 to 30 V.

Ex. 10.15.2 : For a zener voltage regulator of the previous example if $V_{in} = 30$ V constant calculate the range of load current over which the output voltage remains constant.  

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Soln. :  

Given :  
$V_Z = 5V$, $I_{Z\ (min)} = 2$ mA, $I_{Z\ (max)} = 20$ mA, $R_S = 1 \text{ k}\Omega$, $V_{in} = 30$ V.

Step 1 : Calculate the source current :  
Here due to constant $V_{in}$, the source current is going to remain constant.

\[ \therefore \text{Source current } I = \frac{V_{in} - V_Z}{R_S} = \frac{30 - 5}{1 \text{ k}\Omega} = 25 \text{ mA} \quad \ldots (1) \]

Step 2 : Calculate $I_{L\ (min)}$ :  
$I_{L\ (min)}$ is the minimum value of load current which ensures that $I_Z$ is less than $I_{Z\ (max)}$. So corresponding to $I_{L\ (min)}$, the zener current $I_Z = I_{Z\ (max)}$.

\[ \therefore \text{Source current } I = I_{L\ (min)} + I_{Z\ (max)} \]

\[ \therefore I_{L\ (min)} = 1 - I_{Z\ (max)} = (25 - 20) = 5 \text{ mA} \quad \ldots \text{Ans.} \]

Step 3 : Calculate $I_{L\ (max)}$ :  
$I_{L\ (max)}$ is the maximum value of load current which can keep the zener diode in the zener region. So corresponding to $I_{L\ (max)}$, the zener current $I_Z = I_{Z\ (max)}$.

\[ \therefore I = I_{L\ (max)} + I_{Z\ (min)} \]

\[ \therefore I_{L\ (max)} = 1 - I_{Z\ (min)} = 25 - 2 = 23 \text{ mA} \quad \ldots \text{Ans.} \]

Thus the range of load current over which output voltage remains constant is 5 mA to 23 mA.
Ex. 10.15.3 : Design a zener voltage regulator for the following specifications.

\[ V_{in} = 20 \pm 2 \text{ Volt}, \text{ Output voltage } V_o = 6 \text{V}, \text{ Load current } I_L = 50 \text{ mA}, I_{Z, (min)} = 5 \text{ mA}, \text{ Zener wattage } P_Z = 0.5 \text{ Watt.} \]

Soln. :

Given :

\[ V_{in,\text{(min)}} = 18 \text{V}, \quad V_{in,\text{(max)}} = 22 \text{V}, \quad V_o = 6 \text{V}, \quad I_L = 50 \text{ mA}. \]

\[ I_{Z,\text{(min)}} = 5 \text{ mA} \quad \text{and} \quad P_Z = 0.5 \text{ W}. \]

Step 1 : Calculate \( I_{Z,\text{(max)}} \):

\[ I_{Z,\text{(max)}} = \frac{P_Z}{V_Z} = \frac{0.5}{6} = 83.33 \text{ mA} \quad \ldots(1) \]

Step 2 : Calculate \( R_{S,\text{(min)}} \):

When \( R_S = R_{S,\text{(min)}} \), the source current \( I \) can become maximum corresponding to \( V_{in} = V_{in,\text{(max)}} \). As the load current is constant, this increased source current will flow through the zener. Therefore the value of \( R_{S,\text{(min)}} \) should be such that even when \( V_{in} = V_{in,\text{(max)}} \) the zener current \( I_Z \leq I_{Z,\text{(max)}} \).

\[ \therefore R_{S,\text{(min)}} = \frac{V_{in,\text{(max)}} - V_Z}{[I_L + I_{Z,\text{(max)}}]} \quad \ldots(2) \]

\[ \therefore R_{S,\text{(min)}} = \frac{22 - 6}{[50 + 83.33] \times 10^{-3}} = 120 \Omega \quad \ldots\text{Ans.} \]

Step 3 : Calculate \( R_{S,\text{(max)}} \) and select \( R_S \):

When \( R_S = R_{S,\text{(max)}} \) the source current \( I \) can become minimum corresponding to \( V_{in} = V_{in,\text{(min)}} \). As \( I_L \) is constant, care should be taken to ensure that \( I_Z \geq I_{Z,\text{(min)}} \).

\[ \therefore R_{S,\text{(max)}} = \frac{V_{in,\text{(min)}} - V_Z}{[I_L + I_{Z,\text{(min)}}]} \quad \ldots(3) \]

\[ \therefore R_{S,\text{(max)}} = \frac{18 - 6}{[50 + 5] \times 10^{-3}} = 218.18 \Omega \quad \ldots\text{Ans.} \]

Thus \( R_S \geq 120 \Omega \) and \( R_S \leq 218.2 \Omega \).

So, select \( R_S = 180 \Omega \).

Step 4 : Select zener diode :

\[ V_o = 6 \text{V} \]

\[ \therefore V_Z = V_o = 6 \text{V} \]

\[ \therefore \text{Select the zener diode with following specifications :} \]

1. \( V_Z = 6 \text{V} \)
2. \( I_{Z,\text{(max)}} \geq 83.33 \text{ mA} \)
3. \( P_Z = 0.5 \text{W} \).
Ex. 10.15.4: Design and draw a zener regulator circuit to meet the following specifications. Load voltage = 8 V, source voltage = 30 V, $I_L = 50$ mA. Assume $I_{Z(\text{min})} = 5$ mA, $P_Z = 1.0$ Watt.

Soln.:

Given: $V_Z = 8$ V, $V_{\text{in}} = 30$ V, $I_L = 50$ mA, $I_{Z(\text{min})} = 5$ mA, $P_Z = 1$ W.

Step 1: Calculate $I_{Z(\text{max})}$:

$$I_{Z(\text{max})} = \frac{P_Z}{V_Z} = \frac{1}{8} = 125$ mA\ ...(1)$$

Step 2: Calculate $R_{S(\text{min})}$ and $R_{S(\text{max})}$:

$$R_{S(\text{max})} = \frac{V_{\text{in}} - V_Z}{I_L + I_{Z(\text{min})}} = \frac{30 - 8}{(50 + 5) \times 10^{-3}}$$

$$\therefore R_{S(\text{max})} = 400 \Omega \quad \ldots\text{Ans.}$$

$$R_{S(\text{min})} = \frac{V_{\text{in}} - V_Z}{I_L + I_{Z(\text{max})}} = \frac{30 - 8}{(50 + 125) \times 10^{-3}}$$

$$\therefore R_{S(\text{min})} = 125.7 \Omega \quad \ldots\text{Ans.}$$

Thus $R_S$ should be between 125.7$\Omega$ and 400$\Omega$.

So select $R_S = 220 \Omega$.

The circuit diagram is as shown in Fig. P. 10.15.4.

Step 3: Select the zener diode:

$V_o = 8$ V $\therefore V_Z = 8$ V

Select the zener diode having following specifications:

$V_Z = 8$ V, $I_{Z(\text{max})} = 125$ mA, $P_Z = 1$ W

Section 10.18:

Ex. 10.18.2: Design a series voltage regulator with an error amplifier as per the specifications given below:

Specifications:

1. Unregulated d.c. input voltage $V_{\text{in}} = 20$ V
2. Regulated output voltage $V_o = 12$ V
3. Maximum load current $I_{L\text{max}} = 50$ mA

Soln.:

Refer Fig. 10.18.4. This is the regulator circuit to be designed.

Step 1: Selection of zener diode:

Let $V_Z \approx V_o / 2$

$\therefore V_Z = 12/2 = 6$ Volts

So select a zener diode having $V_Z = 6$ Volts.
Step 2: Calculate R :
Let $I_{ZT} = 10$ mA to operate the zener diode in the zener region.

\[
\therefore I_R = 10 \text{ mA}
\]

\[
\therefore R = \frac{V_o - V_Z}{I_R} = \frac{12 - 6}{10 \times 10^{-3}} = 600 \Omega
\]

Use $R = 560 \Omega$ which is a standard value.

\[
\therefore I_{E1 \text{ (max)}} = I_L \text{ (max)} + I_R = 50 \text{ mA} + 10 \text{ mA} = 60 \text{ mA}
\]

Step 3: Selection of $Q_1$ :
$Q_1$ is the series pass transistor. The power dissipation in $Q_1$ is given by,

\[
P_{D \text{ (max)}} = I_{E1 \text{ (max)}} \times (V_{in} - V_o)
\]

\[
= 60 \times 10^{-3} \times (20 - 12) = 480 \text{ mW}
\]

\[
V_{CE1 \text{ (max)}} = V_{in} = 20 \text{ V}
\]

\[
I_{C1 \text{ (max)}} = I_{E1 \text{ (max)}} = 60 \text{ mA}
\]

Select $Q_1$ as per these specifications.

Step 4: Calculate $R_3$ :
Let $h_{FE \text{ (min)}}$ at $I_C = 60$ mA of $Q_1$ be 50.

\[
\therefore I_{B1 \text{ (max)}} = \frac{I_{E1 \text{ (max)}}}{h_{FE \text{ (min)}}}
\]

\[
\therefore I_{B1 \text{ (max)}} = \frac{60 \text{ mA}}{50} = 1.2 \text{ mA}
\]

Let $I_{C2} \gg I_{B1 \text{ (max)}}$

\[
\therefore \text{ Let } I_{C2} = 5 \text{ mA}
\]

\[
\therefore R_3 = \frac{V_{in} - V_{B1}}{I_{C2} + I_{B1 \text{ (max)}}} = \frac{20 - (12 + 0.7)}{5 + 1.2 \text{ mA}}
\]

\[
\therefore R_3 = 1.18 \text{ k}\Omega
\]

Select $R_3 = 1.2 \text{ k}\Omega$ which is the standard value.

Step 5: Calculate $R_2$ :

\[
I_Z = I_{E2} + I_R = 5 \text{ mA} + 10 \text{ mA} = 15 \text{ mA}
\]

It is necessary that $I_2 \gg I_{B2}$.

So let $I_2 = 1$ mA.

\[
\therefore R_2 = \frac{V_Z + V_{BE2}}{I_2} = \frac{6 + 0.7}{1 \text{ mA}}
\]

\[
\therefore R_2 = 6.7 \text{ k}\Omega
\]

Use 6.8 k\Omega which is a standard value.

Step 6: Calculate $R_1$ :

\[
R_1 \approx \frac{V_o - V_{R2}}{I_2} = \frac{12 - 6.7}{1 \text{ mA}} = 5.1 \text{ k}\Omega
\]

Use 4.7 k\Omega or 5.1 k\Omega which is a standard value.
Section 10.19 :  

Ex. 10.19.2 : For a transistorised series pass regulator shown in Fig. P. 10.19.2, calculate the output voltage $V_o$ and hence the temperature stability factor $S_T$.

Given:
- $V_z(0^\circ C) = 10.00$ V, $V_z(50^\circ C) = 10.25$ V,
- $Q_1$ and $Q_2$ are silicon transistors.
- $V_{BEQ2}(0^\circ C) = 0.650$ V, $V_{BEQ2}(50^\circ C) = 0.540$ V
- $R_1$, $R_2$, $R_3$, $R_4$ are stable resistors.
- Assume $I_{b2} << I_{R_1, R_2}$.

Fig. P. 10.19.2

**Sln. :**

**Steps to be followed :**

**Step 1 :** Calculate $V_o$. Since $I_{b2} << I_{R_1, R_2}$, by voltage divider rule.

$$V_o = \frac{R_1 + R_2}{R_2} \times (V_z + V_{BE2})$$

**Step 2 :** Calculate $S_T$.

$$S_T = \frac{\Delta V_o}{\Delta T}$$

**Step 1 :** Calculate $V_o$:

$$V_o = \left(\frac{R_1 + R_2}{R_1}\right) \times (V_{BE2} + V_z)$$

at $0^\circ C$ $V_{o1} = \left(\frac{1 \text{ k} + 1.2 \text{ k}}{1.2 \text{ k}}\right) \times (0.650 + 10) = 19.525$ Volts

at $50^\circ C$ $V_{o2} = 1.833 \times (0.540 + 10.25) = 19.78$ Volts

**Step 2 :** Calculate stability factor $S_T$:

$$S_T = \frac{\Delta V_o}{\Delta T} = \frac{V_{o2} - V_{o1}}{T_2 - T_1} = \frac{19.78 - 19.525}{50 - 0} = 0.055$$

$$S_T = 5.13 \text{ mV/}^\circ C$$
### Section 10.21:

**Ex. 10.21.1:** For a series regulator shown in Fig. P. 10.21.1. $Q_1$ and $Q_2$ are silicon transistors with $h_{fe} = 100$ and $V_{BE} = 0.7$. Calculate:

1. The range over which output voltage can be adjusted.
2. Collector current of $Q_2$.
3. The zener diode current if $V_z = 10 \, \text{V}$. For 2. and 3. above assume, that output voltage has been adjusted to 20 V.

#### Soln.:

**Step I:** To find range over which output voltage can be adjusted:

**Case (i):** With $R_P$ at point A.

\[
\begin{align*}
R_1 & = 1 \, \text{kΩ}, \quad R_2 = 1.5 \, \text{kΩ} + 0.5 \, \text{kΩ} = 2 \, \text{kΩ} \\
V_o & = \left(1 + \frac{R_1}{R_2}\right) \times (V_{BE2} + V_z) \\
\therefore \quad V_o & = \left(1 + \frac{1}{2}\right) (0.7 + 10) \\
\therefore \quad V_o & = 1.5 \times 10.7 = 16.05 \, \text{V}
\end{align*}
\]

**Case (ii):** With $R_P$ at point B.

\[
\begin{align*}
R_1 & = 1 \, \text{kΩ} + 0.5 \, \text{kΩ} = 1.5 \, \text{kΩ} \\
R_2 & = 1.5 \, \text{kΩ} \\
\therefore \quad V_o & = \left(1 + \frac{R_1}{R_2}\right) \times (V_{BE2} + V_z) \\
\therefore \quad V_o & = \left(1 + \frac{1.5 \, \text{kΩ}}{1.5 \, \text{kΩ}}\right) (0.7 + 10) \\
V_o & = (1 + 1) (10.7) = 21.4 \, \text{V}
\end{align*}
\]

The output voltage can be varied from 16 to 21 V.
Step II: To find collector current of $Q_2$:

\[ V_{\text{out}} = 20 \text{ V} \quad \text{...given} \]

\[ I_L = \frac{V_{\text{out}}}{R_L} = \frac{20}{40} = 0.5 \text{ A} \]

Let the current through $R_1$, $R_P$ and $R_2$ be $I$ such that $I > I_{B2}$.

\[ I = \frac{V_{\text{out}}}{R_1 + R_2 + R_P} = \frac{20}{1 \text{ k} + 0.5 \text{ k} + 1.5 \text{ k}} \]

\[ I = \frac{20}{3000} = 6.67 \text{ mA} \quad \text{...Ans.} \]

\[ I_{E1} = I + I_L \]

\[ I_{B1} = \frac{I_{E1}}{1 + h_{ie}} \]

\[ I_{E1} = 6.67 \times 10^{-3} + 0.5 \quad I_{B1} = \frac{506.67}{1 + 100} \]

\[ I_{E1} = 0.5067 \text{ A} \quad I_{B1} = 5.0165 \text{ mA} \]

\[ V_{B1} = V_{BE1} + V_{\text{out}} = 0.7 + 20 = 20.7 \text{ V} \]

\[ I_{R3} = \frac{V_{\text{in}} - V_{B1}}{1.5 \times 10^3} = 6.2 \text{ mA} \]

\[ I_{C2} = I_{R3} - I_{B1} = 6.2 - 5 = 1.1834 \text{ mA} \quad \text{...Ans.} \]

Step III: To find zener diode current:

\[ I_{B2} = \frac{I_{E2}}{h_{ie}} = \frac{11.834 \times 10^{-3} + 1.1834 \times 10^{-3}}{100} = 11.8346 \mu\text{A} \]

\[ I_{B2} = I_{B2} + I_{C2} \]

\[ I_{E2} = 11.83 \times 10^{-6} + 1.1834 \times 10^{-3} \]

\[ I_{E2} = 1.1952 \text{ mA} \]

Zener current, $I_Z = I_{E2} + I_{R4}$

But $I_{R4} = \frac{30 - 10}{2000}$

\[ I_{R4} = 10 \text{ mA} \]

\[ I_Z = 1.192 + 10 = 11.192 \text{ mA} \quad \text{...Ans.} \]

Ex. 10.21.2: In the circuit of Fig. P. 10.21.1 in the previous example, if the dynamic resistance of zener diode $R_Z = 8 \Omega$ and $h_{ie} = 0.5 \text{ k}\Omega$. $h_{ie} = 0.5 \Omega = 0$ for $Q_1$ and $Q_2$. Calculate the approximate output impedance of the series pass regulator.

Soln.:

Given: $R_Z = 8 \Omega$, $h_{ie} = 0.5 \text{ k}\Omega$.

To find: $R_o$

\[ R_o = \frac{\Delta V_{\text{out}}}{\Delta I_L} \quad \text{V}_{\text{in}} \text{ temperature constant} \]
\[ R_o = \frac{R_1 + R_2}{g_{m2} R_2 h_{ie1}} \]
\[ R_1 = 1 \, k\Omega, \quad R_2 = 2 \, k\Omega \]

**Step I :**  
To calculate \( g_{m2} \):

\[ g_{m2} = h_{ie} \times \frac{R_2}{R_1 + R_2} \]
\[ g_{m2} = \frac{\left[ \frac{R_1}{R_2} \right] + \left[ h_{ie2} + \left( 1 + h_{ie2} \right) R_Z \right]}{100 \times \frac{2}{1+2}} \]
\[ g_{m2} = \frac{\left[ \frac{1}{2} \right] + \left[ 0.5 + \left( 1 + 100 \right) 8 \times 10^{-3} \right]}{66.67} \]
\[ g_{m2} = 0.6667 + \left[ 0.5 + 0.808 \right] \]
\[ g_{m2} = 33.763 \, mA/V \]

**Step II :**  
To find \( R_o \):

\[ R_o = \left( 1 + 2 \right) \times 10^3 \]
\[ R_o = 33.763 \times 10^{-3} \times 2 \times 10^3 \times 100 \]
\[ R_o = 0.4442 \, \Omega \]...Ans.

**Ex. 10.21.3 :**  
The emitter follower regulator is to supply a load current of 500 mA at 10.3 V. The unregulated dc supply varies from 16 to 20 V. Use a zener 11 V which requires minimum bias current of 2 mA for stable operation. The series pass transistor has parameters.

Given : \( h_{ie} = 50, V_{BE} = 0.7 \) and \( \frac{dV_z}{dt} = 20 \, \Omega, h_{ie} = 100 \, \Omega. \)

Determine :
1. Value of zener bias resistor \( R_b. \)
2. The wattage of \( R_b. \)
3. Power dissipation rating of zener.
4. Power dissipation rating of transistor.
5. Variation in \( V_o \) for variation in \( V_in \) from 16 to 20 V at \( I_L = 500 \, mA \) constant.
6. Variation in \( V_o \) for load variation from 50 mA at \( V_in = 16 \, V \) constant.

**Soln. :**

**Given :**
\( I_L = 500 \, mA, \quad V_o = 10.3 \, V \)
\( V_{in} = 16 \, to \, 20 \, V, \quad V_z = 11 \, V \)
\( I_{I_{min}} = 2 \, mA, \quad h_{ie} = 50, \quad V_{BE} = 0.7 \)
\( R_z = 20 \, \Omega, \quad h_{ie} = 100 \, \Omega \)

**Step I :**  
To find \( R_b : \)

\[ I_L = I_B = 500 \, mA \]
\[ I_B = \frac{I_B}{1 + \beta} = \frac{500}{1 + 50} = 9.8039 \, mA \]
\[ I_{R_b} = I_B + I_z = 9.89039 \, mA + 2 \, mA \]
\[ I_{R_b} = 11.8039 \text{ mA} \]

But \[ I_{R_b} = \frac{V_{in} - V_z}{R_b} \]

\[ R_b = \frac{16 - 11}{11.80 \times 10^{-3}} = 423.58 \Omega \] ...Ans.

**Step II:** To find wattage of \( R_b \):

Wattage rating \[ = \frac{(V_{in} - V_z)^2}{R_b} \]

Wattage rating \[ = \frac{(20 - 11)^2}{423.58} = 0.1912 \text{ W} \] ...Ans.

**Step III:** To find \( P_D \) of zener:

\[ I_{R_b} = I_B + I_z \]

Maximum \( I_{R_b} = \frac{20 - 11}{423.58} = 21.247 \text{ mA} \) (when \( I_L = 0 \), \( I_B = 0 \) and \( I_{R_b} = I_{z \text{ max}} \))

\[ P_{D \text{ of zener}} = V_z I_{z \text{ max}} \]

But \( I_{z \text{(max)}} = I_{R_b \text{(max)}} \)

\[ P_{D \text{ of zener}} = 11 \times 21.247 \times 10^{-3} = 0.23372 \text{ W} \] ...Ans.

**Step IV:** To find \( P_D \) of transistor:

\[ V_{CE} = V_C - V_E \]

\[ V_{CE} = 20 - 10.3 = 9.7 \text{ V} \]

\[ P_D = V_{CE} I_E = 9.7 \times 0.5 = 4.85 \text{ W} \] ...Ans.

**Step V:** To find \( S_V \):

\[ S_V = \left. \frac{\Delta V_o}{\Delta V_{in}} \right| I_L \text{ constant} \]

\[ S_V = \frac{R_z}{R_b + R_z} \]

\[ S_V = \frac{20}{423.58 + 20} = 0.045 \text{ or } 4.5 \% \] ...Ans.

**Step VI:** To calculate \( R_o \):

For the given circuit,

\[ R_o = \frac{\Delta V_o}{\Delta I_L} \]

\[ R_o = \frac{R_z + h_{fe}}{1 + h_{fe}} \]

\[ R_o = \frac{20 + 100}{1 + 50} = 2.3529 \Omega \] ...Ans.
Ex. 10.21.4: A linear regulator has unregulated supply derived from FWR capacitor filter arrangement. Ripple rejection of regulator is specified to be 60 dB. If input unregulated supply has a ripple of 2 V peak-to-peak, what will be the output RMS ripple? If the regulator has 12 V output with full load current of 1 A, calculate percentage load regulation. Given-output resistance of regulator = 200 milliohms.

Soln.: Given:

Ripple rejection = 60 dB
Peak to Peak input ripple = 2V, \( V_o = 12 \) V, \( I_{FL} = 1 \) A.
\( R_o = 200 \) m\( \Omega \)

To find: Rms ripple in output

\% load regulation

Step 1: Rms ripple output:

\[
\text{Ripple rejection (dB)} = 20 \log_{10} \left[ \frac{V_{\text{ripple (output)}}}{V_{\text{ripple (input)}}} \right]
\]

\[
\therefore -60 = 20 \log_{10} \left[ \frac{V_{r (output)}}{2} \right]
\]

\[
\therefore 1 \times 10^{-3} = \frac{V_{r (output)}}{2}
\]

\[
\therefore V_{r (output)} = 2 \times 10^{-3} \text{ volts or } 2 \text{ mV} \quad \text{(1)}
\]

Note that this is the peak to peak value of output ripple voltage.

Assuming the output ripple to be sinusoidal we get

\[
\text{Rms } V_{r (output)} = \frac{2 \text{ mV}}{2\sqrt{2}} = 0.707 \text{ mV} \quad \text{...Ans.}
\]

Step 2: Percent load regulation:

Referring to Fig. P. 10.21.4 we get

\[
V_{o (NL)} = 12 \text{ V}
\]

and \( V_{o (FL)} = 10 - (R_o \times I_L) \)

\[
= 12 - (200 \times 10^{-3} \times 1)
\]

\[
= 11.8 \text{ volts}
\]

\[
\therefore \% \text{ load regulation} = \frac{V_{o (NL)} - V_{o (FL)}}{V_{o (FL)}} \times 100
\]

\[
= \frac{12 - 11.8}{11.8} \times 100 = 1.6949 \% \quad \text{...Ans.}
\]
Ex. 10.21.5 : Design a Transistor Series Regulator to deliver 800 mA load current to load at + 12 V DC. The input voltage to regulator varies from 18 to 24 V DC. Assume suitable active and passive devices (in terms of their specifications). Suggest practical values of resistors from 5% tolerance series. For your design, calculate:

1. Worst case power dissipated by series pass transistor
2. Power dissipated by Zener diode
3. Maximum power delivered to load
4. Maximum power delivered by input unregulated supply
5. Efficiency of regulator circuit

Soln. :

Given: \( I_L = 800 \text{ mA}, \quad V_o = 12 \text{ V}, \quad V_{in} = 18 \text{ to } 24 \text{ V} \)

Step 1 : Draw the circuit diagram:

Fig. P. 10.21.5 shows the required circuit diagram.

Step 2 : Design of the Regulator:

\[
V_Z = V_o + V_{BE} = 12 + 0.7 = 12.7 \text{ V}
\]

Let \( P_{Z,\text{(max)}} = 1 \text{ W} \)

\[
I_{Z,\text{(max)}} = \frac{P_{Z,\text{(max)}}}{V_Z} = \frac{1 \text{ W}}{12.7} = 78.74 \text{ mA}
\]

Therefore, Select the zener diode with the following specifications:

\( V_Z = 12.7 \text{ V}, \quad P_{Z,\text{(max)}} = 1 \text{ W}, \quad I_{Z,\text{(max)}} = 80 \text{ mA} \)

Now let us select the transistor.

\( I_L = I_E = 800 \text{ mA} \)

Let \( \beta \) of the transistor be 15.

\[
\beta_{\text{typ}} = 15
\]

\[
I_B = \frac{I_L}{1 + \beta} = \frac{800}{16} = 50 \text{ mA}
\]

\[
I_C = \beta I_B = 15 \times 50 = 750 \text{ mA}
\]

Maximum power dissipation of the transistor corresponds to the short circuited output.
Select a transistor with following specifications.

\[ V_{CE\text{ (max)}} = 36 \text{ V}, \quad I_C\text{ (max)} = 1.5 \text{ A}, \quad P_D\text{ (max)} = 54 \text{ W} \]

**Calculate \( R_B \):**

\[ \therefore R_B = \frac{V_{in\text{ (max)}} - V_Z}{I_{RB}} = \frac{14 - 12.7}{I_B + I_Z} \]

**\( R_B\) (min) :**

\( R_B\) (min) should not be too small. Even at maximum value of \( V_{in\text{ (max)}} \), the current through \( I_Z \) should not exceed \( I_Z\text{ (max)} \).

\[ \therefore R_B\text{ (min)} = \frac{V_{in\text{ (max)}} - V_Z}{I_B + I_Z\text{ (max)}} \]

\[ \therefore R_B\text{ (min)} = \frac{24 - 12.7}{50 + 78.78} \text{ mA} = 87.74 \Omega \]

**\( R_B\) (max) :**

\( R_B\) (max) should not be too large. Even at minimum \( V_{in\text{ (min)}} \), the current through \( I_Z \) should not be less than \( I_Z\text{ (min)} \) i.e. 5 mA.

\[ \therefore R_B\text{ (max)} = \frac{V_{in\text{ (min)}} - V_Z}{I_B + I_Z\text{ (min)}} \]

\[ \therefore R_B\text{ (max)} = \frac{18 - 12.7}{50 + 5} \text{ mA} = 96.36 \Omega \]

The value of \( R_B \) should be between \( R_B\text{ (max)} \) and \( R_B\text{ (min)} \).

\[ \therefore R_B = 92 \Omega \]

**Designed values :**

\[ R_B = 92 \Omega, \quad V_Z = 12.7 \text{ V}, \]
\[ P_{Z\text{(max)}} = 1 \text{ W}, \quad I_{Z\text{(max)}} = 80 \text{ mA}, \]
\[ I_{Z\text{(min)}} = 5 \text{ mA}, \quad \beta = 15, \]
\[ P_D\text{ (max)} = 54 \text{ W}, \quad I_C\text{ (max)} = 1.5 \text{ A}, \]
\[ V_{CE\text{ (max)}} = 36 \text{ V}, \]

**Calculations from the designed circuit :**

1. **Worst case power dissipation in the transistor :**

\[ P_D\text{ (max)} = V_{in\text{ (max)}} \times I_L \]
\[ = 24 \times 0.8 = 19.2 \text{ W} \]

...Ans.

This corresponds to short circuited output terminals.
2. **Power dissipated by zener**:

   Maximum zener current corresponds to $V_{in(max)}$.

   $\therefore I_B + I_{Z(max)} = \frac{V_{in(max)} - V_Z}{R_B}$

   $\therefore I_B + I_{Z(max)} = \frac{24 - 12.7}{92} = 122.83 \text{ mA}$

   $\therefore I_{Z(max)} = 122.83 - 50 = 72.83 \text{ mA}$

   $\therefore P_{Z(max)} = V_Z \times I_{Z(max)} = 12.7 \times 72.83 \times 10^{-3}$

   $= 0.9248 \text{ W}$

3. **Maximum power delivered to the load**:

   $P_{L(max)} = V_o \times I_L = 12 \times 0.8 = 9.6 \text{ W}$

4. **Maximum power delivered by input supply**:

   $P_{in(max)} = V_{in(max)} \times [ I_C + I_B + I_{Z(max)} ]$

   $= 24 \times [ 750 + 122.83 ] \text{ mA}$

   $= 20.95 \text{ W}$

5. **Efficiency**:

   $\eta_{min} = \frac{P_{L(max)}}{P_{in(max)}} = \frac{9.6}{20.95} = 0.4582 \text{ or } 45.82\%$

   $\therefore \boxed{\eta_{min} = 0.4582 \text{ or } 45.82\%}$