Solutions Manual

Power Electronics

Circuits, Devices, and Applications

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CHAPTER 2

POWER SEMICONDUCTOR DIODES AND CIRCUITS

Problem 2-1

t_{rr} = 5 μs and di/dt = 80 A/μs

(a) From Eq. (2-10),

Q_{RR} = 0.5 (di/dt) t_{rr}^2 = 0.5 x 80 x 5^2 x 10^{-6} = 1000 μC

(b) From Eq. (2-11),

$$I_{RR} = \sqrt{2Q_{RR}\frac{di}{dt}} = \sqrt{2\times1000\times80} = 400\ A$$

Problem 2-2

V_T = 25.8 mV, V_{D1} = 1.0 V at I_{D1} = 50 A, and V_{D2} = 1.5 V at I_{D2} = 600 A

Taking natural (base e) logarithm on both sides of Eq. (2-3),

$$In\, I_D = In\, I_S + \frac{v_D}{\eta V_T}$$

which, after simplification, gives the diode voltage V_D as

$$v_D = \eta V_T\ In\left(\frac{I_D}{I_S}\right)$$

If I_{D1} is the diode current corresponding to diode voltage V_{D1}, we get

$$V_{D1} = \eta V_T\ In\left(\frac{I_{D1}}{I_S}\right)$$

Similarly, if V_{D2} is the diode voltage corresponding to the diode current I_{D2}, we get

$$V_{D2} = \eta V_T\ In\left(\frac{I_{D2}}{I_S}\right)$$

Therefore, the difference in diode voltages can be expressed by

$$V_{D2} - V_{D1} = \eta V_T\ In\left(\frac{I_{D2}}{I_S}\right) - \eta V_T\ In\left(\frac{I_{D1}}{I_S}\right) = \eta V_T\ In\left(\frac{I_{D2}}{I_{D1}}\right)$$

(a) For V_{D2} = 1.5 V, V_{D1} = 1.0 V, I_{D2} = 600 A, and I_{D1} = 50 A,

$1.5 - 1.0 = \eta \times 0.0258 \times In\left(\frac{600}{50}\right)$, which give $\eta = 7.799$

(b) For V_{D1} = 1.0 V, I_{D1} = 50 A, and η = 7.999

$1.0 = 7.799 \times 0.0258\ In\left(\frac{50}{I_S}\right)$, which gives I_s = 0.347 A.

Problem 2-3

V_{D1} = V_{D2} = 2000 V, R_1 = 100 kΩ

(a) From Fig. P2-3, the leakage current are: I_{S1} = 17 mA and I_{S2} = 25 mA

I_{R1} = V_{D1}/R_1 = 2000/100000 = 20 mA

(b) From Eq. (2-12), $I_{S1} + I_{R1} = I_{S2} + I_{R2}$

or 17 + 20 = 25 + I_{R2}, or I_{R2} = 12 mA

R_2 = 2000/12 mA = 166.67 kΩ

Problem 2-4

For V_D = 1.5 V, Fig. P2-3 gives I_{D1} = 140 A and I_{D2} = 50 A

Problem 2-5

I_T = 200 A, v = 2.5

$I_1 = I_2$, $I_1 = I_T/2$ = 200/2 = 100 A

For I_1 = 100 A, Fig. P2-3 yields V_{D1} = 1.1 V and V_{D2} = 1.95 V

v = $V_{D1} + I_1 R_1$ Or 2.5 = 1.1 + 100 R_1 or R_1 = 14 mΩ

v = $V_{D2} + I_2 R_2$ Or 2.5 = 1.95 + 100 R_2 or R_2 = 5.5 mΩ

Problem 2-6

$R_1 = R_2 = 10\ k\Omega$, $V_s = 5$ kV, $I_{s1} = 25$ mA, $I_{s2} = 40$ mA

From Eq. (2-12), $I_{S1} + I_{R1} = I_{S2} + I_{R2}$

or $I_{S1} + V_{D1}/R_1 = I_{S2} + V_{D2}/R_2$

$25 \times 10^{-3} + V_{D1}/10000 = 40 \times 10^{-3} + V_{D2}/10000$

$V_{D1} + V_{D2} = V_s = 5000$

Solving for V_{D1} and V_{D2} gives $V_{D1} = 2575$ V and $V_{D2} = 2425$ V

Problem 2-7

$t_1 = 100\ \mu s$, $t_2 = 300\ \mu s$, $t_3 = 500\ \mu s$, $f = 250$ Hz, $f_s = 250$ Hz, $I_m = 500$ A and $I_a = 200$ A

(a) The average current is $I_{av} = 2I_m f t_1/\pi - I_a (t_3 - t_2) f = 7.96 - 10 = -2.04$ A.

(b) For sine wave, $I_{r1} = I_m\sqrt{f t_1/2} = 55.9$ A and for a rectangular negative wave, $I_{r2} = I_a\sqrt{f(t_3 - t_2)} = 44.72$ A

The rms current is $I_{rms} = \sqrt{55.92^2 + 44.722^2} = 71.59$ A

(c) The peak current varies from 500 A to -200 A.

Problem 2-8

$t_1 = 100\ \mu s$, $t_2 = 200\ \mu s$, $t_3 = 400\ \mu s$, $t_4 = 800\ \mu s$, $f = 250$ Hz, $I_a = 150$ A, $I_b = 100$ A and $I_p = 300$ A

(a) The average current is

$I_{av} = I_a f t_3 + I_b f(t_5 - t_4) + 2(I_p - I_a) f(t_2 - t_1)/\pi = 15 + 5 + 2.387 = 22.387$ A.

(b) $I_{r1} = \left(I_p - I_a\right)\sqrt{f(t_2 - t_1)/2} = 16.77$ A,

$I_{r2} = I_a\sqrt{f t_3} = 47.43$ A and $I_{r3} = I_b\sqrt{f(t_5 - t_4)} = 22.36$ A

The rms current is $I_{rms} = \sqrt{(16.772^2 + 47.432^2 + 22.362^2)}$ = 55.05 A

Problem 2-9

R = 22 Ω, C = 10 μF, V_o = 220 V

$$0 = v_R + v_C = v_R + \frac{1}{C}\int i\,dt + v_C(t=0)$$

With initial condition: $v_c(t=0) = -V_o$, the current is

$$i(t) = \frac{V_o}{R} e^{-t/RC}$$

The capacitor voltage is

$$v_C(t) = -Ri = -V_o e^{-t/RC} = -220 e^{-t\times 10^6/220}$$

(b) The energy dissipated is

$W = 0.5\, C\, V_o^2 = 0.5 \times 10 \times 10\text{-}6 \times 220 \times 220 = 0.242$ J.

Problem 2-10

R = 10 Ω, L = 5 mH, Vs = 220 V, I_1 = 10 A

The switch current is described by

$$V_S = L\frac{di}{dt} + Ri$$

With initial condition: $i(t=0) = I_1$,

$$i(t) = \frac{V_S}{R}(1 - e^{-tR/L}) + I_1 e^{-tR/L} = 22 - 12e^{-2000t} \text{ A}$$

Problem 2-11

$$V_S = L\frac{di}{dt} + \frac{1}{C}\int i\,dt + v_C(t=0)$$

With initial condition: $i(t=0) = I_o$ and $v_c(t=0) = 0$, we get

$$i(t) = I_o \cos(\omega_o t) + V_S \sqrt{\frac{C}{L}} \sin(\omega_o t)$$

The capacitor voltage is

$$v_C(t) = \frac{1}{C} \int i \, dt = I_o \sqrt{\frac{L}{C}} \sin(\omega_o t) - V_S \cos(\omega_o t) + V_S$$

where $\omega_o = 1/\sqrt{CL}$

Problem 2-12

Fig. p2-12a:

(a) L di/dt or i(t) = V_s t/L

(b) di/dt = V_s/L;

(d) di/dt (at t= 0) = V_s/L.

Fig. p2-12b:

(a) $\frac{1}{C} \int i \, dt + R i = V_S - V_o$ or $i(t) = \frac{V_S - V_o}{R} e^{-t/RC}$

(b) $\frac{di}{dt} = \frac{V_S - V_o}{R^2 C} e^{-t/RC}$

(d) At t = 0, di/dt = (V_s - V_o)/(R^2 C)

Fig. p2-12c:

(a) $L \frac{di}{dt} + R i = V_S$ or $i(t) = \frac{V_S}{R} e^{-t R/L}$

(b) $\frac{di}{dt} = -\frac{V_S}{L} e^{-t R/L}$

(d) At t = 0, di/dt = V_s/L

Fig. p2-12d:

(a) $V_S = L\frac{di}{dt} + \frac{1}{C}\int i\,dt + v_C(t=0)$

With initial condition: $i(t=0) = 0$ and $v_c(t=0) = V_o$,

$$i(t) = \left(V_S - V_o\right)\sqrt{\frac{C}{L}}\sin(\omega_o t) = I_p \sin(\omega_o t)$$

where $\omega_o = 1/\sqrt{LC}$

(b) $\frac{di}{dt} = \frac{V_S - V_o}{L}\cos(\omega_o t)$

(d) At $t = 0$, $di/dt = (V_s - V_o)/L$

Fig. p2-12e:

At t=0, the inductor behaves as an open circuit and a capacitor behaves as a short circuit. Inductor L_1 limits the initial di/dt only. Thus, the initial di/dt is $di/dt = V_s/L_1 = V_s/20\mu H = V_s/20$ A/μs

Problem 2-13

$V_s = 220$ V, $L = 5$ mH, $C = 10$ μF, $R = 22\ \Omega$ and $V_o = 50$ V

(a) From Eq. (2-40), $\alpha = 22 \times 10^3/(2 \times 5) = 2200$

From Eq. (2-41), $\omega_o = 1/\sqrt{(LC)} = 4472$ rad/s

$\omega_r = \sqrt{4472^2 - 2200^2} = 3893$ rad/s

Since $\alpha < \omega_o$, it is an under-damped case and the solution is of the for

$$i(t) = e^{-\alpha t}[A_1\cos(\omega_r t) + A_2\sin(\omega_r t)]$$

At t= 0, i(t=0) = 0 and this gives $A_1 = 0$.

$$i(t) = e^{-\alpha t} A_2 \sin(\omega_r t)$$

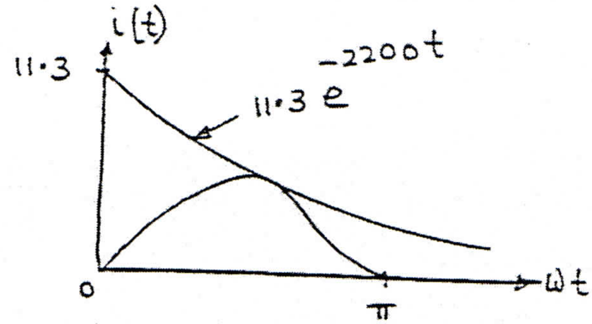
$$\frac{di}{dt} = \omega_r \cos(\omega_r t) A_2 e^{-\alpha t} - \alpha \sin(\omega_r t) A_2 e^{-\alpha t}$$

$$\left.\frac{di}{dt}\right|_{t=0} = \omega_r A_2 = \frac{V_S}{L}$$

or $\quad A_2 = V_s/(\omega_r L) = 220 \times 1000/(3893 \times 5) = 11.3$

The final expression for current i(t) is

$$i(t) = 11.3 \times \sin(3893t) e^{-2200t} \text{ A}$$



(b) The conduction time is

$\omega_r t_1 = \pi$ or $t_1 = \pi/3893 = 807$ μs

(c) The sketch for i(t) is shown.

Problem 2-14

$V_s = 200$ V, $L_m = 150$ μH, $N_1 = 10$, $N_2 = 200$ and $t_1 = 100$ μs

The turns ratio is $a = N_2/N_1 = 200/10 = 20$

(a) From Eq. (2-52) the reverse voltage of diode,

$v_D = 200 \times (1 + 20) = 4620$ V

(b) From Eq. (2-55) the peak value of primary current,

$I_o = 220 \times 100/150 = 146.7$ A

(c) The peak value of secondary current Io' = Io/a = 146.7/20 = 7.3 A

(d) From Eq. (2-58) the conduction time of diode,

t2 = 20 x 100 = 2000 μs.

(e) The energy supplied by the source

$$W = \int_0^{t_1} v\,i\,dt = \int_0^{t_1} V_S \frac{V_S}{L_m} t\,dt = \frac{1}{2}\frac{V_S^2}{L_m} t_1^2$$

From Eq. (2-55), W = 0.5 L_m I_o^2 = 0.5 x 150 x 10-6 x 146.72 = 1.614 J

Problem 2-15

(a) $i_c = i_d + I_m$

$$v_C = \frac{1}{C}\int i_C\,dt + v_C(t=0) = -L\frac{di_d}{dt} = -L\frac{di_C}{dt}$$

With initial condition: $i_c t=0) = I_m$ and $v_c(t=0) = -V_s$,

$$i(t) = V_S\sqrt{\frac{C}{L}}\sin(\omega_o t) + I_m\cos(\omega_o t)$$

where $\omega_o = 1/\sqrt{LC}$

$$v_C(t) = \frac{1}{C}\int_0^t i_C(t)\,dt = I_m\sqrt{\frac{L}{C}}\sin(\omega_o t) - V_S\cos(\omega_o t)$$

$$i_d(t) = V_S\sqrt{\frac{C}{L}}\sin(\omega_o t) + I_m\cos(\omega_o t) - I_m$$

(b) For i_d ($t = t_1$) = 0

$$i_d(t=t_1) = V_S\sqrt{\frac{C}{L}}\sin(\omega_o t_1) + I_m\cos(\omega_o t_1) - I_m = 0$$

or $$\cos(\alpha)\sin(\omega_o t_1) + \sin(\alpha)\cos(\omega_o t_1) = \frac{1}{\sqrt{1+x^2}}$$

or $$\sin(\omega_o t_1 + \alpha) = \frac{1}{\sqrt{1+x^2}}$$

which gives the time t_1

$$\omega_o t_1 = \sin^{-1}\left[\frac{1}{\sqrt{1+x^2}}\right] - \alpha = \sin^{-1}\left[\frac{1}{\sqrt{1+x^2}}\right] - \tan^{-1}\left(\frac{1}{x}\right)$$

where $x = \frac{V_S}{I_m}\sqrt{\frac{C}{L}}$

(c) For $v_c(t=t_q) = 0$

$$v_C(t) = I_m \sqrt{\frac{L}{C}} \sin(\omega_o t) - V_s \cos(\omega_o t) = 0$$

or $\quad t_q = \sqrt{LC}\tan^{-1}(x)$

(d) The time for the capacitor to recharge to the supply voltage at a constant current of I_m, is

$$v_C(t = t_1) = V_s = \frac{1}{C}\int_0^{t_1} I_m dt$$

$$t_1 = V_s C / I_m$$

The total time for discharge and recharge is $t_2 = t_1 + t_q$

CHAPTER 3
DIODE RECTIFIERS

Problem 3-1

V_m = 170 V, R = 10 Ω, f = 60 Hz

From Eq. (3-21), $V_d = 0.6366\ V_m = 0.6366 \times 170 = 113.32$ V

Problem 3-2

V_m = 170 V, R = 10 Ω, f = 60 Hz and L_c = 0.5 mH

From Eq. (3-21), $V_{dc} = 0.6366\ V_m = 0.6366 \times 170 = 113.32$ V

$I_{dc} = V_{dc}/R = 113.32/10 = 11.332$ A

Since there are two commutations per cycle, Eq. (3-79) gives the output voltage reduction, $V_x = 2 \times 60 \times 0.5 \times 10^{-3} \times 11.332 = 0.679$ V and the effective output voltage is (113.32 - 0.679) = 112.64 V

Problem 3-3

R = 10 Ω, V_m = 170 V, f = 60 Hz

For a six-phase star rectifier q = 6 in Eqs. (3-32) and from Eq. (3-32), V_{dc} = 170 (6/π) sin (π/6) = 162.34 V

Problem 3-4

R = 10 Ω, V_m = 170 V, f = 60 Hz, L_c = 0.5 mH

For a six-phase star-rectifier, q = 6 in Eq. (3-69). From Eq. (3-32), V_{dc} = 170 (6/π) sin (π/6) = 162.34, I_{dc} = 162.34/10 = 16.234 A.

Since there are six commutations per cycle, Eq. (3-79) gives the output voltage reduction, $V_x = 6 \times 60 \times 0.5 \times 10^{-3} \times 16.234 = 2.92$ V and the effective output voltage is (162.34 - 2.92) = 159.42 V

Problem 3-5

$R = 100\ \Omega$, $V_s = 280$ V, $f = 60$ Hz

$V_m = 280 \times \sqrt{2}/\sqrt{3} = 228.6$ V

From Eq. (3-40), $V_{dc} = 1.6542 \times 228.6 = 378.15$ V

Problem 3-6

$R = 100\ \Omega$, $V_s = 280$ V, $f = 60$ Hz and $L_c = 0.5$ mH

$V_m = 280 \times \sqrt{2}/\sqrt{3} = 228.6$ V

From Eq. (3-40), $V_{dc} = 1.6542 \times 228.6 = 378.15$ V

$I_{dc} = V_{dc}/R = 378.15/100 = 37.815$ A

Since there are six commutations per cycle, Eq. (3-79) gives the output voltage reduction, $V_x = 6 \times 60 \times 0.5 \times 10^{-3} \times 37.815 = 6.81$ V and the effective output voltage is $(378.15 - 6.81) = 371.34$ V

Problem 3-7

$V_{dc} = 400$ V, $R = 10\ \Omega$

From Eq. (3-21), $V_{dc} = 400 = 0.6366\ V_m$ or $V_m = 628.34$ V

The rms phase voltage is $V_s = V_m/\sqrt{2} = 628.34/\sqrt{2} = 444.3$ V

$I_{dc} = V_{dc}/R = 400/10 = 40$ A

Diodes:

Peak current, $I_p = 628.34/10 = 62.834$ A

Average current, $I_d = I_{dc}/2 = 40/2 = 20$ A

RMS current, $I_R = 62.834/2 = 31.417$ A

Transformer:

RMS voltage, $V_s = V_m/\sqrt{2} = 444.3$ V

RMS current, $I_s = I_m/\sqrt{2} = 44.43$ A

Volt-amp, $VI = 444.3 \times 44.43 = 19.74$ kVA

$P_{dc} = (0.6366\ V_m)^2/R$ and $P_{ac} = V_s I_s = V_m^2/2R$

TUF = $P_{dc}/P_{ac} = 0.6366^2 \times 2 = 0.8105$ and the de-rating factor of the transformer is 1/TUF = 1.2338.

Problem 3-8

$V_{dc} = 750$ V, $I_{dc} = 9000$ A

From Eq. (3-40), $V_{dc} = 750 = 1.6542\ V_m$ or $V_m = 453.39$ V

The phase voltage is $V_s = V_m/\sqrt{2} = 453.39/\sqrt{2} = 320.59$ V

Diodes:

Peak current, $I_p = 9000$ A

Average current, $I_d = I_{dc}/2 = 9000/2 = 4500$ A

RMS current, $I_R = 9000/\sqrt{2} = 6363.96$ A

Transformer:

RMS voltage, $V_s = 320.59$ V

RMS current, $I_s = I_p = 9000$ A

Volt-amp per phase, VI = 320.59 x 9000 = 2885.31 kVA

TUF = P_{dc}/P_{ac} = 750 x 9000/(3 x2885.31) = 0.7798 and the de-rating factor of the transformer is 1/TUF = 1.2824

Problem 3-9

$V_m = 170$ V, f = 60 Hz, R = 15 Ω and $\omega = 2\pi f = 377$ rad/s

From Eq. (3-22), the output voltage is

$$v_L(t) = \frac{2V_m}{\pi} - \frac{4V_m}{3\pi}\cos(2\omega t) - \frac{4V_m}{15\pi}\cos(4\omega t) - \frac{4V_m}{35\pi}\cos(6\omega t) - ..\infty$$

The load impedance, $Z = R + j(n\omega L) = \sqrt{R^2 + (n\omega L)^2}\angle\theta_n$

and $\theta_n = \tan^{-1}(n\omega L / R)$

and the load current is given by

$$i_L(t) = I_{dc} - \frac{4V_m}{\pi\sqrt{R^2 + (n\omega L)^2}}\left[\frac{1}{3}\cos\left(2\omega t - \theta_2\right) - \frac{1}{15}\cos\left(4\omega t - \theta_4\right) - \frac{1}{35}\cos\left(6\omega t - \theta_6\right) - ..\infty\right]$$

where $\quad I_{dc} = \frac{V_{dc}}{R} = \frac{2V_m}{\pi R}$

The rms value of the ripple current is

$$I_{ac}^2 = \frac{(4V_m)^2}{2\pi^2[R^2 + (2\omega L)^2]}\left(\frac{1}{3}\right)^2 + \frac{(4V_m)^2}{2\pi^2[R^2 + (4\omega L)^2]}\left(\frac{1}{15}\right)^2 + \frac{(4V_m)^2}{2\pi^2[R^2 + (6\omega L)^2]}\left(\frac{1}{35}\right)^2 + ..\infty$$

Considering only the lowest order harmonic (n = 2) and neglecting others,

$$I_{ac} = \frac{4V_m}{\sqrt{2}\pi\sqrt{R^2 + (2\omega L)^2}}\left(\frac{1}{3}\right)$$

Using the value of I_{dc} and after simplification, the ripple factor is

$$RF = \frac{I_{ac}}{I_{dc}} = \frac{0.481}{\sqrt{1 + (2\omega L / R)^2}} = 0.04$$

$0.481^2 = 0.04^2\ [1 + (2 \times 377\ L/15)^2]$ or L = 238.4 mH

Problem 3-10

V_m = 170 V, f = 60 Hz, R = 15 Ω and $\omega = 2\pi f$ = 377 rad/s

For q = 6, Eq. (3-39) gives the output voltage as

$$v_L(t) = 0.9549V_m\left[1 + \frac{2}{35}\cos(6\omega t) - \frac{2}{143}\cos(12\omega t) + ..\infty\right]$$

The load impedance, $Z = R + j(n\omega L) = \sqrt{R^2 + (n\omega L)^2}\angle\theta_n$

and $\theta_n = \tan^{-1}(n\omega L / R)$

and the load current is

$$i_L(t) = I_{dc} - \frac{0.9549V_m}{\sqrt{R^2 + (n\omega L)^2}}\left[\frac{2}{35}\cos(6\omega t - \theta_6) - \frac{2}{143}\cos(12\omega t - \theta_{12}) + ..\infty\right]$$

where $I_{dc} = \frac{V_{dc}}{R} = \frac{0.9549V_m}{R}$

The rms value of the ripple current is

$$I_{ac}^2 = \frac{(0.9549V_m)^2}{2[R^2+(6\omega L)^2]}\left(\frac{2}{35}\right)^2 + \frac{(0.9549V_m)^2}{2[R^2+(12\omega L)^2]}\left(\frac{2}{143}\right)^2 + ..\infty$$

Considering only the lowest order harmonic (n = 6) and neglecting others,

$$I_{ac} = \frac{0.9549V_m}{\sqrt{2}\sqrt{R^2+(6\omega L)^2}}\left(\frac{2}{35}\right)$$

Using the value of I_{dc} and after simplification, the ripple factor is

$$RF = \frac{I_{ac}}{I_{dc}} = \frac{1}{\sqrt{2}\times\sqrt{1+(6\omega L/R)^2}}\left(\frac{2}{35}\right) = 0.02$$

$0.0404^2 = 0.02^2\ [1 + (6 \times 377\ L/15)^2]$ or L = 11.64 mH

Problem 3-11

E = 20 V, I_{dc} = 10 A, V_p = 120 V, $V_s = V_p/n$ = 120/2 = 60 V

$V_m = \sqrt{2}\ V_s = \sqrt{2} \times 60$ = 84.85 V

(i) From Eq. (3-17), $\alpha = \sin^{-1}(20/84.85) = 15.15^\circ$ or 0.264 rad

$\beta = 180 - 15.15 = 164.85^\circ$

The conduction angle is $\delta = \beta - \alpha = 164.85 - 15.15 = 149.7^\circ$

(ii) Equation (3-18) gives the resistance R as

$$R = \frac{1}{2\pi I_{dc}}\left[2V_m \cos\alpha + 2\alpha E - \pi E\right]$$

$$R = \frac{1}{2\pi\times 10}\left[2 \times 84.85 \times \cos 15.15^\circ + 2 \times 20 \times 0.264 - \pi \times 20\right] = 1.793\ \Omega$$

(iii) Equation (3-19) gives the rms battery current I_{rms} as

$$I_{rms}^2 = \frac{1}{2\pi R^2}\left[\left(\frac{V_m^2}{2} + E^2\right)\times(\pi - 2\alpha) + \frac{V_m^2}{2}\sin 2\alpha - 4V_m E\cos\alpha\right] = 272.6$$

or $I_{rms} = \sqrt{272.6}$ = 16.51 A

The power rating of R is $P_R = 16.51^2 \times 1.793 = 488.8$ W

(iv) The power delivered P_{dc} to the battery is

$P_{dc} = E\, I_{dc} = 20 \times 10 = 200$ W

$h\, P_{dc} = 100$ or $h = 200/P_{dc} = 200/200 = 1$ hr

(v) The rectifier efficiency η is

$$\eta = \frac{P_{dc}}{P_{dc} + P_R} = \frac{200}{200 + 488.8} = 29\%$$

(vi) The peak inverse voltage PIV of the diode is

$PIV = V_m + E = 84.85 + 20 = 104.85$ V

Problem 3-12

It is not known whether the load current is continuous or discontinuous. Let us assume that the load current is continuous and proceed with the solution. If the assumption is not correct, the load current will be zero current and then move to the case for a discontinuous current.

(a) $R = 5\ \Omega$, $L = 4.5$ mH, $f = 60$ Hz, $\omega = 2\pi \times 60 = 377$ rad/s, $V_s = 120$ V,

$Z = [R^2 + (\omega L)^2]^{1/2} = 5.28\ \Omega$, and $\theta = \tan^{-1}(\omega L/R) = 18.74°$

(i) The steady-state load current at $\omega t = 0$, $I_1 = 6.33$ A. Since $I_1 > 0$, the load current is continuous and the assumption is correct.

(ii) The numerical integration of i_L in Eq. (3-27) yields the average diode current as $I_d = 8.8$ A

(iii) By numerical integration of i_L^2 between the limits $\omega t = 0$ to π, we get the rms diode current as $I_r = 13.83$ A.

(iv) The rms output current $I_{rms} = \sqrt{2}\, I_r = \sqrt{2} \times 13.83 = 19.56$ A

Problem 3-13

(a) $R = 5\ \Omega$, $L = 2.5$ mH, $f = 60$ Hz, $\omega = 2\pi \times 60 = 377$ rad/s, $V_{ab} = 208$ V,

$Z = [R^2 + (\omega L)^2]^{1/2} = 5.09\ \Omega$, and $\theta = \tan^{-1}(\omega L/R) = 10.67°$

(i) The steady-state load current at $\omega t = \pi/3$, $I_1 = 50.6$ A.

(ii) The numerical integration of i_L in Eq. (3-47) yields the average diode current as $I_d = 17.46$ A. Since $I_1 > 0$, the load current is continuous.

(iii) By numerical integration of i_L^2 between the limits $\omega t = \pi/3$ to $2\pi/3$, we get the rms diode current as $I_r = 30.2$ A.

(iv) The rms output current $I_{rms} = \sqrt{3}\, I_r = \sqrt{3} \times 30.2 = 52.31$ A

Problem 3-14

RF = 5%, $R = 200\ \Omega$ and $f = 60$ Hz

(a) Solving for C_e in Eq. (3-62),

$$C_e = \frac{1}{4 \times 60 \times 200}\left[1 + \frac{1}{\sqrt{2} \times 0.05}\right] = 315.46\ \mu\text{F}$$

(b) From Eq. (3-61), the average load voltage V_{dc} is

$$V_{dc} = 169.7 - \frac{169.7}{4 \times 60 \times 200 \times 415.46 \times 10^{-6}} = 169.7 - 11.21 = 158.49\ \text{V}$$

Problem 3-15

RF = 5%, $R = 200\ \Omega$, and $f = 60$ Hz

(a) For a half-wave rectifier, the frequency of output ripple voltage is the same as the supply frequency. Thus, the constant 4 in Eq. (3-62) should be changed to 2.

Solving for C_e in Eq. (3-62),

$$C_e = \frac{1}{2 \times 60 \times 200}\left[1 + \frac{1}{\sqrt{2} \times 0.05}\right] = 630.92\ \mu\text{F}$$

(b) From Eq. (3-61), the average load voltage V_{dc} is

$$V_{dc} = 169.7 - \frac{169.7}{2 \times 60 \times 200 \times 415.46 \times 10^{-6}} = 169.7 - 22.42 = 147.28 \text{ V}$$

Problem 3-16

$\omega = 2\pi \times 60 = 377$ rad/s, $V_{dc} = 48$ V, $V_s = 120$ V, $V_m = \sqrt{2} \times 120 = 169.7$ V

(a) Voltage ratio $x = V_{dc}/V_m = 48/169.7 = 28.28$ %

$\alpha = \sin^{-1}(x) = 16.43°$

Solving Eq. (3-70) for ß gives: $\beta = 117.43°$

Equation (3-105) gives the current ratio $I_{dc}/Ipk = 13.425$ %

Thus, $I_{pk} = I_{dc}/0.13425 = 186.22$ A

The required value of inductance is

$L_e = V_m/(\omega I_{pk}) = 169.7/(377 \times 186.22) = 2.42$ mH.

Equation (3-106) gives the current ratio $I_{rms}/Ipk = 22.59$ %

Thus $I_{rms} = 0.2259 \times I_{pk} = 0.2259 \times 186.22 = 42.07$ A

(b) $I_{dc} = 15$ A, $L_e = 6.5$ mH, $I_{pk} = V_m/(\omega L_e) = 169.7/(377 \times 6.5 \text{ mH}) =$ 69.25 A

$y = I_{dc}/I_{pk} = 15/69.25 = 21.66\%$

Using linear interpolation, we get

$x = x_n - (x_{n+1} - x_n)(y_n - y)/(y_{n+1} - y_n)$

$= 10 - (15 - 10)(25.5 - 21.66)/(21.5 - 25.5) = 14.8\%$

$V_{dc} = x V_m = 0.148 \text{ X } 169.7 = 25.12$ V

$\alpha = \alpha_n - (\alpha_{n+1} - \alpha_n)(y_n - y)/(y_{n+1} - y_n)$

$= 5.74 - (8.63 - 5.74)(25.5 - 21.66)/(21.5 - 25.5) = 8.51°$.

$\beta = \beta_n - (\beta_{n+1} - \beta_n)(y_n - y)/(y_{n+1} - y_n)$

$= 139.74 - (131.88 - 139.74)(25.5 - 21.66)/(21.5 - 25.5) = 132.19°$.

$z = I_{rms}/I_{pk} = z_n - (z_{n+1} - x_n)(y_n - y)/(y_{n+1} - y_n)$

$= 37.06 - (32.58 - 37.06)(25.5 - 21.66)/(21.5 - 25.5) = 32.76\%$

Thus $I_{rms} = 0.3276 \times I_{pk} = 0.3276 \times 69.25 = 22.69$ A

(a)

$f := 60 \quad Vdc := 48 \quad Idc := 25 \quad \omega := 2\cdot\pi\cdot f \quad \omega = 376.99$

$Vs := 120 \quad Vm := \sqrt{2}\cdot Vs$

$x := \dfrac{Vdc}{Vm} \quad \alpha := \mathrm{asin}(x) \quad 180\cdot\dfrac{\alpha}{\pi} = 16.43$

$k := \sqrt{1-(x)^2} + \left(\dfrac{2}{\pi} - \dfrac{\pi}{2}\right)x \quad 100\cdot k = 69.49$

$Ipk := \dfrac{Idc}{k} \quad Ipk = 35.97$

$Lcr := \dfrac{Vm}{\omega\cdot Ipk} \quad 1000\cdot Lcr = 12.51 \quad \text{mH}$

$$k_r := \sqrt{\frac{1}{\pi}\cdot\left[\int_{\alpha}^{\alpha+\pi}\left[(\cos(\alpha) - \cos(\phi)) - x\cdot(\phi-\alpha)\right]^2 d\phi\right]}$$

$100\cdot k_r = 81.91$

$Irms := k_r\cdot Ipk \quad Irms = 29.47$

(b)

$I_{dc} := 15 \qquad Ipk := 69.25$

$$k := \frac{100 \cdot I_{dc}}{Ipk} \qquad k = 21.66$$

$x_n := 60 \qquad x_{n1} := 65$

$\alpha_n := 36.87 \qquad \alpha_{n1} := 40.54$

$k_n := 23.95 \qquad k_{n1} := 15.27$

$kr_n := 31.05 \qquad kr_{n1} := 26.58$

$$x := x_n + \left[\frac{(x_{n1} - x_n)\cdot(k - k_n)}{k_{n1} - k_n}\right] \qquad x = 61.32$$

$$Vdc := x \cdot \frac{Vm}{100} \qquad Vdc = 104.06$$

$$\alpha := \alpha_n + \left[\frac{(\alpha_{n1} - \alpha_n)\cdot(k - k_n)}{k_{n1} - k_n}\right] \qquad \alpha = 37.84$$

$$kr := kr_n + \left[\frac{(kr_{n1} - kr_n)\cdot(k - k_n)}{k_{n1} - k_n}\right] \qquad kr = 29.87$$

$$Irms := \frac{kr \cdot Ipk}{100} \qquad Irms = 20.69$$

Problem 3-17

Let t_1 and t_2 be the charging and discharging time of capacitor. For a single-phase full-wave rectifier, the period of output voltage is T/2, where T is the period of the input voltage and the supply frequency is f = 1/T.

$t_1 + t_2 = T/2$. If $t_2 >> t_1$ which is normally the case, $t_2 \approx T/2$

During discharging of the capacitor, the capacitor discharges exponentially and the output (or capacitor) voltage is

$$v_o(t) = V_m\, e^{-t/RC}$$

where V_m is the peak value of supply voltage.

The peak-to-peak ripple voltage is

$$v_r = v_o(t = t_1) - v_o(t = t_2) = V_m - V_m\, e^{-t_2/RC} = V_m[1 - e^{-t_2/RC}]$$

Since, $e^{-x} \approx 1 - x$, $v_r = V_m (1 - 1 + t_2/RC) = V_m t_2/RC = V_m/(2fRC)$

Thus, the rms value of the output voltage harmonics is

$$V_{ac} = \frac{v_r}{2\sqrt{2}} = \frac{V_m}{4\sqrt{2}\, f\, RC}$$

Problem 3-18

R = 20 Ω, L = 5 mH, f = 60 Hz, $\omega = 2\pi f = 377$ rad/s

Taking a ratio of 10:1, the value of the capacitor is given by

$$\sqrt{R^2 + (6\omega L)^2} = \frac{10}{6\omega C_e}$$

or $$C_e = \frac{10}{6\times 377\sqrt{R^2 + (6\times 377 L)^2}} = 192.4\ \mu\text{F}$$

From Eq. (3-39), the rms value of the 6th harmonic is

$$V_6 = \frac{2}{35\sqrt{2}} \times 0.9549 V_m$$

From Eq. (3-64), the rms vale of the ripple voltage is

$$V_{ac} = \frac{V_6}{(n\omega)^2 L_1 C - 1} = \frac{2}{35\sqrt{2}} \times \frac{0.9549 V_m}{(6\omega)^2 L_1 C - 1}$$

$V_{dc} = 0.9549\ V_m$

The ripple factor is

$$RF = \frac{V_{ac}}{V_{dc}} = \frac{\sqrt{2}}{35} \times \frac{1}{(6\omega)^2 L_1 C - 1} = 0.05$$

or $(6\omega)^2 L_1C - 1 = 0.808$ and $L_1 = 1.837$ mH

Problem 3-19

(a) With q = 6, Eq. (3-39) gives the output voltage as

$$v_L(t) = 0.9549 V_m \left[1 + \frac{2}{35}\cos(6\omega t) - \frac{2}{143}\cos(12\omega t) + ..\infty\right]$$

The load impedance, $Z = R + j(n\omega L) = \sqrt{R^2 + (n\omega L)^2} \angle \theta_n$

and $\theta_n = \tan^{-1}(n\omega L / R)$

and the load current is

$$i_L(t) = I_{dc} - \frac{0.9549 V_m}{\sqrt{R^2 + (n\omega L)^2}}\left[\frac{2}{35}\cos\left(6\omega t - \theta_6\right) - \frac{2}{143}\cos\left(12\omega t - \theta_{12}\right) + ..\infty\right]$$

where $$I_{dc} = \frac{V_{dc}}{R} = \frac{0.9549 V_m}{R}$$

(b) $V_m = 170$ V, f = 60 Hz, R = 200 Ω, ω = 2π f = 377 rad/s

The rms value of the ripple current is

$$I_{ac}^2 = \frac{(0.9549V_m)^2}{2[R^2 + (6\omega L)^2]}\left(\frac{2}{35}\right)^2 + \frac{(0.9549V_m)^2}{2[R^2 + (12\omega L)^2]}\left(\frac{2}{143}\right)^2 + ..\infty$$

Considering only the lowest order harmonic (n = 6) and neglecting others,

$$I_{ac} = \frac{0.9549 V_m}{\sqrt{2}\sqrt{R^2 + (6\omega L)^2}}\left(\frac{2}{35}\right)$$

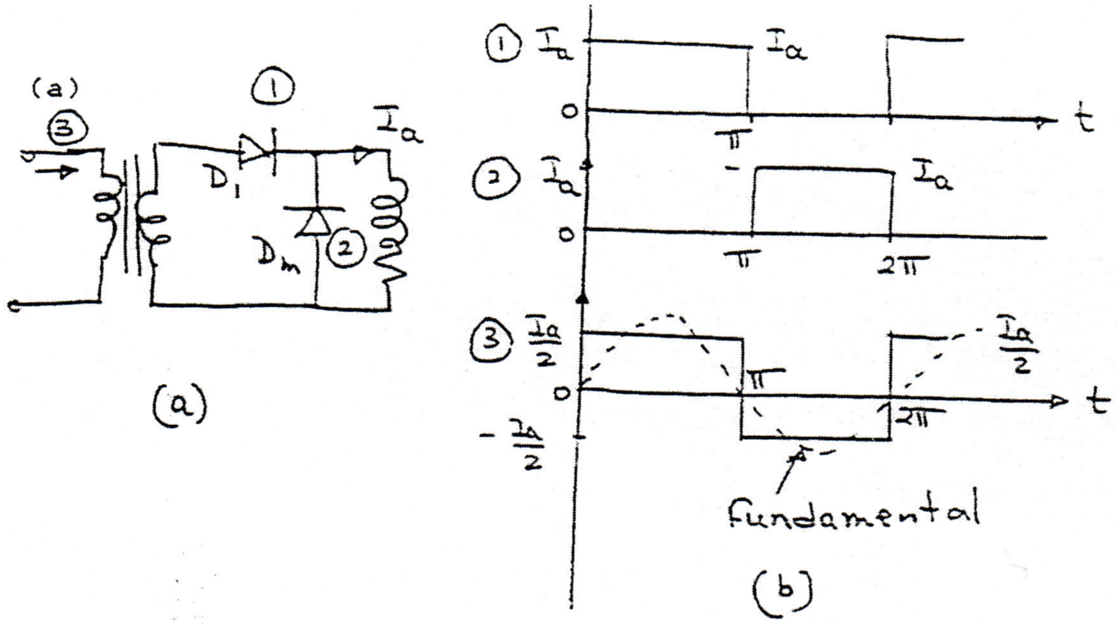
Using the value of I_{dc} and after simplification, the ripple factor is

$$RF = \frac{I_{ac}}{I_{dc}} = \frac{1}{\sqrt{2} \times \sqrt{1 + (6\omega L / R)^2}}\left(\frac{2}{35}\right) = 0.02$$

$0.0404^2 = 0.02^2 [1 + (6 \times 377 L/200)^2]$ or L = 11.64 mH

Problem 3-20

(a)



(b) For the primary (or supply) current,

$a_o = 0$

$$a_n = \frac{1}{\pi}\int_0^{2\pi} \frac{I_a}{2} \cos(n\theta)\, d\theta = 0$$

$$b_n = \frac{1}{\pi}\int_0^{2\pi} \frac{I_a}{2} \sin(n\theta)\, d\theta = \frac{2I_a}{n\pi}$$

$\varphi_n = \tan^{-1}(a_n/b_n) = 0$

$$i_s(t) = \frac{2I_a}{\pi}\left[\frac{\sin\omega t}{1} + \frac{\sin 3\omega t}{3} + \frac{\sin 5\omega t}{5} + ..\infty\right]$$

The rms value of the fundamental current is

$I_1 = 2I_a/(\pi\sqrt{2})$

The rms current is $I_s = I_a/2$. At the primary (or supply) side, $PF = I_1/I_s =$

$2\sqrt{2}/\pi = 0.9$ and $HF = \sqrt{(I_s/I_1)^2 - 1} = 0.4834$.

(c) For the rectifier input (or secondary) side,

$a_o/2 = I_a/2$

$$a_n = \frac{1}{\pi}\int_0^{\pi} I_a \cos(n\theta)\, d\theta = 0$$

$$b_n = \frac{1}{\pi}\int_0^{\pi} I_a \sin(n\theta)\, d\theta = \frac{I_a}{n\pi}(1 - \cos n\theta)$$

$\varphi_n = \tan^{-1} (a_n/b_n) = 0$

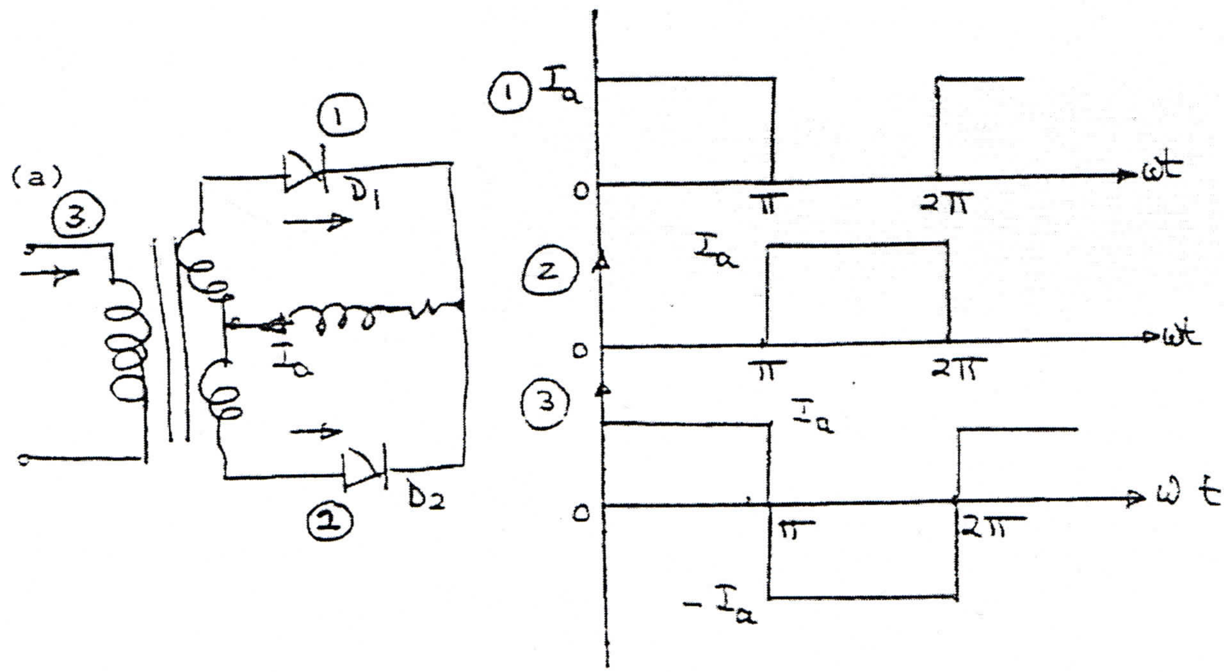
$C_n = \sqrt{(a_n^2 + b_n^2)}$ and $I_1 = C_1/\sqrt{2} = \sqrt{2}I_a/\pi$

and $I_s = I_a/\sqrt{2}$

PF = $I_1/I_s = 2/\pi = 0.6366$ and $HF = \sqrt{(I_s/I_1)^2 - 1} = 1.211$

Problem 3-21

(a)



(b) For the primary (or supply) current: From Eq. (3-23), the primary current is

$$i_s(t) = \frac{4I_a}{\pi}\left[\frac{\sin\omega t}{1} + \frac{\sin 3\omega t}{3} + \frac{\sin 5\omega t}{5} + ..\infty\right]$$

$I_1 = 4I_a/(\pi\sqrt{2})$

The rms current is $I_s = I_a$. PF = $I_1/I_s = 2\sqrt{2}/\pi = 0.9$ and $HF = \sqrt{(I_s/I_1)^2 - 1} =$ 0.4834.

(c) For the rectifier input (or secondary) current:

$a_o/2 = I_a/2$

$$a_n = \frac{1}{\pi}\int_0^{\pi} I_a \cos(n\theta)\, d\theta = 0$$

$$b_n = \frac{1}{\pi}\int_0^{\pi} I_a \sin(n\theta)\, d\theta = \frac{I_a}{n\pi}(1 - \cos n\theta)$$

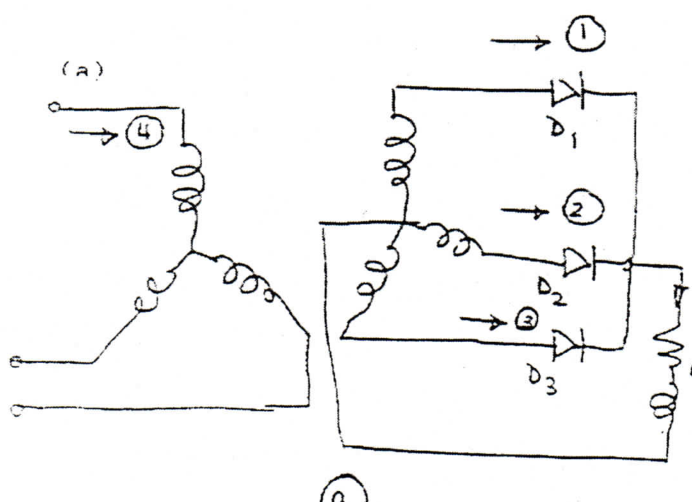
$\varphi_n = \tan^{-1}(a_n/b_n) = 0$

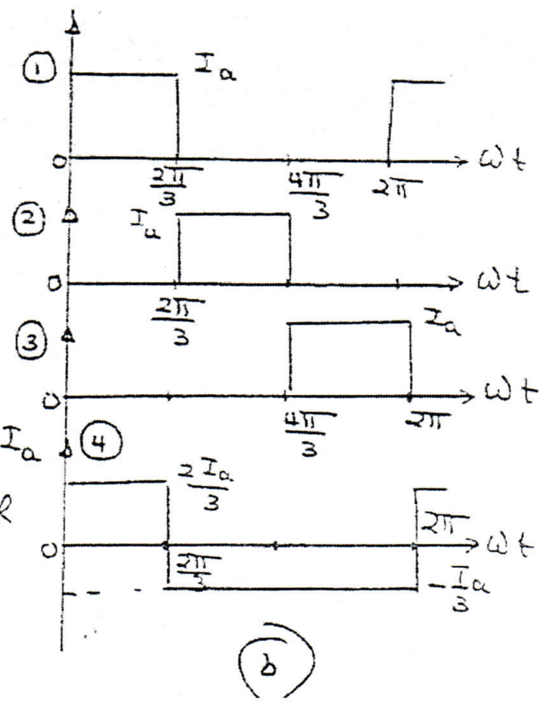
$C_n = \sqrt{(a_n^2 + b_n^2)}$ and $I_1 = C_1/\sqrt{2} = \sqrt{2}I_a/\pi$

and $I_s = I_a/\sqrt{2}$

PF = $I_1/I_s = 2/\pi = 0.6366$ and $HF = \sqrt{(I_s/I_1)^2 - 1} = 1.211$

Problem 3-22 (a)





(b) For the primary (or secondary) phase (or line) current:

$a_o/2 = 0$

$$a_n = \frac{1}{\pi}\int_{\pi/6}^{5\pi/6}\frac{2I_a}{3}\cos(n\theta)\,d\theta - \frac{1}{\pi}\int_{5\pi/6}^{2\pi+\pi/6}\frac{I_a}{3}\cos(n\theta)\,d\theta$$
$$= \frac{2I_a}{n\pi}\cos\frac{n\pi}{2}\sin\frac{n\pi}{3}$$

$$b_n = \frac{1}{\pi}\int_{\pi/6}^{5\pi/6}\frac{2I_a}{3}\sin(n\theta)\,d\theta - \frac{1}{\pi}\int_{5\pi/6}^{2\pi+\pi/6}\frac{I_a}{3}\sin(n\theta)\,d\theta$$
$$= \frac{2I_a}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}$$

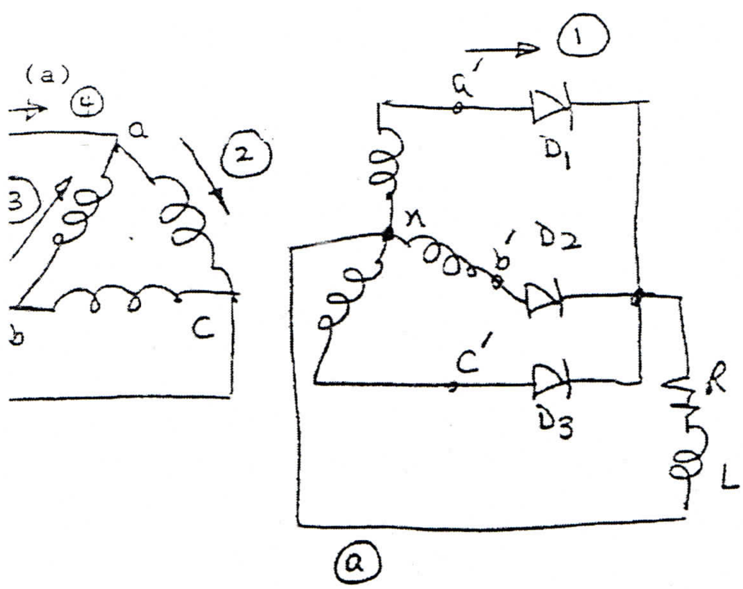
$$C_n = \sqrt{a_n^2 + b_n^2} = \frac{2I_a}{n\pi}\sin\frac{n\pi}{3}$$

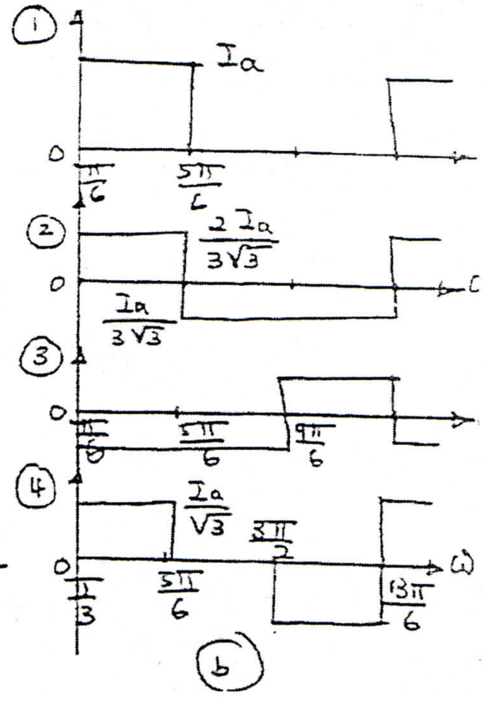
$\varphi_n = \tan^{-1}(a_n/b_n) = \tan^{-1}(\cot n\pi/2)$

(c) $I_1 = C_1/\sqrt{2} = \sqrt{3}I_a/(\pi\sqrt{2})$, $\varphi_1 = 0$ and $I_s = \sqrt{2}\, I_a/3$

PF = $I_1/I_s = 3\sqrt{3}/2\pi = 0.827$ and $HF = \sqrt{(I_s/I_1)^2 - 1} = 0.68$

Problem 3-23 (a)





(b) For the primary line current:

$a_o/2 = 0$

$$a_n = \frac{1}{\pi}\int_{\pi/6}^{5\pi/6} \frac{I_a}{\sqrt{3}}\cos(n\theta)\,d\theta - \frac{1}{\pi}\int_{3\pi/2}^{2\pi+\pi/6} \frac{I_a}{\sqrt{3}}\cos(n\theta)\,d\theta$$

$$= -\frac{2I_a}{\sqrt{3}\,n\pi}\sin\frac{n\pi}{6}(1-\cos\frac{2n\pi}{3})$$

$$b_n = \frac{1}{\pi}\int_{\pi/6}^{5\pi/6} \frac{I_a}{\sqrt{3}}\sin(n\theta)\,d\theta - \frac{1}{\pi}\int_{3\pi/2}^{2\pi+\pi/6} \frac{I_a}{\sqrt{3}}\sin(n\theta)\,d\theta$$

$$= \frac{2I_a}{\sqrt{3}\,n\pi}\cos\frac{n\pi}{6}(1-\cos\frac{2n\pi}{3})$$

$$C_n = \sqrt{a_n^2 + b_n^2} = \frac{2I_a}{\sqrt{3}\,n\pi}(1-\cos\frac{2n\pi}{3})$$

$\varphi_n = \tan^{-1}(a_n/b_n) = \tan^{-1}(-\tan n\pi/6) = -n\pi/6$

$I_1 = C_1/\sqrt{2} = \sqrt{3}I_a/(\pi\sqrt{2})$, $\varphi_1 = -\pi/6$ and $I_s = \sqrt{2}\,I_a/3$

(c) For the secondary (or primary) phase current,

$a_o/2 = 0$

$$a_n = \frac{1}{\pi}\int_{\pi/6}^{5\pi/6} \frac{2I_a}{3\sqrt{3}}\cos(n\theta)\,d\theta - \frac{1}{\pi}\int_{5\pi/6}^{2\pi+\pi/6} \frac{I_a}{3\sqrt{3}}\cos(n\theta)\,d\theta$$

$$= \frac{2I_a}{\sqrt{3}\,n\pi}\cos\frac{n\pi}{2}\sin\frac{n\pi}{3}$$

$$b_n = \frac{1}{\pi}\int_{\pi/6}^{5\pi/6} \frac{2I_a}{3\sqrt{3}}\sin(n\theta)\,d\theta - \frac{1}{\pi}\int_{5\pi/6}^{2\pi+\pi/6} \frac{I_a}{3\sqrt{3}}\sin(n\theta)\,d\theta$$

$$= \frac{2I_a}{\sqrt{3}\,n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}$$

$$C_n = \sqrt{a_n^2 + b_n^2} = \frac{2I_a}{3n\pi}\sin\frac{n\pi}{3}$$

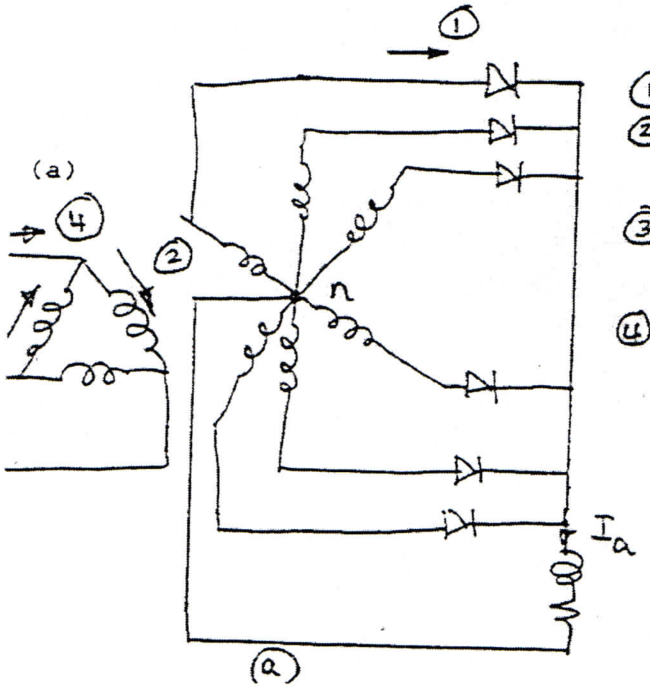
$\varphi_n = \tan^{-1}(a_n/b_n) = \tan^{-1}(\cot n\pi/2) = n\pi/2$

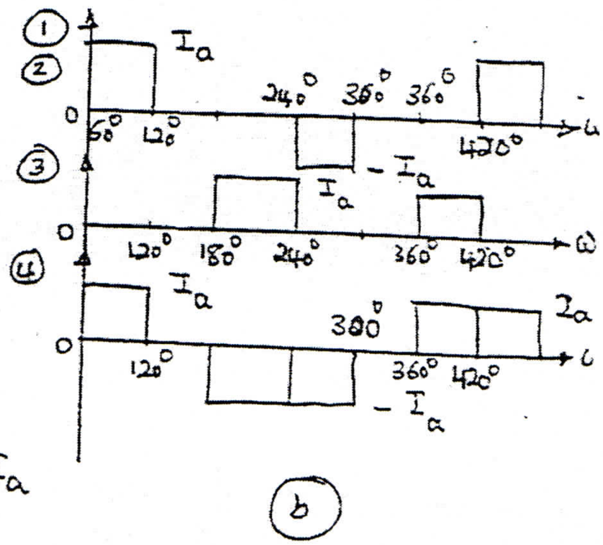
$I_1 = C_1/\sqrt{2} = I_a/(\pi\sqrt{2})$, $\varphi_1 = 0$ and $I_s = \sqrt{2}\,I_a/(3\sqrt{3})$

$PF = I_1/I_s = 3\sqrt{3}/2\pi = 0.827$ and $HF = \sqrt{(I_s/I_1)^2 - 1} = 0.68$

Problem 3-24

(a)





(b) For the primary line current:

$a_o/2 = 0$

$$a_n = \frac{I_a}{\pi}\left[\int_{\pi/3}^{2\pi/3}\cos(n\theta)\,d\theta - \int_{\pi}^{5\pi/3}\cos(n\theta)\,d\theta + \int_{2\pi}^{2\pi+\pi/3}\cos(n\theta)\,d\theta\right]$$

$$= -\frac{2I_a}{n\pi}\sin\frac{n\pi}{2}\cos\frac{7n\pi}{6}$$

$$b_n = \frac{I_a}{\pi}\left[\int_{\pi/3}^{2\pi/3}\sin(n\theta)\,d\theta - \int_{\pi}^{5\pi/3}\sin(n\theta)\,d\theta + \int_{2\pi}^{2\pi+\pi/3}\sin(n\theta)\,d\theta\right]$$

$$= \frac{I_a}{n\pi}\left(1-\cos n\pi - 2\sin\frac{n\pi}{2}\cos\frac{7n\pi}{6}\right)$$

For $n = 1$, $C_1 = \sqrt{(a_1^2 + b_1^2)} = 2\sqrt{3}I_a/\pi$

$\varphi_1 = \tan^{-1}(a_1/b_1) = \tan^{-1}(1/\sqrt{3}) = \pi/6$

$I_1 = C_1/2 = \sqrt{2}\,\sqrt{3} I_a/\pi$, and $I_s = I_a \sqrt{(2/3)}$

(c) For the secondary or primary phase current,

$a_o/2 = 0$

$$a_n = \frac{I_a}{\pi}\left[\int_{\pi/3}^{2\pi/3}\cos(n\theta)\,d\theta - \int_{4\pi/3}^{5\pi/3}\cos(n\theta)\,d\theta\right] = 0$$

$$b_n = \frac{I_a}{\pi}\left[\int_{\pi/3}^{2\pi/3}\sin(n\theta)\,d\theta - \int_{4\pi/3}^{5\pi/3}\sin(n\theta)\,d\theta\right]$$

$$= \frac{4I_a}{n\pi}\sin\frac{n\pi}{2}\,\sin\frac{n\pi}{6}$$

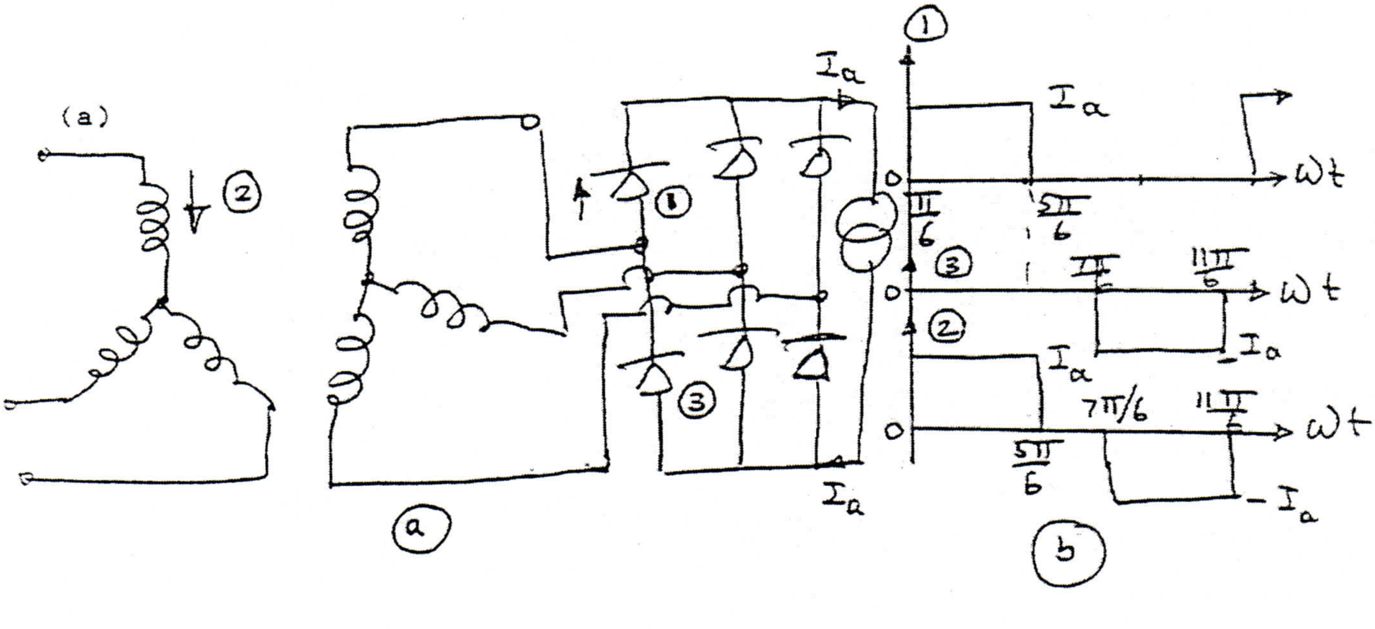
$C_n = b_n$ and $\varphi_n = 0$

$C_1 = 2\,I_a/\pi$, $I_1 = C_1/\sqrt{2} = 2I_a/(\sqrt{2}\,\pi)$, $\varphi_1 = 0$ and $I_s = I_a/\sqrt{3}$

$PF = I_1/I_s = \sqrt{2}\,\sqrt{3}/\pi = 0.78$ and $HF = \sqrt{(I_s/I_1)^2 - 1} = 0.803$

Problem 3-25

(a)



(b) For the primary (or secondary) phase (or line) current:

$a_o/2 = 0$

$$a_n = \frac{2I_a}{\pi}\int_{\pi/6}^{5\pi/6}\cos(n\theta)\,d\theta = \frac{4I_a}{n\pi}\sin\frac{n\pi}{3}\cos\frac{n\pi}{2}$$

$$b_n = \frac{2I_a}{\pi}\int_{\pi/6}^{5\pi/6}\sin(n\theta)\,d\theta = \frac{4I_a}{n\pi}\sin\frac{n\pi}{3}\sin\frac{n\pi}{2}$$

$C_n = \frac{4I_a}{n\pi}\sin\frac{n\pi}{3}$ and $\varphi_n = \tan^{-1}(a_n/b_n) = \tan^{-1}(\cot n\pi/2)$

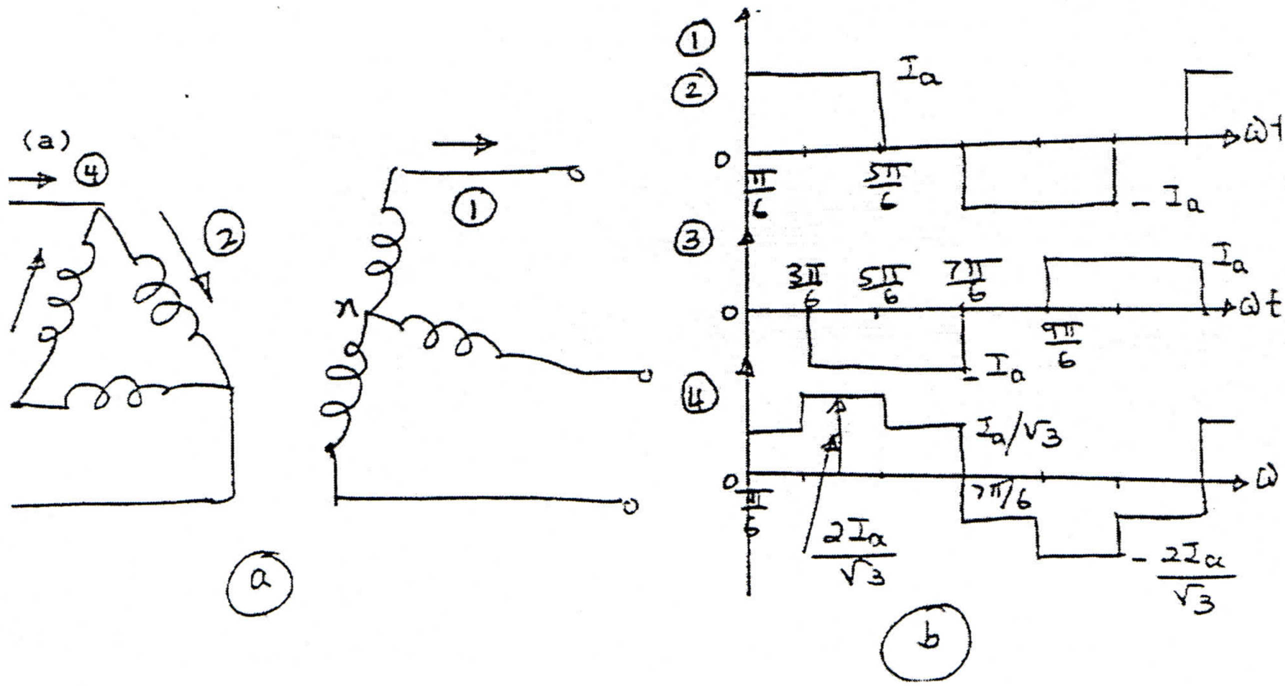
(c) $C_1 = 2\sqrt{3}I_a/\pi$ and $\varphi_1 = 0$

$I_1 = C_1/\sqrt{2} = \sqrt{2}\,\sqrt{3}I_a/\pi$, and $I_s = I_a\sqrt{(2/3)}$

PF = $I_1/I_s = 3/\pi = 0.9549$ and $HF = \sqrt{(I_s/I_1)^2 - 1} = 0.3108$

Problem 3-26

(a)



(b) For the primary line current,

$a_o/2 = 0$

$$a_n = \frac{2I_a}{\sqrt{3}\pi}\left[\int_{\pi/6}^{\pi/2}\cos(n\theta)\,d\theta + \int_{\pi/2}^{5\pi/6}2\cos(n\theta)\,d\theta + \int_{5\pi/6}^{7\pi/6}\cos(n\theta)\,d\theta\right]$$

$$= -\frac{8I_a}{\sqrt{3}n\pi}\cos\frac{2n\pi}{3}\sin\frac{n\pi}{3}\cos\frac{n\pi}{6}$$

$$b_n = \frac{2I_a}{\sqrt{3}\pi}\left[\int_{\pi/6}^{\pi/2}\sin(n\theta)\,d\theta + \int_{\pi/2}^{5\pi/6}2\sin(n\theta)\,d\theta + \int_{5\pi/6}^{7\pi/6}\sin(n\theta)\,d\theta\right]$$

$$= \frac{8I_a}{\sqrt{3}n\pi}\sin\frac{2n\pi}{3}\sin\frac{n\pi}{3}\cos\frac{n\pi}{6}$$

$$C_n = \frac{8I_a}{\sqrt{3}n\pi}\sin\frac{n\pi}{3}\cos\frac{n\pi}{6}$$

$\varphi_n = \tan^{-1}(a_n/b_n) = \tan^{-1}(\cot(2n\pi/3))$

$C_1 = 2\sqrt{3}I_a/\pi$ and $I_1 = C_1/\sqrt{2} = \sqrt{2}\,\sqrt{3}I_a/\pi$, $\varphi_1 = \tan^{-1}(-1/\sqrt{3}) = -\pi/6$

(c) For the primary (or secondary) phase current,

$a_o/2 = 0$

$$a_n = \frac{2I_a}{\pi}\int_{\pi/6}^{5\pi/6}\cos(n\theta)\,d\theta = \frac{4I_a}{n\pi}\sin\frac{n\pi}{3}\cos\frac{n\pi}{2}$$

$$b_n = \frac{2I_a}{\pi}\int_{\pi/6}^{5\pi/6}\sin(n\theta)\,d\theta = \frac{4I_a}{n\pi}\sin\frac{n\pi}{3}\sin\frac{n\pi}{2}$$

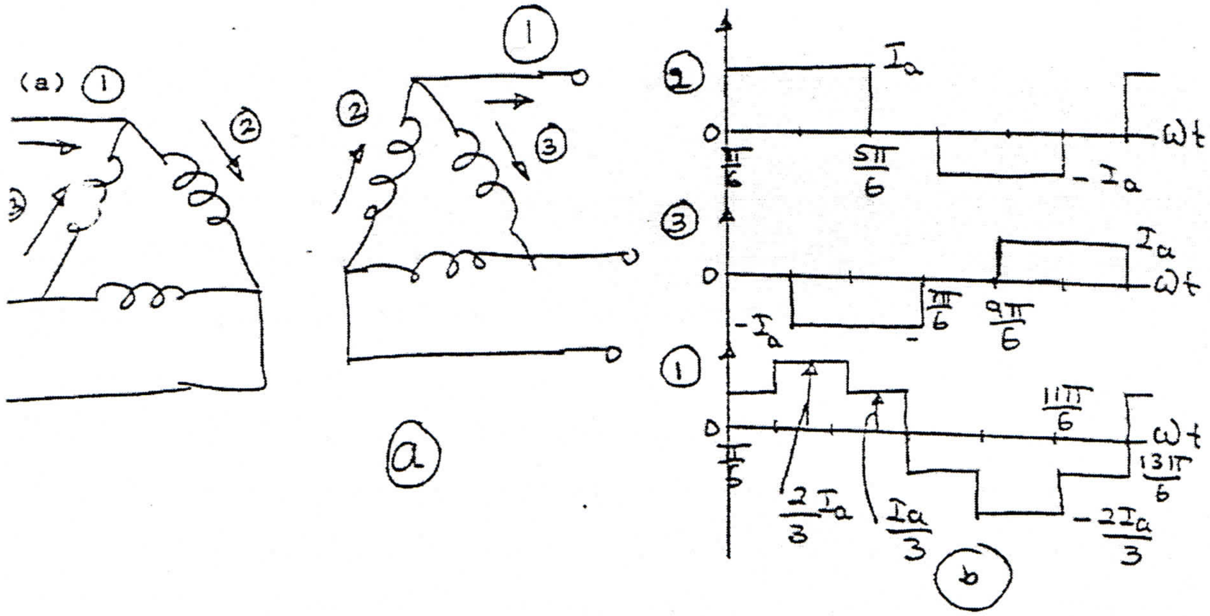
$C_n = \dfrac{4I_a}{n\pi}\sin\dfrac{n\pi}{3}$ and $\varphi_n = \tan^{-1}(a_n/b_n) = \tan^{-1}(\cot n\pi/2)$

$I_1 = C_1/\sqrt{2} = \sqrt{2}\,\sqrt{3}I_a/\pi$, and $I_s = I_a\sqrt{(2/3)}$

PF $= I_1/I_s = 3/\pi = 0.9549$ and $HF = \sqrt{(I_s/I_1)^2 - 1} = 0.3108$

Problem 3-27

(a)



(b) For the primary (or secondary) line current,

$a_o/2 = 0$

$$a_n = \frac{2I_a}{\pi}\int_{\pi/6}^{5\pi/6}\cos(n\theta)\,d\theta = \frac{4I_a}{n\pi}\sin\frac{n\pi}{3}\cos\frac{n\pi}{2}$$

$$b_n = \frac{2I_a}{\pi}\int_{\pi/6}^{5\pi/6}\sin(n\theta)\,d\theta = \frac{4I_a}{n\pi}\sin\frac{n\pi}{3}\sin\frac{n\pi}{2}$$

$C_n = \dfrac{4I_a}{n\pi}\sin\dfrac{n\pi}{3}$ and $\varphi_n = \tan^{-1}(a_n/b_n) = \tan^{-1}(\cot n\pi/2)$

$I_1 = C_1/\sqrt{2} = \sqrt{2}\,\sqrt{3}I_a/\pi$, and $I_s = I_a\sqrt{(2/3)}$

(c) For the primary (or secondary) phase current,

$a_o/2 = 0$

$$a_n = \frac{2I_a}{3\pi}\left[\int_{\pi/6}^{\pi/2}\cos(n\theta)\,d\theta + \int_{\pi/2}^{5\pi/6}2\cos(n\theta)\,d\theta + \int_{5\pi/6}^{7\pi/6}\cos(n\theta)\,d\theta\right]$$

$$= \frac{8I_a}{3n\pi}\cos\frac{2n\pi}{3}\sin\frac{n\pi}{3}\cos\frac{n\pi}{6}$$

$$b_n = \frac{2I_a}{3\pi}\left[\int_{\pi/6}^{\pi/2} \sin(n\theta)\, d\theta + \int_{\pi/2}^{5\pi/6} 2\sin(n\theta)\, d\theta + \int_{5\pi/6}^{7\pi/6} \sin(n\theta)\, d\theta\right]$$

$$= \frac{8I_a}{3n\pi} \sin\frac{2n\pi}{3} \sin\frac{n\pi}{3} \cos\frac{n\pi}{6}$$

$$C_n = \frac{8I_a}{3n\pi} \sin\frac{n\pi}{3} \cos\frac{n\pi}{6}$$

$\varphi_n = \tan^{-1}(a_n/b_n) = \tan^{-1}(\cot(2n\pi/3))$

$C_1 = 2\sqrt{3}I_a/\pi$ and $I_1 = C_1/\sqrt{2} = \sqrt{2}\,\sqrt{3}I_a/\pi$, $\varphi_1 = \tan^{-1}(-1/\sqrt{3}) = -\pi/6$

$I_s = \sqrt{2}I_a/3$, $PF = I_1/I_s = 3/\pi = 0.9549$

$HF = [(I_s/I_1)^2 - 1]^{½} = 0.3108$

CHAPTER 4

POWER TRANSISTORS

Problem 4-1

V_{CC} = 100 V, β_{min} = 10, β_{max} = 60, R_C = 5 Ω, ODF = 20, V_B = 8 V, $V_{CE(sat)}$ = 2.5 V and $V_{BE(sat)}$ = 1.75 V.

From Eq. (4-14), I_{CS} = (100 - 2.5)/5 = 19.5 A

From Eq. (4-15), I_{BS} = 19.5/β_{min} = 19.5/10 = 1.95 A

Eq. (4-16) gives the base current for a overdrive factor of 20,

I_B = 20 x 1.95 = 33 A

(a) Eq. (4-9) gives the required value of R_B,

$R_B = (V_B - V_{BE(sat)})/I_B$ = (8 - 1.75)/33 = 0.1894 Ω

(b) From Eq. (4-17), β_f = 19.5/33 = 0.59

(c) Eq. (4-18) yields the total power loss as

P_T = 1.75 x 33 + 2.5 x 19.5 = 106.5 W

Problem 4-2

V_{CC} = 40 V, β_{min} = 12, β_{max} = 75, R_C = 1.5 Ω, V_B = 6 V, $V_{CE(sat)}$ = 1.2 V and $V_{BE(sat)}$ = 1.6 V.

From Eq. (4-14), I_{CS} = (40 - 1.2)/1.5 = 25.87 A

From Eq. (4-15), I_{BS} = 25.87/β_{min} = 25.87/12 = 2.156 A

I_B = (6 -1.6)/0.7 = 4.4/0.7 = 6.286 A

(a) ODF = I_B/I_{BS} = 6.286/2.156 = 2.916

(b) From Eq. (4-17), β_f = 25.8/6.286 = 4.104

(c) Eq. (4-18) yields the total power loss as

P_T = 1.2 x 25.87 + 1.6 x 6.286 = 41.104 W

Problem 4-3

V_{cc} = 200 V, $B_{BE(sat)}$ = 3 V, I_B = 8 A, $V_{CE(sat)}$ = 2 V, I_{CS} = 100 A, t_d = 0.5 μs, t_r = 1μs, t_s = 5 μs, t_f = 3 μs, f_s = 10 kHz, k = 0.5, T = 1/f_s = 100 μs. kT = t_d + t_r + t_n = 50 μs and t_n = 50 - 0.5 - 1 = 48.5 μs, (1-k)T = t_s + t_f + t_o = 50 μs and t_o = 50 - 5 - 3 = 42 μs.

(a) From Eq. (4-21),

$P_c(t) = 3 \times 10^{-3} \times 200 = 0.6$ W

$P_d = 3 \times 10^{-3} \times 200 \times 0.5 \times 10^{-6} \times 10 \times 10^3 = 3$ mW

During rise time, $0 \le t \le t_r$:

From Eq. (4-23), $t_m = 1 \times 200/[2(200 - 2)] = 0.505$ μs

From Eq. (4-24), $P_p = 200^2 \times 100/[4(200 - 2)] = 5050.5$ W

From Eq. (4-25),

$P_r = 10 \times 10^3 \times 100 \times 1 \times 10^{-6} [220/2 + (2 - 200)/3] = 34$ W

$P_{on} = P_d + P_r = 0.003 + 34 = 34.003$ W

(b) Conduction Period, $0 \le t \le t_n$:

$P_c(t) = 2 \times 100 = 200$ W

From Eq. (4-27), $P_n = 2 \times 100 \times 48.5 \times 10^{-6} \times 10 \times 10^3 = 97$ W

(c) Storage Period, $0 \le t \le t_s$:

$P_c(t) = 2 \times 100 = 200$ W

From Eq. (4-28), $P_s = 2 \times 100 \times 5 \times 10^{-6} \times 10 \times 10^3 = 10$ W

Fall time, $0 \le t \le t_f$:

From Eq. (4-30), $P_p = 200 \times 100/4 = 5000$ W

From Eq. (4-31), $P_f = 200 \times 100 \times 3 \times 10^{-6} \times 10 \times 10^3/6 = 100$ W

$P_{off} = P_s + P_f = 10 + 100 = 110$ W

(d) Off-period, $0 \le t \le t_o$:

$P_c(t) = 3 \times 10^{-3} \times 200 = 0.6$ W

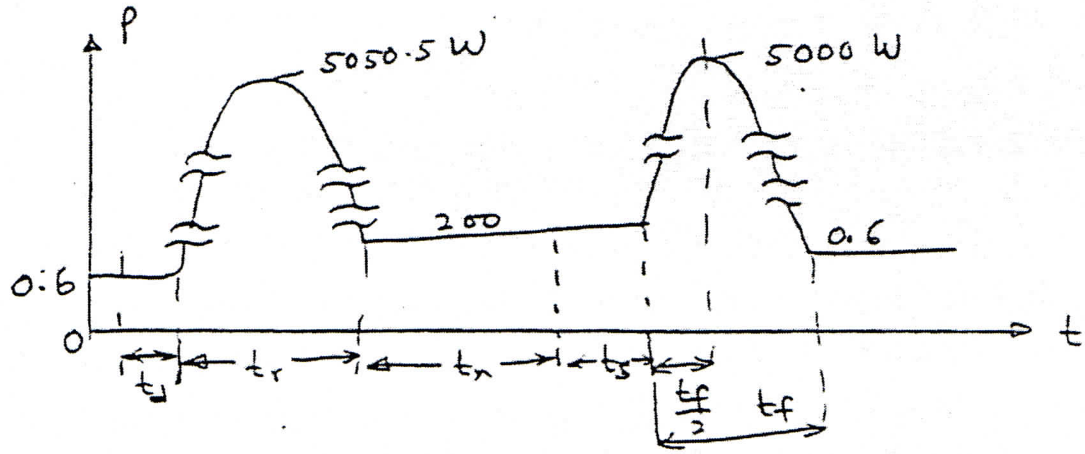
From Eq. (4-33),

$P_o = 3 \times 10^{-3} \times 200 \times 42 \times 10^{-6} \times 10 \times 10^3 = 0.252$ W

(e) The total power loss in the transistor due to collector current is

$P_T = P_{on} + P_n + P_{off} + P_o = 34.003 + 97 + 110 + 241.255$ W

(f)



Problem 4-4

$T_J = 150\ ^\circ C$, $T_A = 25\ ^\circ C$, $R_{JC} = 0.04\ ^{o}C/W$, $R_{CS} = 0.05\ ^{o}C/W$

From Problem 4-3, $P_T = 241.25$ W

$P_T(R_{JC} + R_{CS} + R_{SA}) = T_J - T_A = 150 - 25 = 125$

$R_{SA} = 125/241.25 - 0.04 - 0.05 = 0.0681\ ^\circ C/W$

Problem 4-5

$B_{BE(sat)} = 3$ V, $I_B = 8$ A, $T = 1/f_s = 100\ \mu s$, $k = 0.5$, $kT = 50\ \mu s$, $t_d = 0.5\ \mu s$, $t_r = 1\ \mu s$, $t_n = 50 - 1.5 = 48.5\ \mu s$, $t_s = 5\ \mu s$, $t_f = 3\ \mu s$, $t_{on} = t_d + t_r = 1.5\ \mu s$, $t_{off} = t_s + t_f = 5 + 3 = 8\ \mu s$

(a) During the period, $0 \le t \le (t_{on} + t_n)$:

$i_b(t) = I_{BS}$

$v_{BE}(t) = V_{BE(sat)}$

The instantaneous power due to the base current is

$P_b(t) = i_b\, v_{BE} = I_{BS}\, V_{BE(sat)} = 8 \times 3 = 24$ W

During the period, $0 \le t \le t_o = (T - t_{on} - t_n)$: $P_b(t) = 0$

From Eq. (4-35), the average power loss is

$P_B = I_{BS}\, V_{BE(sat)}\, (t_{on} + t_n + t_s) f_s$

$= 8 \times 3 \times (1.5 + 48.5 + 5) \times 10^{-6} \times 10 \times 10^3 = 13.2$ W

Problem 4-6

$V_{cc} = 200$ V, $B_{BE(sat)} = 2.3$ V, $I_B = 8$ A, $V_{CE(sat)} = 1.4$ V, $I_{CS} = 100$ A, $t_d = 0.1$ μs, $t_r = 0.45$ μs, $t_s = 3.2$ μs, $t_f = 1.1$ μs, $f_s = 10$ kHz, $k = 0.5$, $T = 1/f_s = 100$ μs. $kT = t_d + t_r + t_n = 50$ μs and $t_n = 50 - 0.45 - 0.1 = 49.45$ μs, $(1-k)T = t_s + t_f + t_o = 50$ μs and $t_o = 50 - 3.2 - 1.1 = 45.7$ μs.

(a) From Eq. (4-21),

$P_c(t) = 3 \times 10^{-3} \times 200 = 0.6$ W

$P_d = 3 \times 10^{-3} \times 200 \times 0.1 \times 10^{-6} \times 10 \times 10^3 = 0.6$ mW

During rise time, $0 \le t \le t_r$:

From Eq. (4-23), $t_m = 0.45 \times 200/[2(200 - 1.4)] = 0.2266$ □s

From Eq. (4-24), $P_p = 200^2 \times 100/[4(200 - 1.4)] = 5035.25$ W

From Eq. (4-25),

$P_r = 10 \times 10^3 \times 100 \times 0.45 \times 10^{-6}\, [220/2 + (1.4 - 200)/3] = 15.21$ W

$P_{on} = P_d + P_r = 0.0006 + 15.21$ W $= 15.21$ W

(b) Conduction Period, $0 \le t \le t_n$:

$P_c(t) = 1.4 \times 100 = 280$ W

From Eq. (4-27), $P_n = 1.4 \times 100 \times 49.45 \times 10^{-6} \times 10 \times 10^3 = 69.23$ W

(c) Storage Period, $0 \le t \le t_s$:

$P_c(t) = 1.4 \times 100 = 140$ W

From Eq. (4-28), P_s =1.4 x 100 x 3.2 x 10^{-6} x 10 x 10^3 = 4.48 W

Fall time, $0 \le t \le t_f$:

From Eq. (4-30), P_p = 200 x 100/4 = 5000 W

From Eq. (4-31), P_f = 200 x 100 x 1.1 x 10^{-6} x 10 x 10^3/6 = 36.67 W

$P_{off} = P_s + P_f$ = 4.48 + 36.67 = 41.15 W

(d) Off-period, $0 \le t \le t_o$:

$P_c(t)$ = 3 x 10^{-3} x 200 = 0.6 W

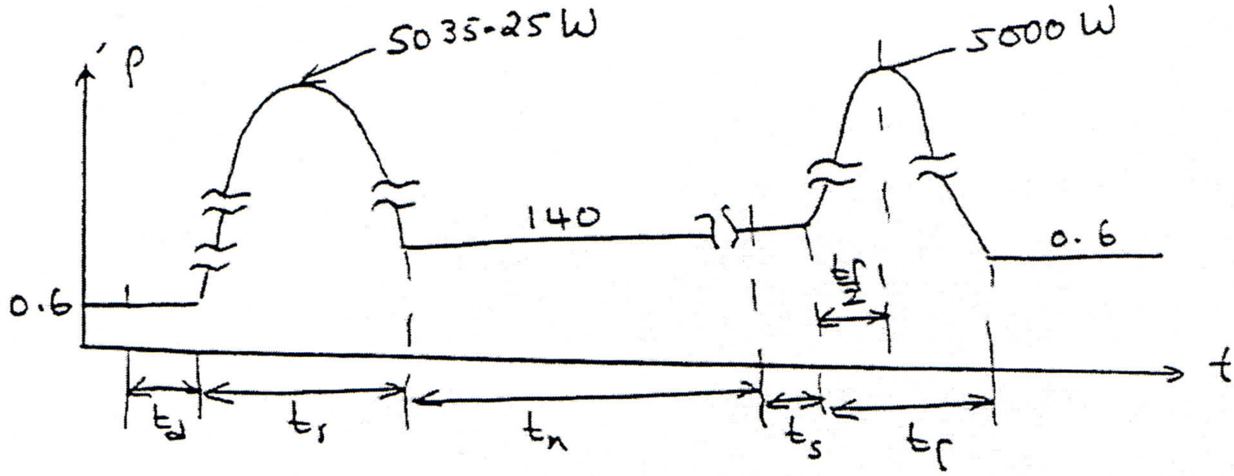
From Eq. (4-33),

P_o = 3 x 10^{-3} x 200 x 45.7 x 10^{-6} x 10 x 10^3 = 0.274 W

(e) The total power loss in the transistor due to collector current is

$P_T = P_{on} + P_n + P_{off} + P_o$ = 15.21 + 69.23 + 41.15 + 0.274 = 125.87 W

(f)



Problem 4-7

V_{DD} = 40 V, I_D = 35 A, I_{DSS} = 250 μA, R_{DS} = 28 mΩ, V_{GS} = 10 V, $t_{d(on)}$ = 25 ns, t_r = 60 ns, $t_{d(off)}$ = 70 ns, t_f = 25 ns, f_s = 20 kHz, k = 0.6, T = 1/f_s = 50 μs. kT = $t_{d(on)} + t_r + t_n$ = 50000 ns and t_n = 50000 - 25 - 60 = 29915 ns, (1-k)T = $t_f + t_{d(off)} + t_o$ = 20000 ns and t_o = 20000 - 70 - 25 = 19905 ns.

(a) During delay time, $0 \le t \le t_{d(on)}$:

$i_D(t) = I_{DSS}$

$v_{DS}(t) = V_{DD}$

The instantaneous power due to the collector current is

$P_D(t) = i_D\ v_{DS} = I_{DSS}\ V_{DD} = 250 \times 10^{-3} \times 40 = 0.01$ W

The average power loss during the delay time is

From Eq. (4-21), $P_d = I_{DSS}\ V_{DD}\ t_{d(on)}\ f_s$

$= 250 \times 10^{-3} \times 40 \times 25 \times 10^{-9} \times 20 \times 10^{3} = 5$ mW

During rise time, $0 \le t \le t_r$:

$$i_D(t) = \frac{I_{DS}}{t_r} t$$

$$v_{DS}(t) = V_{DD} + (R_{DS} I_{DS} - V_{DD}) \frac{t}{t_r}$$

From Eq. (4-22)

$$P_D(t) = i_D v_{DS} = \frac{I_{DS}}{t_r} t \left[V_{DD} + (R_{DS} I_{DS} - V_{DD}) \frac{t}{t_r} \right]$$

From Eq. (4-23) the power $P_D(t)$ will be maximum when $t = t_m$, where

$$t_m = \frac{t_r V_{DD}}{2(V_{DD} - R_{DS} I_{DS})} = \frac{60 \times 10^{-9} \times 40}{2 \times (40 - 25 \times 10^{-3} \times 35)} = 30.67 \text{ ns}$$

and Eq. (4-24) yields the peak power

$$P_p = \frac{V_{DD}^2 I_{DS}}{4(V_{CC} - V_{CE(sat)})} = \frac{40^2 \text{x } 35}{4(40 - 25 \text{ x } 10^{-3} \text{x } 35)} = 357.83 \text{ W}$$

From Eq. (4-25).

$$P_r = f_S I_{DS} t_r \left[\frac{V_{DD}}{2} + \frac{R_{DS} I_{DS} - V_{CC}}{3} \right]$$

$= 20 \times 10^{3} \times 35 \times 60 \times 10^{-9}\ [40/2 + (25 \times 10^{-3} \times 35 - 40)/3] = 1.3877$ W

The total power loss during the turn-on is

$P_{on} = P_d + P_r = 0.005 + 1.3877 = 1.39275$ W

(b) Conduction Period, $0 \le t \le t_n$:

$i_D(t) = I_{DS}$

$v_{DS}(t) = R_{DS}\, I_{DS}$

$P_D(t) = i_D\, v_{DS} = R_{DS}\, I_{DS}\, I_{DS} = 25 \times 10^{-3} \times 35^2 = 30.625$ W

From Eq. (4-27), $P_n = R_{DS}\, I_{DS}\, I_{DS}\, t_n\, f_s$

$= 25 \times 10^{-3} \times 35^2 \times 29915 \times 10^{-9} \times 20 \times 10^3 = 18.32$ W

(c) Storage Period, $0 \le t \le t_{d(off)}$:

$i_D(t) = I_{DS}$

$v_{DS}(t) = R_{DS}\, I_{DS}$

$P_c(t) = i_D\, v_{DS} = R_{DS}\, I_{DS}\quad I_{DS} = 25 \times 10^{-3} \times 35^2 = 30.625$ W

$P_{D(off)} = R_{DS}\, I_{DS}\, I_{DS}\, t_{d(off)}\, f_s$

$= 25 \times 10^{-3} \times 35^2 \times 70 \times 10^{-9} \times 20 \times 10^3 = 42.87$ mW

Fall time, $0 \le t \le t_f$:

$$i_D(t) = I_{DS}\left(1 - \frac{t}{t_f}\right)$$

$$v_{DS}(t) = \frac{V_{DD}}{t_f}t$$

$$P_D(t) = V_{DD} I_{DS}\left[\left(1 - \frac{t}{t_f}\right)\frac{t}{t_f}\right]$$

This power loss during fall time will be maximum when $t = t_f/2 = 12.5$ ns.

From Eq. (4-30), the peak power,

$P_D = V_{DD}\, I_{DS}/4 = 40 \times 35/4 = 350$ W

From Eq. (4-31), $P_f = V_{DD}\, I_{DS}\, t_f\, f_s/6$

$= 40 \times 35 \times 25 \times 10^{-9} \times 20 \times 10^3/6 = 0.117$ W

The power loss during turn-off is

$P_{off} = P_{D(off)} + P_f = 0.04287 + 0.117 = 0.15987$ W

(d) Off-period, $0 \le t \le t_o$:

$i_D(t) = I_{DSS}$

$v_{DS}(t) = V_{DD}$

$P_D(t) = i_D\, v_{DS} = I_{DSS}\, V_{DD} = 250 \times 10^{-6} \times 40 = 10$ mW

$P_o = I_{DSS}\, V_{DD}\, t_o\, f_s$

$= 250 \times 10^{-6} \times 40 \times 19905 \times 10^{-9} \times 20 \times 10^3 = 3.981$ mW

(e) The total power loss in the transistor due to collector current is

$P_T = P_{on} + P_n + P_{off} + P_o$

$= 1.3927 + 18.32 + 0.04287 + 0.01 = 20.466$ W

Problem 4-8

From Problem 4-7, $P_T = 20.466$ W

$R_{JC} = 1\ ^oK/W$, $R_{CS} = 1\ ^oK/W$, $T_J = 150\ ^oC$, $T_A = 30\ ^oC$

$T_J = 150\ ^oC + 273 = 423\ ^oK$

$T_A = 30\ ^oC + 273 = 303\ ^oK$

$P_T(R_{JC} + R_{CS} + R_{SA}) = T_J - T_A = 423 - 303 = 120$

$R_{SA} = 120/20.466 - 1 - 1 = 3.863\ ^oK/W$

Problem 4-9

$I_T = 200$ A, $V_{CE1} = 1.5$ V, $V_{CE2} = 1.1$ V

(a) $R_{e1} = 10\ m\Omega$, $R_{e2} = 20\ m\Omega$

$I_{E1} + I_{E2} = I_T$

$V_{CE1} + I_{E1}\, R_{e1} = V_{CE2} + I_{E2}\, R_{e2}$

or $I_{E1} = (V_{CE2} - V_{CE1} + I_T\, R_{e2})/(R_{e1} + R_{e2})$

$= (1.1 - 1.5 + 200 \times 20 \times 10^{-3})/(0.01 + 0.02) = 120$ A or 60 %

$I_{E2} = 200 - 120 = 80$ A or 40 %. $\Delta I = 60 - 40 = 20$ %

(b) $R_{e1} = R_{e2} = 20\ m\Omega$

$I_{E1} = (1.1 - 1.5 + 200 \times 20 \times 10^{-3})/(0.01 + 0.02) = 90$ A or 45 %

$I_{E2} = 200 - 90 = 110$ A or 55 %. $\Delta I = 55 - 45 = 10$ %

Problem 4-10

$I_L = 100$ A, $V_s = 400$ V, $f_s = 20$ kHz, $t_r = 1$ µs, and $t_f = 3$ µs.

(a) From Eq. (4-44), $L_s = 440 \times 1/100 = 4$ µH

(b) From Eq. (4-46), $C_s = 100 \times 3/400 = 0.75$ µF

(c) From Eq. (4-47), $R_s = 2\sqrt{(4/0.75)} = 4.62\ \Omega$

(d) From Eq. (4-48), $R_s = 10^3/(3 \times 20 \times 0.75) = 22.2\ 2\ \Omega$

(e) $V_s/R_s = 0.05 \times I_L$ or $400/R_s = 0.05 \times 100$ or $R_s = 80\ \Omega$

(f) From Eq. (4-49), the snubber loss is

$P_s = 0.5\ C_s\ V_s^2\ f_s = 0.5 \times 0.75 \times 10^{-6} \times 400^2 \times 20 \times 10^3 = 1200$ W

Problem 4-11

$I_L = 40$ A, $V_s = 30$ V, $f_s = 50$ kHz, $t_r = 60$ ns, and $t_f = 25$ ns

(a) From Eq. (4-44), $L_s = 30 \times 60 \times 10^{-9}/40 = 0.045$ µH

(b) From Eq. (4-46), $C_s = 40 \times 25 \times 10^{-9}/30 = 0.0333$ µF

(c) From Eq. (4-47), $R_s = 2\sqrt{(45/33.33)} = 2.324\ \Omega$

(d) From Eq. (4-48), $R_s = 10^6/(3 \times 50 \times 33.33 = 200\ \Omega$

(e) $V_s/R_s = 0.05 \times I_L$ or $30/R_s = 0.05 \times 40$ or $R_s = 15\ \Omega$

(f) From Eq. (4-49), the snubber loss is

$P_s = 0.5\ C_s\ V_s^2\ f_s$

$= 0.5 \times 33.33 \times 10^{-9} \times 30^2 \times 50 \times 10^3 = 0.75$ W

CHAPTER 5

DC-DC CONVERTERS

Problem 5-1

V_s = 220 V, k = 0.8, R = 20 Ω and v_{ch} = 1.5 V.

(a) From Eq. (5-1), $V_a = 0.8 \times (220 - 1.5) = 174.8$ V

(b) From Eq. (5-2), $V_o = \sqrt{0.8} \times 220 =$ V

(c) From Eq. (5-5), $P_o = 0.8 \times (220 - 1.5)^2 /20 = 3819.4$ W

From Eq. (5-6), $P_i = 0.8 \times 220 \times (220 -1.5)/20 = 3845.6$ W

The chopper efficiency is $P_o/P_i = 3819.4/3845.6 = 99.32$ %

(d) From Eq. (5-4), $R_i = 20/0.8 = 12.5$ Ω

(e) From Eq. (5-8), the output voltage is

$$v_o(t) = \frac{220}{\pi}\left[\sin(2\pi \times 0.8)\cos(2\pi \times 10000t) + 0.691 \times \sin(2\pi \times 10000t)\right]$$
$$= 82.32 \times \sin(62832t + \phi)$$

where $\phi = \tan^{-1}[\sin(0.8 \times 2\pi)/0.691] = 54°$.

The rms value is $V_1 = 82.32/\sqrt{2} = 58.2$ V

Note: The efficiency calculation, which includes the conduction loss of the chopper, does not take into account the switching loss due to turn-on and turn-off of the converter.

Problem 5-2

V_s = 220 V, R = 10 Ω, L = 15.5 mH, E = 20 V, k = 0.5 and f = 5000 Hz

From Eq. (5-15), $I_2 = 0.9375\, I_1 + 1.2496$

From Eq. (5-16), $I_1 = 0.9375\, I_2 - 1.2496$

(a) Solving these two equations, $I_1 = 8.6453$ A

(b) I_2 = 9.3547 A

(c) $\Delta I = I_2 - I_1$ = 9.35475 - 8.6453 = 0.7094 A

From Eq. (5-21), ΔI_{max} = 0.7094 A

and Eq. (5-22) gives the approximately value, ΔI_{max} = 0.7097 A

(d) The average load current is approximately,

$I_a = (I_2 + I_1)/2$ = (9.35475 + 8.6453)/2 = 9 A

(e) From Eq. (5-24),

$$I_o = \left[I_1^2 + \frac{(I_2 - I_1)^2}{3} + I_1 (I_2 - I_1) \right]^{1/2} = 9.002 \text{ A}$$

(f) $I_s = k\, I_a$ = 0.8 x 9 = 7.2 A

and the input resistance is $R_i = V_s/I_s$ = 220/7.2 = 30.56 Ω

(g) From Eq. (5-25), $I_R = \sqrt{k}\, I_o = \sqrt{0.8}$ x 22.1 = 15.63 A

Problem 5-3

V_s = 220 V, R = 0.2 Ω, E = 10 V, f = 200 Hz, T = 1/f = 0.005 s

Δi = 200 x 0.5 = 10 A.

$V_a = k\, V_s = R\, I_a$

The voltage across the inductor is given by

$$L\frac{di}{dt} = V_S - RI_a = V_S - kV_S = (1-k)V_S$$

For a linear rise of current, dt = t_1 = kT and di = Δi

$$\Delta i = \frac{(1-k)\, V_S}{L} k\, T$$

For worst case ripple condition: $\dfrac{d(\Delta i)}{dk} = 0$

and this gives, k = 0.5

Δi L = 10 x L = 220 (1 - 0.5) 0.5 x 0.005 or L = 27.5 mH

Problem 5-4

V_s = 110 V, E = 220 V, P_o = 30 kW = 30000 W

(c) Since the input power must be the same as the output power,

$V_s I_s = P_o$ or 110 x I_s = 30000 or I_s = A

(a) The battery current, $I_b = P_o/E$ = 30000/220 = 136.36 A

$I_b = (1 - k) I_s$ or k = 136.36/272.73 - 1 = 0.5

(b) $R_{ch} = (1 - k) E/I_s$ = (1 - 0.5) x 220/272.73 = 0.4033 Ω

Problem 5-5

V_s = 110 V, L = 7.5 mH, E = 220 V

From Eq. (5-28), $i_1(t) = (110 \times 10^3/7.5)\, t + I_1$

From Eq. (5-29),

$i_2(t) = [(110 - 220) \times 10^3/7.5)\, t + I_2 = -(110 \times 10^3/7.5)\, t + I_2$

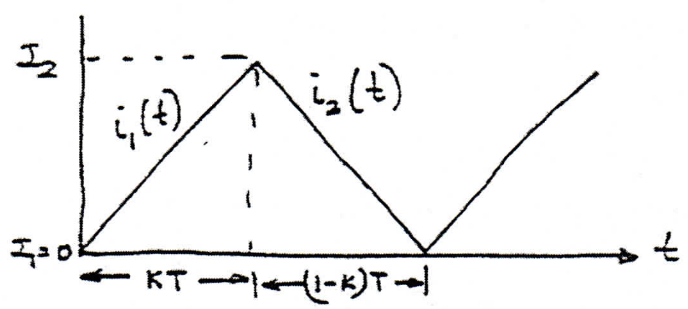
where $I_2 = i_1(t=kT) = (110 \times 10^3/7.5)\, kT + I_1$

$I_1 = i_2[t=(1-k)\, kT] = -110 \times 10^3/7.5)\, (1-k)kT + I_2$

Solving for I_1 and I_2 yields $I_1 = 0$, $I_2 = (110 \times 10^3/7.5)\, kT$

$i_1(t) = (110 \times 10^3/7.5)\, t$, for $0 \le t \le kT$

$i_2(t) = -(110 \times 10^3/7.5)t + (110 \times 10^3/7.5)(1-k)T$, for $0 \le t \le (1 - k)\, T$.



Problem 5-6

V_s = 600 V, R = 0.25 Ω, L = 20 mH, E = 150 V, k = 0.1 to 0.9 and f = 250 Hz

For k=0.1, the load current is discontinuous

From Eq. (5-15), $I_2 = 8.977$

From Eq. (5-16), $I_1 = 0$, $\Delta I = 8.977$ A and $I_a = 4.4885$ A

For k=0.2, the load current is discontinuous

$I_2 = 17.9103$ A, $I_1 = 0$ A, $\Delta I = 17.9103$ A and $I_a = 8.955$ A

For k = 0.3

$I_2 = 0.9851\ I_1 + 26.7985$, $I_1 = 0.9656\ I_2 - 20.6367$

$I_2 = 132.64$ A, $I_1 = 107.44$ A, $\Delta I = 25.2$ A and $I_a = 120.04$ A

For k = 0.4

$I_2 = 0.9802\ I_1 + 35.64$, $I_1 = 0.97044\ I_2 - 17.733$

$I_2 = 374.42$ A, $I_1 = 345.62$ A, $\Delta I = 28.8$ A and $I_a = 360.02$ A

For k = 0.5

$I_2 = 0.9753\ I_1 + 44.44$, $I_1 = 0.97045\ I_2 - 14.814$

$I_2 = 615$ A, $I_1 = 585$ A, $\Delta I = 30$ A and $I_a = 600$ A

For k = 0.6

$I_2 = 0.97044\ I_1 + 53.2$, $I_1 = 0.9802\ I_2 - 11.881$

$I_2 = 854.38$ A, $I_1 = 825.58$ A, $\Delta I = 28.8$ A and $I_a = 840$ A

For k = 0.7

$I_2 = 0.9656\ I_1 + 61.91$, $I_1 = 0.9851\ I_2 - 8.933$

$I_2 = 1092.6$ A, $I_1 = 1067.4$ A, $\Delta I = 25.2$ A and $I_a = 1080$ A

For k = 0.8

$I_2 = 0.9608\ I_1 + 70.58$, $I_1 = 0.99\ I_2 - 5.97$

$I_2 = 1329.6$ A, $I_1 = 1310.4$ A, $\Delta I = 19.2$ A and $I_a = 1320$ A

For k = 0.9

$I_2 = 0.956\ I_1 + 79.2$, $I_1 = 0.995\ I_2 - 2.99$

$I_2 = 1565.4$ A, $I_1 = 1554.6$ A, $\Delta I = 10.8$ A and $I_a = 1560$ A

Problem 5-7

$V_s = 600$ V, $R = 0.25\ \Omega$, $L = 20$ mH, $E = 150$ V, $k = 0.1$ to 0.9 and $f = 250$ Hz

The maximum ripple occurs at $k = 0.5$.

From Eq. (5-21), $\Delta I_{max} = (600/0.25) \tanh [0.25/(4 \times 250 \times 0.02)] = 29.9985$ A.

From Eq. (5-22), $\Delta I_{max} = [600/(4 \times 250 \times 0.02)] = 30$ A

Problem 5-8

$V_s = 10$ V, $f = 1$ kHz, $R = 10\ \Omega$, $L = 6.5$ mH, $E = 5$ V and $k = 0.5$.

$V_s := 10 \qquad R := 10 \qquad L := 6.5 \cdot 10^{-3} \qquad f := 1000$

$E := 5 \qquad k := 0.5 \qquad T := \frac{1}{f} \qquad z := \frac{T \cdot R}{L} \qquad z = 1.54$

From Eq. (5-35), we get

$$I_1 := \frac{V_s \cdot k \cdot z}{R} \cdot \frac{e^{-(1-k)\cdot z}}{1 - e^{-(1-k)\cdot z}} + \frac{V_s - E}{R} \qquad I_1 = 1.16 \quad \text{A}$$

From Eq. (5-36), we get

$$I_2 := \frac{V_s \cdot k \cdot z}{R} \cdot \frac{1}{1 - e^{-(1-k)\cdot z}} + \frac{V_s - E}{R} \qquad I_2 = 1.93 \quad \text{A}$$

$$\Delta I := I_2 - I_1 \qquad \Delta I = 0.77 \quad \text{A}$$

Problem 5-9

$V_s = 15$ V, $\Delta V_c = 10$ mV, $\Delta I = 0.5$ A, f = 20 kHz, $V_a = 5$ V and $I_a = 0.5$ A

(a) From Eq. (5-48), $V_a = k\ V_s$ and $k = V_a/V_s = 5/15 = 0.3333$

(b) From Eq. (5-52), $L = 5\ (15 - 5)/(0.5 \times 20000 \times 15) = 333.3\ \mu H$

(c) From Eq. (5-53), $C = 0.5/(8 \times 10 \times 10^{-3} \times 20000) = 312.5\ \mu F$

(d) $R := \dfrac{V_a}{I_a}$ $\quad R = 10$

From Eq. (5-56) $\quad L_c(k) := \dfrac{(1-k)\cdot R}{2\cdot f}$ $\quad L_c(0.333)\cdot 10^6 = 166.75\ \ \mu H$

From Eq. (5-89) $\quad C_c(k) := \dfrac{1-k}{16\cdot L_c(0.333)\cdot f^2}$ $\quad C_c(0.333)\cdot 10^6 = 0.63\ \ \mu F$

Problem 5-10

$V_s = 6$ V, $V_a = 15$ V, $I_a = 0.5$ A, f = 20 kHz, L = 250 μH, and C = 440 μF.

(a) From Eq. (5-62) $15 = 6/(1 - k)$ or $k = 3/5 = 0.6 = 60\ \%$

(b) From Eq. (5-67), $\Delta I = 6 \times (15 - 6)/(20000 \times 250 \times 10^{-6} \times 15)$

$= 0.72$ A

(c) From Eq. (5-65), $I_s = 0.5/(1 - 0.6) = 1.25$ A

Peak inductor current, $I_2 = I_s + \Delta I/2 = 1.25 + 0.72/2 = 1.61$ A

(d) From Eq. (5-71), $\Delta V_c = 0.5 \times 0.6/(20000 \times 440 \times 10^{-6}) = 34.1$ mV

(e) $R := \dfrac{V_a}{I_a}$ $\quad R = 30$

From Eq. (5-72) $\quad L_c(k) := \dfrac{k \cdot (1-k) \cdot R}{2 \cdot f}$ $\quad L_c(0.6) \cdot 10^6 = 180$ μH

From Eq. (5-73) $\quad C_c(k) := \dfrac{k}{2 \cdot f \cdot R}$ $\quad C_c(0.6) \cdot 10^6 = 0.5$ μF

Problem 5-11

V_s = 12 V, k = 0.6, I_a = 1.5 A, f = 25 kHz, L = 250 μH, and C = 220 μF

(a) From Eq. (5-78), V_a = - 12 x 0.6/(1 - 0.6) = - 18 V

(b) From Eq. (5-87), the peak-to-peak output ripple voltage is

$\Delta V_c = 1.5 \times 0.6/(25000 \times 220 \times 10^{-6}) = 163.64$ mV

(c) From Eq. (5-84), the peak-to-peak inductor ripple voltage is

$\Delta I = 12 \times 0.6/(25000 \times 250 \times 10^{-6}) = 1.152$ A

(d) From Eq. (5-81), I_s = 1.5 x 0.6/(1 - 0.6) = 2.25 A

Since I_s is the average of duration kT, the peak to peak current of transistor,

$I_p = I_s/k + \Delta I/2 = 2.25/0.6 + 1.152/2 = 4.326$ A

(e) $R := \dfrac{-V_a}{I_a}$ $\quad R = ▮$

From Eq. (5-88) $\quad L_c(k) := \dfrac{(1-k) \cdot R}{2 \cdot f}$ $\quad L_c(0.6) \cdot 10^6 = ▮$ μH

From Eq. (5-89) $\quad C_c(k) := \dfrac{k}{2 \cdot f \cdot R}$ $\quad C_c(0.6) \cdot 10^6 = ▮$ μF

Problem 5-12

V_s = 15 V, k = 0.4, I_a = 1.25 A, f = 25 kHz, L_1 = 250 μH, C_1 = 400 μF, L_2 = 350 μH and C_2 = 220 μF

(a) From Eq. (5-100), V_a = - 0.4 x 15/(1 - 0.4) = - 10 V

(b) From Eq. (5-103), I_s = 1.25 x 0.4/(1 - 0.4) = 0.83 A

(c) From Eq. (5-106), ΔI_1 =15 x 0.4/(25000 x 250 x 10^{-6}) = 0.96 A

(d) From Eq. (5-112), ΔV_{c1} = 0.83 (1 - 0.4)/(25000 x 400 x 10^{-6}) = 50 mV

(e) From Eq. (5-109), ΔI_2 = 0.4 x 15/(25000 x 350 x 10^{-6}) = 0.69 A

(f) From Eq. (5-113), ΔV_{c2} = 0.69/(8 x 25000 x 220 x 10^{-6}) = 15.58 mV

(g) From Eq. (5-120), ΔI_{L2} = 1.25/(1.0- 2 X 0.4) = 6.25 A

$I_p = I_s + I_1/2 + I_{L2} + \Delta I_2/2$ = 0.83 + 0.96/2 + 6.25 + 0.69/2 = 7.91 A

Problem 5-13

V_s = 15 V, k = 0.4, I_a = 1.25 A, f = 25 kHz, L_1 = 250 μH, C_1 = 400 μF, L_2 = 350 μH and C_2 = 220 μF

$V_s := 15 \quad k := 0.4 \quad I_a := 1.25 \quad f := 25\cdot 10^3$

From Eq. (5-115) $\quad L_{c1}(k) := \dfrac{(1-k)\cdot R^2}{2\cdot k\cdot f} \quad L_{c1}(0.4)\cdot 1000 = 4.32$ mH

From Eq. (5-116) $\quad L_{c2}(k) := \dfrac{(1-k)\cdot R}{2\cdot f} \quad L_{c2}(0.4)\cdot 1000 = 0.14$ mH

From Eq. (5-117) $\quad C_{c1}(k) := \dfrac{k}{2\cdot f\cdot R} \quad C_{c1}(0.5)\cdot 10^6 = 0.83$ μF

From Eq. (5-118) $\quad C_{c2}(k) := \dfrac{1}{8\cdot f\cdot R} \quad C_{c2}(0.5)\cdot 10^6 = 0.42$ μF

Problem 5-14

V_s = 110 V, V_a = 80 V, I_a = 20 A

$\Delta V_c = 0.05 \times V_a = 0.05 \times 80 = 4$ V

$R = V_a/I_a = 80/20 = 4\ \Omega$

From Eq. (5-48), $k = V_a/V_s = 80/110 = 0.7273$

From Eq. (5-49) $I_s = k\ I_a = 0.7273 \times 20 = 14.55$ A

$\Delta I_L = 0.025 \times I_a = 0.025 \times 20 = 0.5$ A

$\Delta I = 0.1 \times I_a = 0.1 \times 20 = 2$ A

(a) From Eq. (5-51), we get the value of L_e

$$L_e = \frac{V_a(V_S - V_a)}{\Delta I\ f\ V_S} = \frac{80\times(110-80)}{2\times 10kHz \times 110} = 1.091 \text{ mH}$$

From Eq. (5-128), we get the value of C_e

$$C_e = \frac{\Delta I}{V_C\, 8f} = \frac{2}{4\times 8\times 10kHz} = 6.25\ \mu\text{F}$$

Assuming a linear rise of load current i_L during the time from $t = 0$ to $t_1 = k$ T, Eq. (5-129) gives the approximate value of L as

$$L_e = \frac{k\, T\Delta V_C}{\Delta I_L} = \frac{k\, \Delta V_C}{\Delta I_L\ f} = \frac{0.7273\times 4}{0.5\times 10kHz} = 0.582 \text{ mH}$$

Problem 5-15

PSpice simulation

Problem 5-16

$k = 0.4$, $R = 150\ \Omega$, $r_L = 1\ \Omega$ and $r_c = 0.2\ \Omega$.

$k := 0.5 \qquad R := 150 \qquad r_L := 1 \qquad r_c := 0.2$

(a) Buck

$$G(k) := \frac{k \cdot R}{R + r_L} \qquad G(0.5) = 0.5$$

(b)Boost

$$G(k) := \frac{1}{1-k} \cdot \left[\frac{(1-k)^2 \cdot R}{(1-k)^2 \cdot R + r_L + k \cdot (1-k) \cdot \frac{r_c \cdot R}{r_c + R}} \right] \qquad G(0.5) = 1.95$$

(c)Buck – Boost

$$G(k) := \frac{-k}{1-k} \cdot \left[\frac{(1-k)^2 \cdot R}{(1-k)^2 \cdot R + r_L + k \cdot (1-k) \cdot \frac{r_c \cdot R}{r_c + R}} \right] \qquad G(0.5) = -0.97$$