Solution Manual for Fitzgerald and Kingsleys Electric Machinery 7th Edition by Umans ISBN 0073380466 9780073380469

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Chapter 1

Part (a):

$$\mathcal{R}_c = \frac{l_c}{\mu A_c} = \frac{l_c}{\mu_r \mu_0 A_c} = 0 \quad \text{A/Wb}$$

$$\mathcal{R}_g = \frac{g}{\mu_0 A_c} = 5.457 \times 10^6 \quad \text{A/Wb}$$

Part (b):

$$\Phi = \frac{NI}{\mathcal{R}_c + \mathcal{R}_g} = 2.437 \times 10^{-5} \quad \text{Wb}$$

Part (c):

$$\lambda = N\Phi = 2.315 \times 10^{-3} \quad \text{Wb}$$

Part (d):

$$L = \frac{\lambda}{I} = 1.654 \quad \text{mH}$$

Problem 1-2

Part (a):

$$\mathcal{R}_c = \frac{l_c}{\mu A_c} = \frac{l_c}{\mu_r \mu_0 A_c} = 2.419 \times 10^5 \quad \text{A/Wb}$$

$R_g = \mu A$

$= 5.457 \times 10^6$ A/Wb

Part (b):

$$\Phi = \frac{NI}{\mathcal{R}_c + \mathcal{R}_g} = 2.334 \times 10^{-5} \quad \text{Wb}$$

Part (c):

$$\lambda = N\Phi = 2.217 \times 10^{-3} \quad \text{Wb}$$

Part (d):

$$L = \frac{\lambda}{I} = 1.584 \ \text{mH}$$

Problem 1-3

Part (a):

$$N = \sqrt{\frac{Lg}{\mu_0 A_c}} = 287 \text{ turns}$$

Part (b):

$$I = \frac{B_{\text{core}}}{\mu_0 N/g} = 7.68 \quad \text{A}$$

Problem 1-4

Part (a):

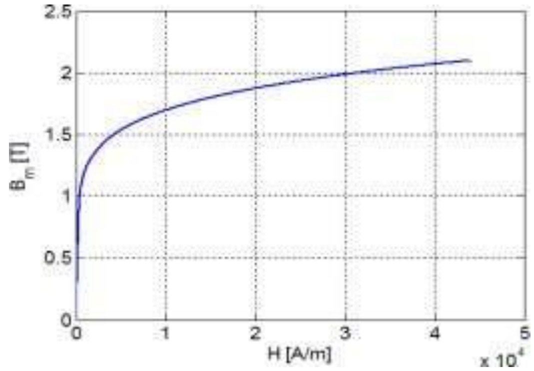
$$N = \sqrt{\frac{L(g + l_c\mu_0/\mu)}{\mu_0 A_c}} = \sqrt{\frac{L(g + l_c\mu_0/(\mu_r\mu_0))}{\mu_0 A_c}} = 129 \text{ turns}$$

Part (b):

$$I = \frac{B_{\mathrm{core}}}{\mu_0 N/(g + l_c \mu_0/\mu)} = 20.78 \quad \mathrm{A}$$

Problem 1-5

Part (a):



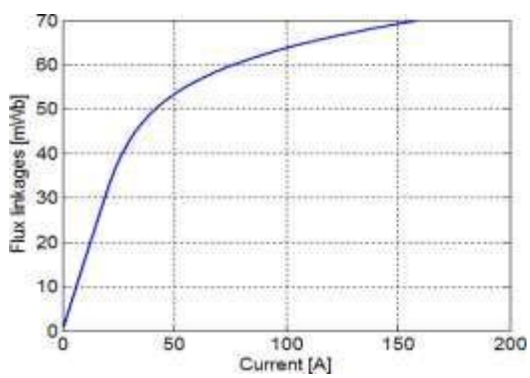
Part (b):

$$B_g = B_m = 2.1 \text{ T}$$

For $B_m = 2.1$ T, $\mu_r = 37.88$ and thus

$$I = \frac{B_m}{\mu_0 N}\left(g + \frac{l_c}{\mu_r}\right) = 158\ A$$

Part (c):



Problem 1-6

Part (a):

$$\underline{\mu_0 N I}$$

B
g
=

2
g

$$B_c = B_g \frac{A_g}{A_c} = \frac{\mu_0 NI}{2g}\left(1 - \frac{x}{X_0}\right)$$

Part (b): Will assume l_c is "large" and l_p is relatively "small". Thus,

$$B_g A_g = B_p A_g = B_c A_c$$

We can also write

$$2gH_g + H_p l_p + H_c l_c = NI;$$

and

$$B_g = \mu_0 H_g; \qquad B_p = \mu H_p \qquad B_c = \mu H_c$$

These equations can be combined to give

$$B_g = \left(\frac{\mu_0 NI}{2g + \frac{\mu_0}{\mu} l_p + \frac{\mu_0}{\mu}\frac{A_g}{A_c} l_c}\right) = \left(\frac{\mu_0 NI}{2g + \frac{\mu_0}{\mu} l_p + \frac{\mu_0}{\mu}\left(1 - \frac{x}{X_0}\right) l_c}\right)$$

and

$$B_c = \left(1 - \frac{x}{X_0}\right) B_g$$

Problem 1-7

From Problem 1-6, the inductance can be found as

$$L = \frac{NA_c B_c}{I} = \frac{\mu_0 N^2 A_c}{2g + \frac{\mu_0}{\mu}\left(l_p + (1 - x/X_0) l_c\right)}$$

from which we can solve for μ_r

$$\mu_r = \frac{\mu}{\mu_0} = \frac{L\, l_p + (1 - x/X_0)\, l_c}{\mu_0 N^2 A_c - 2gL} = 88.5$$

Problem 1-8

Part (a):

$$L = \frac{\mu_0 (2N)^2 A_c}{2g}$$

and thus

$$N = 0.5\sqrt{\frac{2gL}{A_c}} = 38.8$$

which rounds to $N = 39$ turns for which $L = 12.33$ mH.

Part (b): $g = 0.121$ cm

Part(c):

$$B_c = B_g = \frac{2\mu_0 N I}{2g}$$

and thus

$$I = \frac{B_c g}{\mu_0 N} = 37.1 \text{ A}$$

Problem 1-9

Part (a):

$$L = \frac{\mu_0 N^2 A_c}{2g}$$

and thus

$$N = \sqrt{\frac{2gL}{A_c}} = 77.6$$

which rounds to $N = 78$ turns for which $L = 12.33$ mH.

Part (b): $g = 0.121$ cm

Part(c):

$$B_c = B_g = \frac{\mu_0 (2N)(I/2)}{2g}$$

and thus

$$I = \frac{2B_c g}{\mu_0 N} = 37.1 \text{ A}$$

Problem 1-10

Part (a):

$$L = \frac{\mu_0 (2N)^2 A_c}{2(g + (\frac{\mu_0}{\mu}) l_c)}$$

and thus

$$N = 0.5 \sqrt{\frac{2(g + (\frac{\mu_0}{\mu}) l_c) L}{A_c}} = 38.8$$

which rounds to $N = 39$ turns for which $L = 12.33$ mH.

Part (b): $g = 0.121$ cm

Part(c):

$$B_c = B_g = \frac{2\mu_0 N I}{2\left(g + \frac{\mu_0}{\mu} l_c\right)}$$

and thus

$$I = \frac{B_c\left(g + \frac{\mu_0}{\mu} l_c\right)}{\mu_0 N} = 40.9 \text{ A}$$

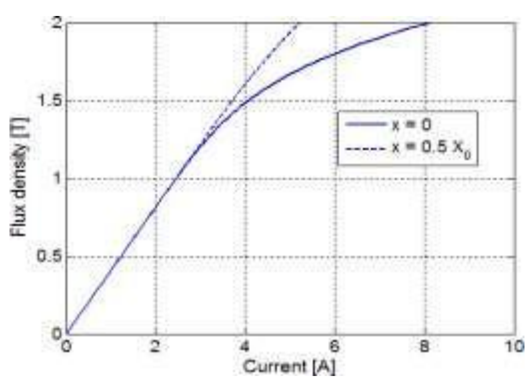
Problem 1-11

Part (a): From the solution to Problem 1-6 with $x = 0$

$$I = \frac{B_g\left(2g + 2\frac{\mu_0}{\mu}(l_p + l_c)\right)}{\mu_0 N} = 1.44 \text{ A}$$

Part (b): For $B_m = 1.25$ T, $\mu_r = 941$ and thus $I = 2.43$ A

Part (c):



Problem 1-12

$$g = \frac{\mu_0 N^2 A_c}{L} - \frac{\mu_0}{\mu} l_c = 7.8 \times 10^{-4} \text{ m}$$

Problem 1-13

Part (a):

$$l_c = 2\pi \left(\frac{R_i + R_o}{2} \right) - g = 22.8 \text{ cm}$$

$$A_c = h(R_o - R_i) = 1.62 \text{ cm}^2$$

Part (b):

$$\mathcal{R}_c = \frac{l_c}{\mu A_c} = 0$$

$$\mathcal{R}_g = \frac{g}{\mu_0 A_c} = 7.37 \times 10^6 \text{ H}^{-1}$$

Part (c):

$$L = \frac{N^2}{\mathcal{R}_c + \mathcal{R}_g} = 7.04 \times 10^{-4} \text{ H}$$

Part (d):

$$I = \frac{B_g A_c (\mathcal{R}_c + \mathcal{R}_g)}{N} = 20.7 \text{ A}$$

Part (e):

$$\lambda = LI = 1.46 \times 10^{-2} \text{ Wb}$$

Problem 1-14

See solution to Problem 1-13

Part (a):

$$l_c = 22.8 \text{ cm}$$

$$A_c = 1.62 \text{ cm}^2$$

Part (b):

$$\mathcal{R}_c = 1.37 \times 10^6 \text{ H}^{-1}$$

$$\mathcal{R}_g = 7.37 \times 10^6 \text{ H}^{-1}$$

Part (c):

$$L = 5.94 \times 10^{-4} \text{ H}$$

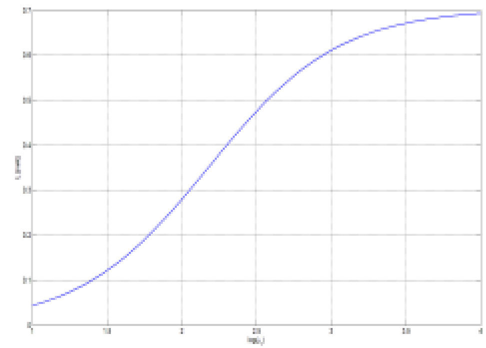
Part (d):

$$I = 24.6 \text{ A}$$

Part (e):

$$\lambda = 1.46 \times 10^{-2} \text{ Wb}$$

Problem 1-15



μ_r must be greater than 2886.

Problem 1-16

$$L = \frac{\mu_0 N^2 A_c}{g + l_c/\mu_r}$$

Problem 1-17

Part (a):

$$L = \frac{\mu_0 N^2 A_c}{g + l_c/\mu_r} = 36.6 \text{ mH}$$

Part (b):

$$B = \frac{\mu_0 N^2}{g + l_c/\mu_r} I = 0.77 \text{ T}$$

$$\lambda = LI = 4.40 \times 10^{-2} \text{ Wb}$$

Problem 1-18

Part (a): With $\omega = 120\pi$

$$V_{\text{rms}} = \frac{\omega N A_c B_{\text{peak}}}{\sqrt{2}} = 20.8 \text{ V}$$

Part (b): Using L from the solution to Problem 1-17

$$I_{\text{peak}} = \frac{\sqrt{2} V_{\text{rms}}}{\omega L} = 1.66 \text{ A}$$

$$W_{\text{peak}} = \frac{L I_{\text{peak}}^2}{2} = 9.13 \times 10^{-2} \text{ J}$$

Problem 1-19

$B = 0.81$ T and $\lambda = 46.5$ mWb

Problem 1-20

Part (a):

$$R_3 = \sqrt{(R_1^2 + R_2^2)} = 4.49 \text{ cm}$$

Part (b): For

$$l_c = 4l + R_2 + R_3 - 2h;$$

and

$$A_g = \pi R_1^2$$

$$L = \frac{\mu_0 A_g N^2}{g + (\mu_0/\mu) l_c} = 61.8 \text{ mH}$$

Part (c): For $B_{\text{peak}} = 0.6$ T and $\omega = 2\pi 60$

$$\lambda_{\text{peak}} = A_g N B_{\text{peak}}$$

$$V_{\text{rms}} = \frac{\omega \lambda_{\text{peak}}}{\sqrt{2}} = 23.2 \text{ V}$$

$$I_{\text{rms}} = \frac{V_{\text{rms}}}{\omega L} = 0.99 \text{ A}$$

$$W_{\text{peak}} = \frac{1}{2} L I_{\text{peak}}^2 = \frac{1}{2} L(\sqrt{2} I_{\text{rms}})^2 = 61.0 \text{ mJ}$$

Part (d): For $\omega = 2\pi 50$

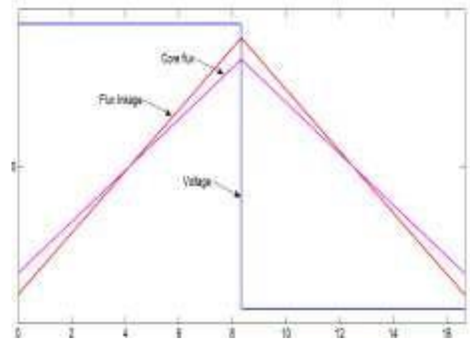
$$V_{\text{rms}} = 19.3 \text{ V}$$

$$I_{\text{rms}} = 0.99 \text{ A}$$

$$W_{\text{peak}} = 61.0 \text{ mJ}$$

Problem 1-21

Part (a);


Core flux
Flux linkage
Voltage
0
0
2
4
6
8
10
12
14
16

Part (b):

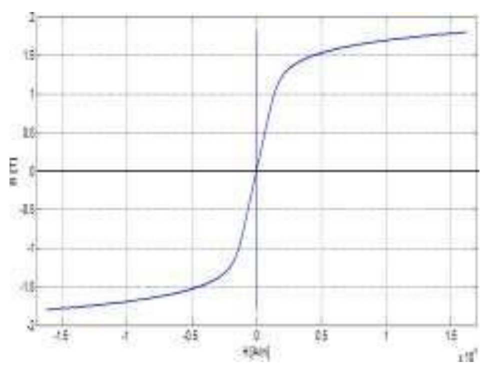
$$E_{max} = 4fNA_cB_{peak} = 118\ V$$

part (c): For $\mu = 1000\mu_0$

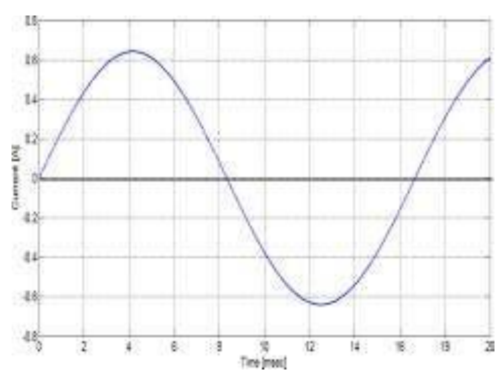
$$I_{peak} = \frac{l_cB_{peak}}{\mu N} = 0.46\ \text{A}$$

Problem 1-22

Part (a);



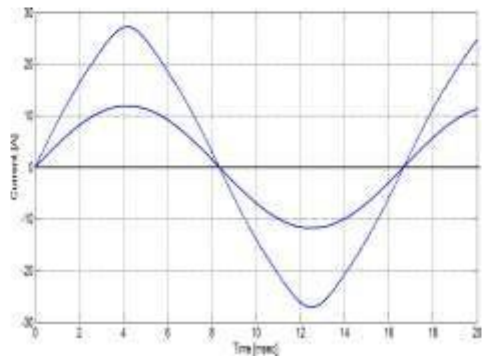
Part (b): $I_{peak} = 0.6\,\text{A}$



Part (c): $I_{peak} = 4.0\ \text{A}$

Problem 1-23

For part (b), I_{peak} = 11.9 A. For part (c), I_{peak} = 27.2 A.



Problem 1-24

$$L = \frac{\mu_0 A_c N^2}{g + (\mu_0/\mu) l_c}$$

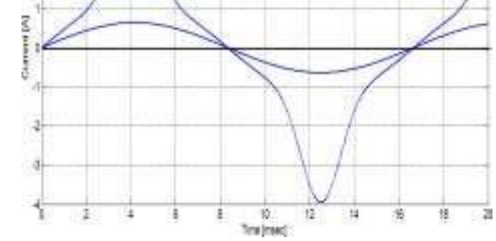
$$B_c = \frac{\mu_0 N I}{g + (\mu_0/\mu) l_c}$$

Part (a): For I = 10 A, L = 23 mH and B_c = 1.7 T

$$N = \frac{LI}{A_c B_c} = 225 \text{ turns}$$

$$g = \frac{\mu_0 N I}{B_c} - \frac{\mu_0 l_c}{\mu} = 1.56 \text{ mm}$$

Part (b): For I = 10 A and $B_c = B_g$ = 1.7 T, from Eq. 3.21


Current [A]
Time [msec]

$$W_{core} = \frac{B_c^2}{2\mu} V_g = 0.072 \text{ J}$$

based upon

$$V_{core} = A_c l_c \quad V_g = A_c g$$

Part (c):

$$W_{tot} = W_g + W_{core} = 1.15 \text{ J} = \frac{1}{2} L I^2$$

Problem 1-25

$$L_{min} = 3.6 \text{ mH} \quad L_{max} = 86.0 \text{ mH}$$

Problem 1-26

Part (a):

$$N = \frac{LI}{BA_c} = 167$$

$$g = \frac{\mu_0 N I}{2BA_c} = 0.52 \text{ mm}$$

Part (b):

$$N = \frac{LI}{2BA_c} = 84$$

$$g = \frac{\mu_0 N I}{B A_c} = 0.52 \text{ mm}$$

Problem 1-27

Part (a):

$$N = \frac{LI}{BA_c} = 167$$

$$g = \frac{\mu_0 NI}{2BA_c} - (\mu_0/\mu) l_c = 0.39 \text{ mm}$$

Part (b):

$$N = \frac{LI}{2BA_c} = 84$$

$$g = \frac{\mu_0 NI}{BA_c} - (\mu_0/\mu) l_c = 0.39 \text{ mm}$$

Problem 1-28

Part (a): $N = 450$ and $g = 2.2$ mm

Part (b): $N = 225$ and $g = 2.2$ mm

Problem 1-29

Part (a):

$$L = \frac{\mu_0 N^2 A}{l} = 11.3 \text{ H}$$

where

$$A = \pi a^2 \quad l = 2\pi r$$

Part (b):

$$W = \frac{B^2}{2\mu_0} \times \text{Volume} = 6.93 \times 10^7 \text{ J}$$

where

$$\text{Volume} = (\pi a^2)(2\pi r)$$

Part (c): For a flux density of 1.80 T,

$$I = \frac{lB}{\mu_0 N} = \frac{2\pi r B}{\mu_0 N} = 6.75 \text{ kA}$$

and

$$V = L \frac{\Delta I}{\Delta t} = 113 \times 10^{-3} \frac{6.75 \times 10^3}{40} = 1.90 \text{ kV}$$

Problem 1-30

Part (a):

$$\text{Copper cross} - \text{sectional area} \equiv A_{cu} = f_w ab$$

$$\text{Copper volume} = \text{Vol}_{cu} = f_w b \left[\left(a + \frac{w}{2}\right)\left(h + \frac{w}{2}\right) - wh \right]$$

Part (b):

$$B = \frac{\mu_0 J_{cu} A_{cu}}{g}$$

Part (c):

$$J_{cu} = \frac{NI}{A_{cu}}$$

Part (d):

$$P_{\text{diss}} = \rho J_{\text{cu}}^2 \text{Vol}_{\text{cu}}$$

Part (e):

$$W_{\text{stored}} = \frac{B^2}{2\mu_0} \times \text{gap volume} = \frac{\mu_0 J_{\text{cu}}^2 A_{\text{cu}}^2 wh}{2g}$$

Part (f):

$$\frac{W_{\text{store}}}{P_{\text{diss}}} = \frac{\frac{1}{2} I^2 L}{I^2 R}$$

and thus

$$\frac{L}{R} = 2\frac{W_{\text{stored}}}{P_{\text{diss}}} = \frac{\mu_0 A_{\text{cu}}^2 wh}{g \rho \text{Vol}_{\text{cu}}}$$

Problem 1-31

$$P_{\text{diss}} = 6.20 \text{ W} \quad I = 155 \text{ mA} \quad N = 12{,}019 \text{ turns}$$

$$R = 258\ \Omega \quad L = 32 \text{ H} \quad \tau = 126 \text{ msec} \quad \text{Wire size} = 34 \text{ AWG}$$

Problem 1-32

Part (a) (i):

$$B_{\text{g1}} = \frac{\mu_0 N_1}{g_1} I_1 \qquad B_{\text{g2}} = \frac{\mu_0 N_1}{g_2} I_1$$

(ii)

$$\lambda_1 = N_1(A_1B_{g1} + A_2B_{g2}) = \mu_0 N_1^2 \left(\frac{A_1}{g_1} + \frac{A_2}{g_2}\right) I_1$$

$$\lambda_2 = N_2 A_2 B_{g2} = \mu_0 N_1 N_2 \frac{A_2}{g_2} I_1$$

Part (b) (i):

$$B_{g1} = 0 \qquad B_{g2} = \frac{\mu_0 N_2}{g_2} I_2$$

(ii)

$$\lambda_1 = N_1 (A_1 B_{g1} + A_2 B_{g2}) = \mu_0 N_1 N_2 \frac{A_2}{g_2} I_2$$

$$\lambda_2 = N_2 A_2 B_{g2} = \mu_0 N_2^2 \frac{A_2}{g_2} I_2$$

Part (c) (i):

$$B_{g1} = \frac{\mu_0 N_1}{g_1} I_1 \qquad B_{g2} = \frac{\mu_0 N_1}{g_2} I_1 + \frac{\mu_0 N_2}{g_2} I_2$$

(ii)

$$\lambda_1 = N_1(A_1 B_{g1} + A_2 B_{g2}) = \mu_0 N_1^2 \left(\frac{A_1}{g_1} + \frac{A_2}{g_2}\right) I_1 + \mu_0 N_1 N_2 \frac{A_2}{g_2} I_2$$

$$\lambda_2 = N_2 A_2 B_{g2} = \mu_0 N_1 N_2 \frac{A_2}{g_2} I_1 + \mu_0 N_2^2 \frac{A_2}{g_2} I_2$$

Part (d):

$$L_1 = \mu_0 N_1^2 \left(\frac{A_1}{g_1} + \frac{A_2}{g_2}\right) \qquad L_2 = \mu_0 N_2^2 \frac{A_2}{g_2}$$

$$L_{12} = \mu_0 N_1 N_2 \frac{A_2}{g_2}$$

Problem 1-33

$$\mathcal{R}_g = \frac{g}{\mu_0 A_c} \qquad \mathcal{R}_1 = \frac{l_1}{\mu A_c}$$

$$\mathcal{R}_2 = \frac{l_2}{\mu A_c} \qquad \mathcal{R}_A = \frac{l_A}{\mu A_c}$$

Part (a):

$$L_1 = \frac{N_1^2}{\mathcal{R}_g + \mathcal{R}_1 + \mathcal{R}_2 + \mathcal{R}_A/2}$$

$$L_A = L_B = \frac{N^2}{\mathcal{R}}$$

where

$$\mathcal{R} = \mathcal{R}_A + \frac{\mathcal{R}_A(\mathcal{R}_g + \mathcal{R}_1 + \mathcal{R}_2)}{\mathcal{R}_A + \mathcal{R}_g + \mathcal{R}_1 + \mathcal{R}_2}$$

Part (b):

$$L_{1B} = -L_{1A} = \frac{N_1 N}{2(\mathcal{R}_g + \mathcal{R}_1 + \mathcal{R}_2 + \mathcal{R}_A/2)}$$

$$N^2(\mathcal{R}_g + \mathcal{R}_1 + \mathcal{R}_2)$$

$$L_{12} = \frac{}{2R_A(R_g + R_1 + R_2) + R_A^2}$$

Part (c):

$$v_1(t) = L_{1A}\frac{di_A}{dt} + L_{1B}\frac{di_B}{dt} = L_{1A}\frac{d(i_A - i_B)}{dt}$$

Problem 1-34

Part (a):

$$L_{12} = \frac{\mu_0 N_1 N_2 D(w - x)}{2g}$$

Part (b):

$$v_2(t) = -\omega I_o \frac{\mu_0 N_1 N_2 D w}{4g} \cos \omega t$$

Problem 1-35

Part (a):

$$H = \frac{2N_1 i_1}{(R_o + R_i)}$$

Part (b):

$$v_2(t) = N_2 w(n\Delta)\frac{dB(t)}{dt}$$

Part (c):

$$v_0(t) = GN_2 w(n\Delta)B(t)$$

Problem 1-36

Must have

$$\frac{\mu_0}{\mu} l_c < 0.05\, g + \frac{\mu_0}{\mu} l_c \quad \Rightarrow \quad \mu = \frac{B}{H} > 19\mu_0 \frac{l_c}{g}$$

For $g = 0.05$ cm and $l_c = 30$ cm, must have $\mu > 0.014$. This is satisfied over the approximate range $0.65 \text{ T} \leq B \leq 1.65 \text{ T}$.

Problem 1-37

Part (a): See Problem 1-35. For the given dimensions, $V_{peak} = 20$ V, $B_{peak} = 1$ T and $\omega = 100\pi$ rad/sec

$$N_1 = \frac{V_{peak}}{\omega(R_o - R_i)(n\Delta)} = 79 \text{ turns}$$

Part (b): (i)

$$B_{peak} = \frac{V_{0,peak}}{GN_2(R_0 - R_i)(n\Delta)} = 0.83 \text{ T}$$

(ii)

$$V_{peak} = \omega N_1(R_o - R_i)(n\Delta)B_{peak} = 9.26 \text{ V}$$

Problem 1-38

Part (a): From the M-5 dc-magnetization characteristic, $H_c = 19$ A-turns/m at $B_c = B_g = 1.3$ T. For $H_g = 1.3 \text{ T}/\mu_0 = 1.03 \times 10^6$ A-turns/m

$$I = \frac{H_c(l_A + l_C - g) + H_g g}{N_1} = 30.2\, A$$

Part(b):

$$W_{gap} = gA_C \frac{B_g^2}{2\mu_0} = 3.77 \text{ J}$$

For $\mu = B_c/H_c = 0.0684$ H/m

$$W_c = (l_A A_A + l_B A_B + (l_C - g)A_C)\frac{B_c^2}{2\mu} = 4.37 \times 10^{-3} \text{ J}$$

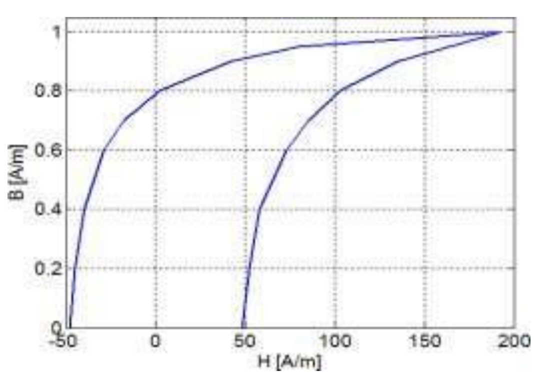
$$L = \frac{2(W_{gap} + W_c)}{I^2} = 8.26 \text{ mH}$$

Part (c):

$$L = \frac{2W_{gap}}{I^2} = 8.25 \text{ mH}$$

Problem 1-39

Part (a):



Part (b): Loop area = 191 J/m^3

Part (c):

Core loss = $\frac{f \times \text{Loop area}}{\rho}$

For f = 60 Hz, $\rho = 7.65 \times 10^3$ kg/m^3, Core loss = 1.50 W/kg

Problem 1-40

B_{rms} = 1.1 T and f = 60 Hz,

$$V_{rms} = \omega N A_c B_{rms} = 86.7 \quad \text{V}$$

Core volume = $A_c l_c = 1.54 \times 10^{-3}$ m^3. Mass density = 7.65×10^3 kg/m^3. Thus, the core mass = $(1.54 \times 10^{-3})(7.65 \times 10^3) = 11.8$ kg.

At B = 1.1 T rms = 1.56 T peak, core loss density = 1.3 W/kg and rms VA density is 2.0 VA/kg. Thus, the core loss = $1.3 \times 11.8 = 15.3$ W. The total exciting VA for the core is $2.0 \times 11.8 = 23.6$ VA. Thus, its reactive component is given by $\sqrt{23.6^2 - 15.3^2} = 17.9$ VAR.

The rms energy storage in the air gap is

$$W_{gap} = \frac{g A_c B_{rms}^2}{\mu_0} = 5.08 \quad \text{J}$$

corresponding to an rms reactive power of

$$\text{VAR}_{gap} = \omega W_{gap} = 1917 \quad \text{VAR}$$

Thus, the total rms exciting VA for the magnetic circuit is

$$\text{VA}_{rms} = \sqrt{15.3^2 + (1917 + 17.9)^2} = 1935 \quad \text{VA}$$

and the rms current is $I_{rms} = \text{VA}_{rms}/V_{rms} = 22.3$ A.

Problem 1-41

Part(a): Area increases by a factor of 4. Thus the voltage increases by a factor of 4 to $e = 1096 \cos(377t)$.

Part (b): l_c doubles therefore so does the current. Thus I = 0.26 A.

Part (c): Volume increases by a factor of 8 and voltage increases by a factor of 4. There $I_{\varphi,\mathrm{rms}}$ doubles to 0.20 A.

Part (d): Volume increases by a factor of 8 as does the core loss. Thus P_c = 128 W.

Problem 1-42

From Fig. 1.19, the maximum energy product for samarium-cobalt occurs at (approximately) B = 0.47 T and H = -360 kA/m. Thus the maximum energy product is 1.69×10^5 J/m^3.

Thus,

$$A_m = \frac{0.8}{0.47}\ 2\ \text{cm}^2 = 3.40\ \text{cm}^2$$

and

$$l_m = -0.2\ \text{cm}\ \frac{0.8}{\mu_0(-3.60\times 10^5)} = 0.35\ \text{cm}$$

Thus the volume is $3.40 \times 0.35 = 1.20$ cm^3, which is a reduction by a factor of 5.09/1.21 = 4.9.

Problem 1-43

From Fig. 1.19, the maximum energy product for neodymium-iron-boron occurs at (approximately) B = 0.63 T and H = -470 kA/m. Thus the maximum energy product is 2.90×10^5 J/m^3.

Thus,

$$A_m = \frac{0.8}{0.63}\ 2\ \text{cm}^2 = 2.54\ \text{cm}^2$$

and

$$l_m = -0.2\ \text{cm}\left(\frac{0.8}{\mu_0(-4.70\times 10^5)}\right) = 0.27\ \text{cm}$$

Thus the volume is $2.54 \times 0.25 = 0.688\ \text{cm}^3$, which is a reduction by a factor of 5.09/0.688 = 7.4.

Problem 1-44

From Fig. 1.19, the maximum energy product for samarium-cobalt occurs at (approximately) $B = 0.47$ T and $H = -360$ kA/m. Thus the maximum energy product is 1.69×10^5 J/m^3. Thus, we want $B_g = 1.3$ T, $B_m = 0.47$ T and $H_m = -360$ kA/m.

$$h_m = -g\left(\frac{H_g}{H_m}\right) = -g\left(\frac{B_g}{\mu_0 H_m}\right) = 2.87\ \text{mm}$$

$$A_m = A_g\left(\frac{B_g}{B_m}\right) = 2\pi R h\left(\frac{B_g}{B_m}\right) = 45.1\ \text{cm}^2$$

$$R_m = \sqrt{\frac{A_m}{\pi}} = 3.66\ \text{cm}$$

Problem 1-45

From Fig. 1.19, the maximum energy product for samarium-cobalt occurs at (approximately) $B = 0.63$ T and $H = -482$ kA/m. Thus the maximum energy product is 3.03×10^5 J/m^3. Thus, we want $B_g = 1.3$ T, $B_m = 0.47$ T and $H_m = -360$ kA/m.

$$h_m = -g\left(\frac{H_g}{H_m}\right) = -g\left(\frac{B_g}{\mu_0 H_m}\right) = 2.15\ \text{mm}$$

$$A_{\mathrm{m}} = A_{\mathrm{g}} \quad \frac{B_{\mathrm{g}}}{B_{\mathrm{m}}} = 2\pi Rh \quad \frac{B_{\mathrm{g}}}{B_{\mathrm{m}}} = 31.3 \quad \mathrm{cm}^2$$

$$R_m = \sqrt{\frac{A_m}{\pi}} = 3.16 \quad \text{cm}$$

Problem 1-46

For $B_m = \mu_R(H_m - H_c)$, the maximum value of the product $-B_mH_m$ occurs at $H_m = H_c/2$ and the value is $B_r^2/4\mu_R$.

T [C]	$-(B_mH_m)_{max}$ [kJ/m^3]	Corresponding H_m [kA/m]	B_m[T]
20	253.0	-440.0	0.57
60	235.7	-424.7	0.56
80	223.1	-413.2	0.54
150	187.5	-378.8	0.50
180	169.0	-359.6	0.47
210	151.5	-340.5	0.45

Problem 1-47

From Fig. 1.19, the maximum energy product for neodymium-iron-boron occurs at (approximately) $B_m = 0.63$ T and $H_m = -470$ kA/m. The magnetization curve for neodymium-iron-boron can be represented as

$$B_m = \mu_R H_m + B_r$$

where $B_r = 1.26$ T and $\mu_R = 1.067\mu_0$. The magnetic circuit must satisfy

$$H_m d + H_g g = Ni; \quad B_m A_m = B_g A_g$$

part (a): For $i = 0$ and $B_g = 0.6$ T, the minimum magnet volume will occur when the magnet is operating at the maximum energy point.

$$A_m = \frac{B_g}{B_m} A_g = 6.67 \quad \text{cm}^2$$

$$d = -\frac{H_g}{H_m}$$

$g = 3.47 \quad \text{mm}$

part (b): Want $B_g = 0.8$ T when $i = I_{peak}$

$$I_{peak} = \frac{B_g\left(\frac{dA_g}{\mu_R A_m} + \frac{g}{\mu_0}\right) - \frac{B_r d}{\mu_R}}{N} = 6.37 \text{ A}$$

Because the neodymium-iron-boron magnet is essentially linear over the operating range of this problem, the system is linear and hence a sinusoidal flux variation will correspond to a sinusoidal current variation.

Problem 1-48

Part(a): Fromthesolution to Problem 1-46, themaximumenergyproductforneodymium-iron-boron at 180 C occurs at (approximately) $B_m = 0.47$ T and $H_m = -360$ kA/m. The magnetization curve for neodymium-iron-boron can be represented as

$$B_m = \mu_R H_m + B_r$$

where $B_r = 0.94$ T and $\mu_R = 1.04\mu_0$. The magnetic circuit must satisfy

$$H_m d + H_g g = 0; \quad B_m A_m = B_g A_g$$

For $B_g = 0.8$ T, the minimum magnet volume will occur when the magnet is operating at the maximum energy point.

$$A_m = \frac{B_g}{B_m} A_g = 15.3 \text{ cm}^2$$

$$d = -\frac{H_g}{H_m} g = 5.66 \text{ mm}$$

Part(b): At 60 C, $B_r = 1.12$ T. Combining

$$B_m = \mu_R H_m + B_r$$

$$H_{\mathrm{m}}d + H_{\mathrm{g}}g = 0$$

$$A_m B_m = A_g A_g = \mu_0 H_g A_g$$

gives

$$B_g = \frac{\mu_0 d A_m}{\mu_0 d A_g + \mu_R g A_m} B_r = 0.95 \text{ T}$$

PROBLEM SOLUTIONS: Chapter 2

Problem 2-1

At 60 Hz, $\omega = 120\pi$.

$$\text{primary:} \quad (V_{\text{rms}})_{\text{max}} = N_1 \omega A_c (B_{\text{rms}})_{\text{max}} = 3520 \quad \text{V, rms}$$

$$\text{secondary:} \quad (V_{\text{rms}})_{\text{max}} = N_2 \omega A_c (B_{\text{rms}})_{\text{max}} = 245 \quad \text{V, rms}$$

At 50 Hz, $\omega = 100\pi$. Primary voltage is 2934 V, rms and secondary voltage is 204 V, rms.

Problem 2-2

$$N = \frac{\sqrt{2} V_{\text{rms}}}{\omega A_c B_{\text{peak}}} = 147 \quad \text{turns}$$

Problem 2-3

$$N = \sqrt{\frac{300}{75}} = 2 \quad \text{turns}$$

Problem 2-4

Part (a):

$$R1 = \left(\frac{N_1}{N_2}\right)^2 R_2 = 9.38\ \Omega \quad I_1 = \frac{V_1}{I_1} = 1.28\ \text{A}$$

$$V_2 = \frac{N_2}{N_1} V_1 = 48 \text{ V} \quad P_2 = \frac{V_2^{\,2}}{R_2} = 14.6 \text{ W}$$

Part (b): For $\omega = 2\pi f = 6.28 \times 10^3\ \Omega$

$$X_1 = \omega L = 2.14\ \Omega \quad I_1 = \frac{V_1}{R_1 + jX_1} = 1.25\ \text{A}$$

$$I_2 = \frac{N_1}{N_2} I_1 = 0.312\ \text{A} \quad V_2 = I_2 R_2 = 46.8\ \text{V}$$

$$P_2 = V_2 I_2 = 14.6\ \text{W}$$

Problem 2-5

For $\omega = 100]\pi$, $Z_L = R_L + j\omega L = 5.0 + j0.79\ \Omega$

$$V_L = 110 \frac{20}{120} = 18.3\ \text{V} \quad I_L = \frac{V_L}{I_L} = 3.6\ \text{A}$$

and

$$I_H = I_L \frac{120}{20} = 604\ \text{mA}$$

Problem 2-6

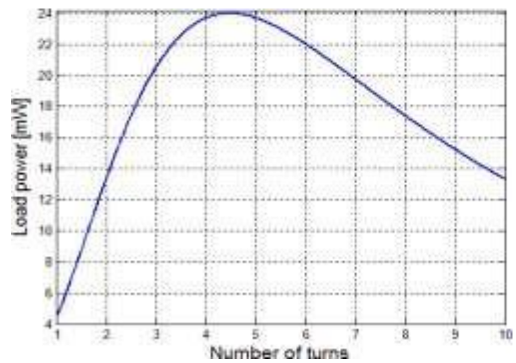
The maximum power will be supplied to the load resistor when its impedance, as reflected to the primary of the ideal transformer, equals that of the source (1.5 kΩ). Thus the transformer turns ratio N to give maximum power must be

$$N = \sqrt{\frac{R_s}{R_{load}}} = 4.47$$

Under these conditions, the source voltage will see a total resistance of $R_{tot} = 3$ kΩ and the source current will thus equal $I = V_s/R_{tot} = 4$ mA. Thus, the power delivered to the load will equal

$$P_{load} = I^2(N^2 R_{load}) = 24 \text{ mW}$$

Here is the desired MATLAB plot:



Problem 2-7

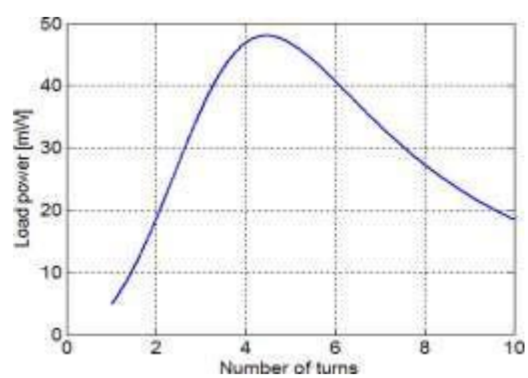
The maximum power will be supplied to the load resistor when its impedance, as reflected to the primary of the ideal transformer, equals that of the source (1.5 kΩ). Thus the transformer turns ratio N to give maximum power must be

$$N = \sqrt{\frac{X_s}{R_{load}}} = 4.47$$

Under these conditions, the source voltage will see a total impedance of $Z_{tot} = 1.5 + j1.5$ kΩ whose magnitude is $1.5\sqrt{2}$ kΩ. The current will thus equal $I = V_s/|Z_{tot}| = 5.7\ 2$ mA. Thus, the power delivered to the load will equal

$$P_{load} = I^2(N^2 R_{load}) = 48 \text{ mW}$$

Here is the desired MATLAB plot:



Problem 2-8

$$V_2 = V_1 \left(\frac{X_m}{X_{l_1} + X_m} \right) = V_1 \left(\frac{L_m}{L_{l_1} + L_m} \right) = 119.86 \ \text{V}$$

Problem 2-9

Part (a): Referred to the secondary

$$L_{m,2} = \frac{L_{m,1}}{N^2} = 37.9 \ \text{mH}$$

Part(b): Referred to the secondary, $X_m = \omega L_{m,2} = 14.3\ \Omega$, $X_2 = 16.6\ \text{m}\Omega$ and $X_1 = 16.5\ \text{m}\Omega$. Thus,

$$(i) \quad V_1 = N \left(\frac{X_m}{X_m + X_2} \right) V_2 = 7961 \ \text{V}$$

and

$$(ii) \quad I_{sc} = \frac{V_2}{X_{sc}} = \frac{V_2}{X_2 + X_m || X_1} = 3629 \ \text{A}$$

Problem 2-10

Part (a):

$$I_1 = \frac{V_1}{X_{l_1} + X_m} = 4.98 \ \text{A}; \qquad V_2 = N V_1 \left(\frac{X_m}{X_{l_1} + X_m} \right) = 6596 \ \text{V}$$

Part (b): Let $X'_{l_2} = X_{l_2}/N^2$ and $X_{sc} = X_{l_1} + X_m || (X_m + X'_{l_2})$. For I_{rated} = 45 kVA/230 V =

196 A

$$V_1 = I_{\mathrm{rated}} X_{\mathrm{sc}} = 11.4 \quad \mathrm{V}$$

$$I_2 = \frac{1}{N} \left(\frac{X_{\mathrm{m}}}{X_{\mathrm{m}} + X_{l2}} \right) I_{\mathrm{rated}} = 6.81 \quad \mathrm{A}$$

Problem 2-11

Part (a): At 60 Hz, all reactances increase by a factor of 1.2 over their 50-Hz values. Thus

$$X_m = 55.4\ \Omega \qquad X_{l,1} = 33.4\ \text{m}\Omega \qquad X_{l,2} = 30.4\ \Omega$$

Part (b): For $V_1 = 240$ V

$$I_1 = \frac{V_1}{X_1 + X_m} = 4.33\ \text{A} \qquad V_2 = NV_1 \frac{X_m}{X_m + X_{l,1}} = 6883\ \text{V}$$

Problem 2-12

The load voltage as referred to the high-voltage side is $V'_L = 447 \times 2400/460 = 2332$ V. Thus the load current as referred to the high voltage side is

$$I'_L = \frac{P_L}{V'_L} = 18.0\ \text{A}$$

and the voltage at the high voltage terminals is

$$V_H = |V'_L + jX_{l,1}I'_L| = 2347\ \text{V}$$

and the power factor is

$$\text{pf} = \frac{P_L}{V_H I'_L} = 0.957\ \text{lagging}$$

here we know that it is lagging because the transformer is inductive.

Problem 2-13

At 50 Hz, $X_l = 39.3 \times (5/6) = 32.8\ \Omega$. The load voltage as referred to the high-voltage side is $V_L{}' = 362 \times 2400/460 = 1889$ V. Thus the load current as referred to the high voltage side is

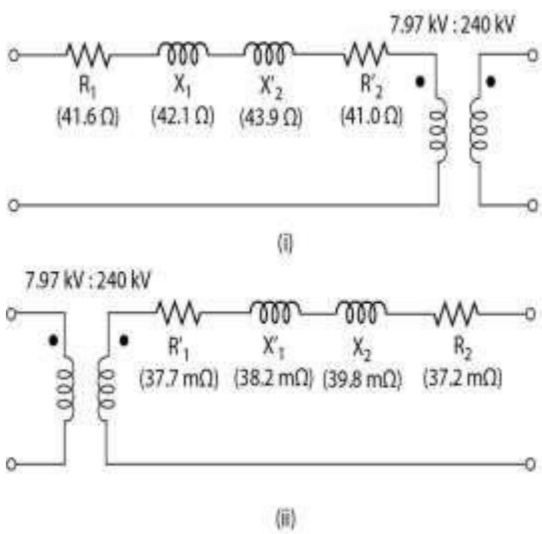
$$I_L' = \frac{P_L}{V_L'} = 18.3 \text{ A}$$

and the voltage at the high voltage terminals is

$$V_H = |V_L' + jX_{l,1} I_L'| = 1981 \text{ V}$$

Problem 2-14

Part (a):



Part (b):

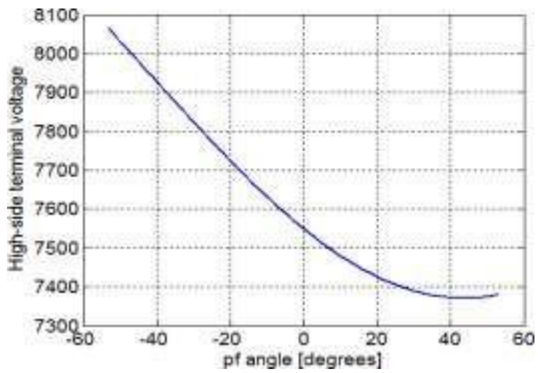
$$\hat{I}_{\text{load}} = \frac{40 \text{ kW}}{240 \text{ V}} e^{j\varphi} = 166.7\, e^{j\varphi} \text{ A}$$

where φ is the power-factor angle. Referred to the high voltage side, $\hat{I}_H = 5.02\, e^{j\varphi}$ A.

$$\hat{V}_{\mathrm{H}} = Z_{\mathrm{H}} \hat{I}_{\mathrm{H}}$$

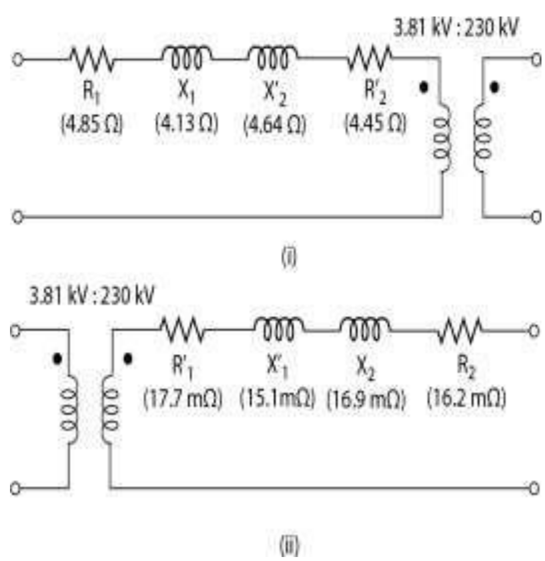
Thus, (i) for a power factor of 0.87 lagging, V_{H} = 7820 V and (ii) for a power factor of 0.87 leading, V_{H} = 7392 V.

part (c):



Problem 2-15

Part (a):



Part (b):

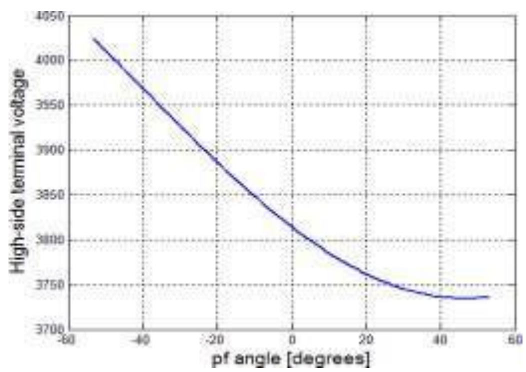
$$\hat{I}_{\text{load}} = \frac{40\ \text{kW}}{240\ \text{V}} e^{j\varphi} = 326.1\, e^{j\varphi}\ \text{A}$$

where φ is the power-factor angle. Referred to the high voltage side, $\hat{I}_{\text{H}} = 19.7\, e^{j\varphi}$ A.

$$\hat{V}_{\text{H}} = Z_{\text{H}}\hat{I}_{\text{H}}$$

Thus, (i) for a power factor of 0.87 lagging, $V_{\text{H}} = 3758$ V and (ii) for a power factor of 0.87 leading, $V_{\text{H}} = 3570$ V.

part (c):



Problem 2-16

Part (a): $\hat{I}_{\text{load}} = (178/.78)\ \text{kVA}/2385\ \text{V} = 72.6\ \text{A}$ at $\angle = \cos^{-1}(0.78) = 38.7^{\circ}$

$$\hat{V}_{\text{t,H}} = N(\hat{V}_{\text{L}} + Z_{\text{t}}\,\hat{I}_{\text{load}}) = 34.1\ \text{kV}$$

Part (b):

$$\hat{V}_{\text{send}} = N(\hat{V}_{\text{L}} + (Z_{\text{t}} + Z_{\text{f}})\,\hat{I}_{\text{load}}) = 33.5\ \text{kV}$$

Part (c): $\hat{I}_{\text{send}} = \hat{I}_{\text{load}}/N$ and

$$S_{\text{send}} = P_{\text{send}} + jQ_{\text{send}} = \hat{V}_{\text{send}}\hat{I}^{*}_{\text{send}} = 138\ \text{kW} - j93.4\ \text{kVAR}$$

Thus P_{send} = 138 kW and Q_{send} = −93.4 kVAR.

Problem 2-17

Part (a):

pf = 0.78 leading:

part (a): $V_{t,H}$ = 34.1 kV
part (b): V_{send} = 33.5 kV
part (c): P_{send} = 138.3 kW, Q_{send} = -93.4 kVA

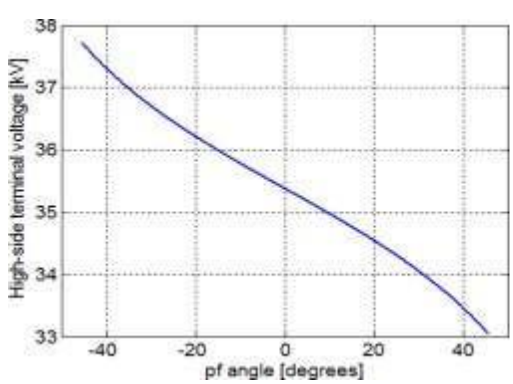
pf = unity:

part (a): $V_{t,H}$ = 35.0 kV
part (b): V_{send} = 35.4 kV
part (c): P_{send} = 137.0 kW, Q_{send} = 9.1 kVA

pf = 0.78 lagging:

part (a): $V_{t,H}$ = 35.8 kV
part (b): V_{send} = 37.2 kV
part (c): P_{send} = 138.335 kW, Q_{send} = 123.236 kVA

Part (b):



Problem 2-18

Following the methodology of Example 2.6, efficiency = 98.4 percent and regulation = 1.25 percent.

Problem 2-19

Part (a): The core cross-sectional area increases by a factor of two thus the primary voltage must double to 22 kV to produce the same core flux density.

Part (b): The core volume increases by a factor of $2\sqrt{2}$ and thus the excitation kVA must increase by the same factor which means that the current must increase by a factor of $\sqrt{2}$ to 0.47 A and the power must increase by a factor of $2\sqrt{2}$ to 7.64 kW.

Problem 2-20

Part (a):

$$|Z_{\mathrm{eq,H}}| = \frac{V_{\mathrm{sc,H}}}{I_{\mathrm{sc,H}}} = 14.1\ \Omega$$

$$R_{\mathrm{eq,H}} = \frac{P_{\mathrm{sc,H}}}{I_{\mathrm{sc,H}}^2} = 752\ \mathrm{m}\Omega$$

$$X_{\mathrm{eq,H}} = \sqrt{|Z_{\mathrm{eq,H}}|^2 - R_{\mathrm{eq,H}}^2} = 14.1\ \Omega$$

and thus

$$Z_{\mathrm{eq,H}} = 0.75 + j14.1\ \Omega$$

Part (b): With $N = 78/8 = 9.75$

$$R_{\mathrm{eq,H}}$$

$$R_{eq,L} = \frac{}{N^2} = 7.91\ m\Omega$$

$$X_{eq,L} = \frac{X_{eq,H}}{N^2} = 148 \text{ m}\Omega$$

and thus

$$Z_{eq,L} = 7.9 + j148 \text{ m}\Omega$$

Part (c): From the open-circuit test, the core-loss resistance and the magnetizing reactance as referred to the low-voltage side can be found:

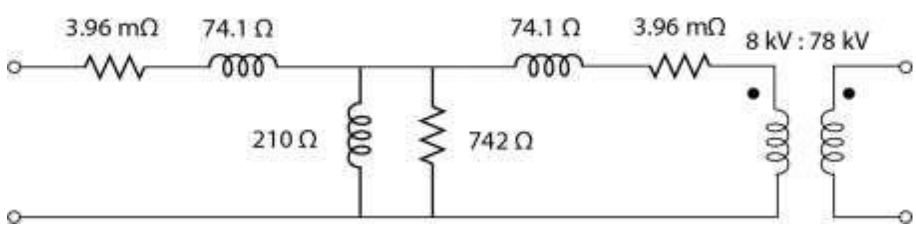
$$R_{c,L} = \frac{V_{oc,L}^2}{P_{oc,L}} = 742\ \Omega$$

$$S_{oc,L} = V_{oc,L} I_{oc,L} = 317 \text{ kVA}; \quad Q_{oc,L} = \sqrt{S_{oc,L}^2 - P_{oc,L}^2} = 305 \text{ kVAR}$$

and thus

$$X_{m,L} = \frac{V_{oc,L}^2}{Q_{oc,L}} = 210\ \Omega$$

The equivalent-T circuit for the transformer from the low-voltage side is thus:



Problem 2-21

Part (a):

$$|Z_{eq,H}| = \frac{V_{sc,H}}{I_{sc,H}} = 14.1\ \Omega$$

$$R_{eq,H} = \frac{P_{sc,H}}{I_{sc,H}^2} = 752\ \text{m}\Omega$$

$$X_{eq,H} = \sqrt{|Z_{eq,H}|^2 - R_{eq,H}^2} = 14.1\ \Omega$$

and thus

$$Z_{eq,H} = 0.75 + j14.1\ \Omega$$

Part (b): With $N = 78/8 = 9.75$

$$R_{eq,L} = \frac{R_{eq,H}}{N^2} = 7.91\ \text{m}\Omega$$

$$X_{eq,L} = \frac{X_{eq,H}}{N^2} = 148\ \text{m}\Omega$$

and thus

$$Z_{eq,L} = 7.9 + j148\ \text{m}\Omega$$

Part (c): From the open-circuit test, the core-loss resistance and the magnetizing reactance as referred to the low-voltage side can be found:

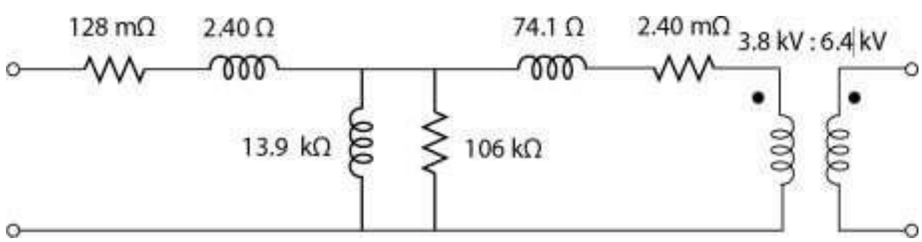
$$R_{c,L} = \frac{V_{c,L}^2}{P_{oc,L}} = 742\ \Omega$$

$$S_{oc,L} = V_{oc,L} I_{oc,L} = 317 \text{ kVA}; \quad Q_{oc,L} = \sqrt{S_{oc,L}^2 - P_{oc,L}^2} = 305 \text{ kVAR}$$

and thus

$$X_{m,L} = \frac{V_{oc,L}^2}{Q_{oc,L}} = 210\ \Omega$$

The equivalent-T circuit for the transformer from the low-voltage side is thus:



Problem 2-22

Parts (a) & (b): For $V_{oc,L} = 7.96$ kV, $I_{oc,L} = 17.3$ A and $P_{oc,L} = 48$ kW

$$R_{c,L} = \frac{V_{oc,L}^2}{P_{oc,L}} = 1.32 \text{ k}\Omega \qquad R_{c,H} = N^2 R_{c,L} = 33.0 \text{ k}\Omega$$

$$Q_{oc,L} = \sqrt{S_{oc,L}^2 - P_{oc,L}^2} = \sqrt{(V_{oc,L} I_{oc,L})^2 - P_{oc,L}^2} = 129 \text{ kVAR}$$

$$X_{m,L} = \frac{V_{oc,L}^2}{Q_{oc,L}} = 491\ \Omega \qquad X_{m,H} = N^2 X_{m,L} = 12.3 \text{ k}\Omega$$

For $V_{sc,H} = 1.92$ kV, $I_{oc,L} = 252$ A and $P_{oc,L} = 60.3$ kW

$P_{sc,H}$

$$R_{\mathrm{H}} = \quad I_{sc,\mathrm{H}}^{2} = 950\ \mathrm{m}\Omega$$

$$X_H = \sqrt{Z_H^2 - R_H^2} = \sqrt{(V_{sc,H}/I_{sc,H})^2 - R_H^2} = 7.56\ \Omega$$

$$R_L = \frac{R_H}{N^2} = 38.0\ \text{m}\Omega \qquad X_L = \frac{X_H}{N^2} = 302\ \text{m}\Omega$$

Part (c):

$$P_{diss} = P_{oc,L} + P_{sc,H} = 108\ \text{kW}$$

Problem 2-23

Parts (a) & (b): For $V_{oc,L} = 3.81$ kV, $I_{oc,L} = 9.86$ A and $P_{oc,L} = 8.14$ kW

$$R_{c,L} = \frac{V_{oc,L}^2}{P_{oc,L}} = 1.78\ \text{k}\Omega \qquad R_{c,H} = N^2 R_{c,L} = 44.8\ \text{k}\Omega$$

$$Q_{oc,L} = \sqrt{S_{oc,L}^2 - P_{oc,L}^2} = \sqrt{(V_{oc,L}I_{oc,L} - P_{oc,L}^2)^2} = 36.7\ \text{kVAR}$$

$$X_{m,L} = \frac{V_{oc,L}^2}{Q_{oc,L}} = 395\ \Omega \qquad X_{m,H} = N^2 X_{m,L} = 9.95\ \text{k}\Omega$$

For $V_{sc,H} = 920$ V, $I_{oc,L} = 141$ A and $P_{oc,L} = 10.3$ kW

$$R_H = \frac{P_{sc,H}}{I_{sc,H}^2} = 518\ \text{m}\Omega$$

$$X_H = \sqrt{Z_H^2 - R_H^2} = \sqrt{(V_{sc,H}/I_{sc,H})^2 - R_H^2} = 6.50\ \Omega$$

$$R_L = \frac{R_H}{N^2} = 20.6\ \text{m}\Omega \qquad X_L = \frac{X_H}{N^2} = 259\ \text{m}\Omega$$

Part (c):

$$P_{\text{diss}} = P_{\text{oc,L}} + P_{\text{sc,H}} = 18.4 \text{ kW}$$

Problem 2-24

Solution the same as Problem 2-22

Problem 2-25

Part (a): 7.69 kV:79.6 kV, 10 MVA

Part (b): 17.3 A, 48.0 kW

Part (c): Since the number of turns on the high-voltage side have doubled, this will occur at a voltage equal to twice that of the original transformer, i.e. 3.84 kV.

Part (d): The equivalent-circuit parameters referred to the low-voltage side will be unchanged from those of Problem 2-22. Those referred to the high-voltage side will have 4 times the values of Problem 2-22.

$$R_{\text{c,L}} = 1.32 \text{ k}\Omega \quad R_{\text{c,H}} = 132 \text{ k}\Omega$$

$$X_{\text{m,L}} = 491 \ \Omega \quad X_{\text{m,H}} = 49.1 \text{ k}\Omega$$

$$R_{\text{L}} = 38.0 \text{ m}\Omega \quad R_{\text{H}} = 3.80 \ \Omega$$

$$X_{\text{L}} = 302 \text{ m}\Omega \qquad X_{\text{H}} = 30.2 \ \Omega$$

Problem 2-26

Part (a): Under this condition, the total transformer power dissipation is 163.7 kW. Thus the efficiency is

$$\eta = 100 \times \frac{25\ \text{MW}}{25\ \text{MW} + 163.7\ \text{kW}} = 99.4\%$$

From Problem 2-20, the transformer equivalent series impedance from the low voltage side is $Z_{\text{eq,L}} = 7.91 + j148\ \text{m}\Omega$. The transformer rated current is $I_{\text{rated}} = 3125$ A and thus under load the transformer high-side voltage (neglecting the effects of magnetizing current) referred to the primary is

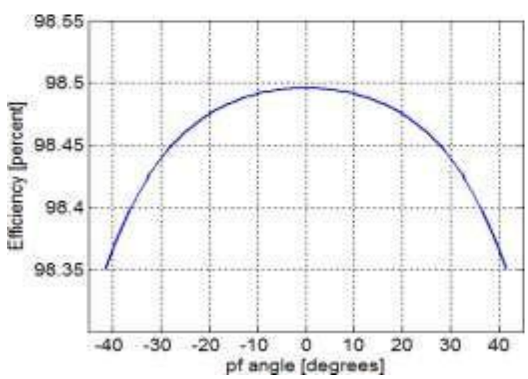
$$|V_H'| = |V_L - I_{\text{rated}} Z_{\text{eq,L}}| = 7.989\ \text{kV}$$

and thus the voltage regulation is $100 \times (7.989 - 8.00)/7.989 = 0.14\%$.

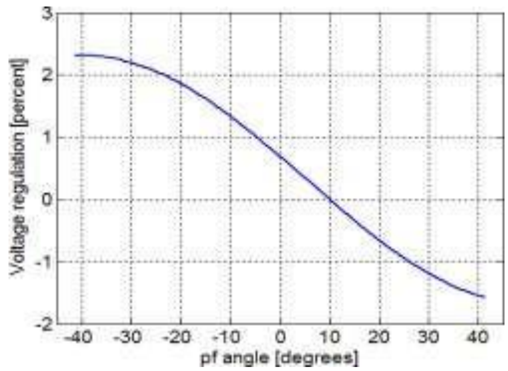
Part (b): Same methodology as part (a) except that the load is 22.5 MW and the current is $\hat{I} = I_{\text{rated}} \angle \varphi$ where $\varphi = \cos^{-1}(0.9) = 25.8°$. In this case, the efficiency is 99.3% and the regulation is 1.94%.

Problem 2-27

Part (a):



Part (b);



Problem 2-28

Part (a): The transformer loss will be equal to the sum of the open-circuit and short- circuit losses, i.e. 313 W. With a load of $0.85 \times 25 = 21.25$ kW, the efficiency is equalto

$$\eta = \frac{21.25}{21.25 + 0.313} = 0.9855 = 98.55\%$$

Part (b): The transformer equivalent-circuit parameters are found as is shown in the solution to Problem 2-23.

$$R_{c,L} = 414\ \Omega \quad R_{c,H} = 41.4\ \mathrm{k}\Omega$$

$$X_{m,L} = 193\ \Omega \quad X_{m,H} = 19.3\ \mathrm{k}\Omega$$

$$R_L = 17.1\ \mathrm{m}\Omega \quad R_H = 1.71\ \Omega$$

$$X_L = 64.9\ \mathrm{m}\Omega \quad X_H = 6.49\ \Omega$$

The desired solution is 0.963 leading power factor, based upon a MATLAB search for the load power factor that corresponds to rated voltage at both the low- and high-voltage terminals.

Problem 2-29

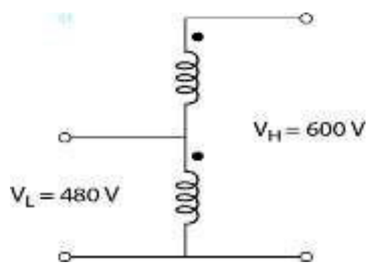
Efficiency = 98.4% and regulation = 2.38%.

Problem 2-30

The voltage rating is 280 V:400 V. The rated current of the high voltage terminal is equal to that of the 120-V winding, $I_{rated} = 45 \times 10^3/120 = 375$ A. Hence the kVA rating of the transformer is 400 × 375 = 150 kVA.

Problem 2-31

Part (a):



Part (b): The rated current of the high voltage terminal is equal to that of the 120-V winding, $I_{rated} = 10^4/120 = 83.3$ A. Hence the kVArating of the transformer is $600 \times 83.3 =$ 50 kVA.

Part (c): The full load loss is equal to that of the transformer in the conventional connection, $P_{loss} = (1 - 0.979)$ 10 kW = 180 W. Hence as an autotransformer operating with a load at 0.93 power factor ($P_{load} = 0.93 \times 50$ kW = 46.5 kW), the efficiency will be

$$\eta = \frac{46.5 \text{ kW}}{46.78 \text{ kW}} = 0.996 = 99.6 \text{ percent}$$

Problem 2-32

Part (a): The voltage rating is 78 kV:86 kV. The rated current of the high voltage terminal is equal to that of the 8-kV winding, $I_{rated} = 50 \times 10^6/8000 = 3.125$ kA. Hence the kVA rating of the transformer is 86 kV $\times$ 3.125 kA = 268.8 MVA.

Part (b): The loss at rated voltage and current is equal to 164 kW and hence the efficiency will be

$$\eta = \frac{268.8 \text{ MW}}{268.96 \text{ MW}} = 0.9994 = 99.94 \text{ percent}$$

Problem 2-33

MATLAB script should reproduce the answers to Problem 2-32.

Problem 2-34

Part (a): 7.97 kV:2.3 kV; 188 A:652 A; 1500 kVA

Part (b): 13.8 kV:1.33 kV; 109 A:1130 A; 1500 kVA

Part (c): 7.97 kV:1.33 kV; 188 A:1130 A; 1500 kVA

part (d): 13.8 kV:2.3 kV; 109 A:652 A; 1500 kVA

Problem 2-35

Part (a):

(i) 68.9 kV:230 kV, 225 MVA
(ii) $Z_{\text{eq}} = 0.087 + j1.01\ \Omega$
(iii) $Z_{\text{eq}} = 0.97 + j11.3\ \Omega$

Part (b):

(i) 68.9 kV:133 kV, 225 MVA
(ii) $Z_{\text{eq}} = 0.087 + j1.01\ \Omega$

(iii) $Z_{eq} = 0.32 + j3.77\ \Omega$

Problem 2-36

Part (a):

(i) 480 V:13.8 kV, 675 kVA
(ii) $Z_{eq} = 0.0031 + j0.0215\ \Omega$
(iii) $Z_{eq} = 2.57 + j17.8\ \Omega$

Part (b):

(i) 480 V:7.97 kV, 675 MVA
(ii) $Z_{eq} = 0.0031 + j0.0215\ \Omega$
(iii) $Z_{eq} = 0.86 + j5.93\ \Omega$

Problem 2-37

Following the methodology of Example 2.8, V_{load} = 236 V, line-to-line.

Problem 2-38

Part (a): The rated current on the high-voltage side of the transformer is

$$I_{rated,H} = \frac{25\ \text{MVA}}{\sqrt{3} \times 68\ \text{kV}} = 209\ \text{A}$$

The equivalent series impedance reflected to the high-voltage side is

$$Z_{eq,H} = N^2 Z_{eq,L} = 1.55 + j9.70\ \Omega$$

and the corresponding line-neutral voltage magnitude is

$$V_H = I_{rated,H}\,|Z_{eq,H}| = 2.05\ \text{kV}$$

corresponding to a line-line voltage of 3.56 kV.

Part (b): The apparent power at the high-voltage winding is $S = 18/.75 = 24$ MVA and the corresponding current is

$$I_{\text{load}} = \frac{24\ \text{MVA}}{\sqrt{3} \times 68\ \text{kV}} = 209\ \text{A}$$

The power factor angle $\theta = -\cos^{-1}(0.75) = -41.4^\circ$ and thus

$$\hat{I}_{\text{load}} = 209\ \angle -41.4^\circ$$

With a high-side line-neutral voltage $V_H = 69\ \text{kV}/\sqrt{3} \equiv 39.8$ kV, referred to the high-voltage side, the line-neutral load voltage referred to the high-voltage side is thus

$$V'_{\text{load}} = |V_H - \hat{I}_{\text{load}} Z_{\text{eq,H}}| = 38.7\ \text{kV}$$

Referred to the low-voltage winding, the line-neutral load voltage is

$$V_{\text{load}} = \frac{13.8}{69} V'_{\text{load}} = 7.68\ \text{kV}$$

corresponding to a line-line voltage of 13.3 kV.

Problem 2-39

Part (a): The line-neutral load voltage $V_{\text{load}} = 24\ \text{kV}/\sqrt{3} = 13.85$ kV and the load current is

$$\hat{I}_{\text{load}} = \left(\frac{375\ \text{MVA}}{\sqrt{3}\ 24\ \text{kV}}\right) e^{j\varphi} = 9.02 e^{j\varphi}\ \text{kA}$$

where $\varphi = \cos^{-1} 0.89 = 27.1^\circ$.

The transformer turns ratio $N = 9.37$ and thus referred to the high voltage side, $V'_{\text{load}} = NV_{\text{load}} = 129.9$ kV and $\hat{I}'_{\text{load}} = \hat{I}_{\text{load}}/N = 962 e^{j\varphi}$ A. Thus, the transformer high-side line-neutral terminal voltage is

$$V_{\mathrm{H}} = |V_{\mathrm{L}} + jX_{\mathrm{t}}\hat{I}_{\mathrm{load}}| = 127.3\ \mathrm{kV}$$

–

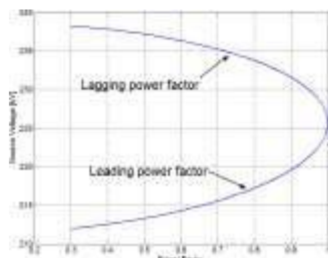
corresponding to a line-line voltage of 220.6 kV.

Part (b): In a similar fashion, the line-neutral voltage at the source end of the feeder is given by

$$V_s = |\hat{V}_L + (Z_f + jX_t)\hat{I}_{\text{load}}| = 126.6 \text{ kV}$$

corresponding to a line-line voltage of 219.3 kV.

Problem 2-40



Problem 2-41

Part (a): For a single transformer

$$R_{\text{eq,H}} = \frac{P_{\text{sc}}}{I_{\text{sc}}^2} = 342 \text{ m}\Omega$$

$$S_{\text{sc}} = V_{\text{sc}} I_{\text{sc}} = 8.188 \text{ kVA}$$

$$Q_{\text{sc}} = \sqrt{S_{\text{sc}}^2 - P_{\text{sc}}^2} = 8.079 \text{ kVAR}$$

and thus

$$X_{\text{eq,H}} = \frac{Q_{\text{sc}}}{I_{\text{sc}}^2} = 2.07 \ \Omega$$

s
c

For the there-phase bank with the high-voltage side connected in Δ, the transformer series impedance reflected to the high-voltage side will be 1/3 of this value. Thus

$$Z_{t,H} = \frac{R_{eq,H} + jX_{eq,H}}{3} = 114 + j689 \text{ m}\Omega$$

Part (b): Referred to the high voltage side, the line-neutral load voltage is V_{load} = 2400/*sqrt*3 = 1386 V and the 450-kW load current will be

$$I_{load} = \frac{P_{load}}{3V_{load}} = 108 \text{ A}$$

Thus the line-neutral source voltage is

$$V_s = |V_{load} + (Z_{t,H} + Z_f)I_{load}| = 1.40 \text{ kV}$$

corresponding to a line-line voltage of 2.43 kV.

Problem 2-42

Part (a): The transformer turns ratio is $N = 13800/120 = 115$. The secondary voltage will thus be

$$\hat{V}_2 = \frac{V_1}{N}\left(\frac{jX_m}{R_1 + jX_1 + jX_m}\right) = 119.87 \angle 0.051^\circ$$

Part (b): Defining $R'_L = N^2 R_L = 9.92$ MΩ and

$$Z_{eq} = jX_m || (R'_2 + R'_L + jX'_2)$$

$$\hat{V}_2 = \frac{V_1}{N}\left(\frac{Z_{eq}}{R_1 + jX_1 + Z_{eq}}\right) = 119.80 \angle 0.012^\circ$$

Part (c): Defining $X'_L = N^2 X_L = 9.92$ MΩ and

$$Z_{eq} = jX_m || (R + jX_L' + jX_2')$$

$$\hat{V}_2 = \frac{V_1}{N}\left(\frac{Z_{eq}}{R_1 + jX_1 + Z_{eq}}\right) = 119.78\angle 0.083^\circ$$

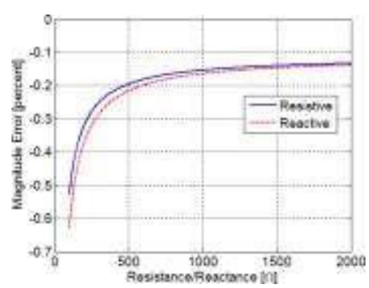
Problem 2-43

Following the methodology of Part (c) of Problem 2-42 and varying X_L one finds that the minimum reactance is 80.9Ω.

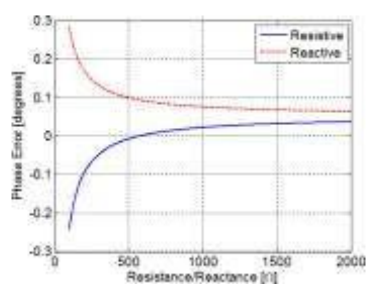
Problem 2-44

This solution uses the methodology of Problem 2-42.

Part (a):



Part (b):



Problem 2-45

Part (a): For I_1 = 150 A and turns ratio N = 150/5 = 30

$$\hat{I}_2 = \frac{I_1}{N}\,\frac{jX_m}{R'_2 + j(X_m + X'_2)} = 4.995\,\angle{-0.01^\circ}\ \text{A}$$

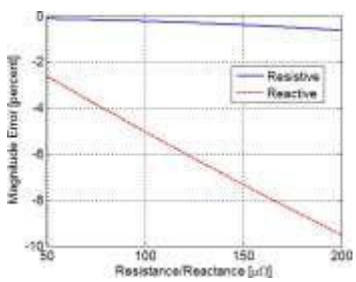
Part (b): With $R_b = 0.1\ \text{m}\Omega$ and $R'_b = N^2 R_b = 90\ \text{m}\Omega$

$$\hat{I}_2 = \frac{I_1}{N}\,\frac{jX_m}{R'_2 + R'_b + j(X_m + X'_2)} = 4.988\,\angle{-2.99^\circ}\ \text{A}$$

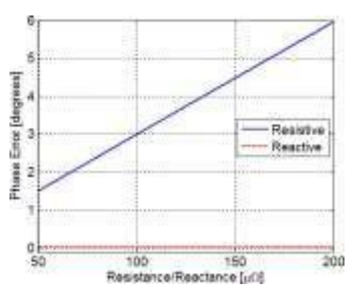
Problem 2-46

This solution uses the methodology of Problem 2-45.

Part (a):



Part (b):



Problem 2-47

The base impedance on the high-voltage side of the transformer is

$$Z_{\text{base,H}} = \frac{V^2_{\text{rated,H}}}{P_{\text{rated}}} = 136.1\ \Omega$$

Thus, in Ohms referred to the high-voltage side, the primary and secondary impedances are

$$Z = (0.0029 + j0.023)Z_{\text{base,H}} = 0.29 + j23.0 \text{ m}\Omega$$

and the magnetizing reactance is similarly found to be $X_{\text{m}} = 172\ \Omega$.

Problem 2-48

From the solution to Problem 2-20, as referred to the low voltage side, the total series impedance of the transformer is $7.92 + j148.2$ mΩ, the magnetizing reactance is 210 Ω and the core-loss resistance is 742 Ω. The low-voltage base impedance of this transformer is

$$Z_{\text{base,L}} = \frac{(8 \times 10^3)^2}{25 \times 10^6} = 2.56\ \Omega$$

and thus the per-unit series impedance is $0.0031 + j0.0579$, the per-unit magnetizing reactance is 82.0 and the per-unit core-loss resistance is 289.8.

Problem 2-49

From the solution to Problem 2-23, as referred to the low voltage side, the total series impedance of the transformer is $20.6 + j259$ mΩ, the magnetizing reactance is 395 Ω and the core-loss resistance is 1780 Ω. The low-voltage base impedance of this transformer is

$$Z_{\text{base,L}} = \frac{(3.81 \times 10^3)^2}{2.5 \times 10^6} = 5.81\ \Omega$$

and thus the per-unit series impedance is $0.0035 + j0.0446$, the per-unit magnetizing reactance is 68.0 and the per-unit core-loss resistance is 306.6.

Problem 2-50

Part (a): (i) The high-voltage base impedance of the transformer is

$$Z_{\text{base,H}} = \frac{(7.97 \times 10^3)^2}{2.5 \times 10^3} = 2.54 \text{ k}\Omega$$

and thus the series reactance referred high-voltage terminal is

$$X_{\mathrm{H}} = 0.075 Z_{\mathrm{base,H}} = 191\ \Omega$$

(ii) The low-voltage base impedance is 2.83 Ω and thus the series reactance referred to the low-voltage terminal is 212 mΩ.

Part (b):

(i) Power rating: 3×25 kVA = 75 kVA
Voltage rating: $\sqrt{3} \times 7.97$ kV : $\sqrt{3} \times 266$ V = 13.8 kV : 460 V
(ii) The per-unit impedance remains 0.075 per-unit
(iii) Referred to the high-voltage terminal, $X_{\mathrm{H}} = 191\ \Omega$
(iv) Referred to the low-voltage terminal, $X_{\mathrm{L}} = 212\ \mathrm{m}\Omega$

Part (c):

(i) Power rating: 3×25 kVA = 75 kVA
Voltage rating: $\sqrt{3} \times 7.97$ kV : 266 V = 13.8 kV : 266 V
(ii) The per-unit impedance remains 0.075 per-unit
(iii) Referred to the high-voltage terminal, $X_{\mathrm{H}} = 191\ \Omega$
(iv) Referred to the low-voltage terminal, the base impedance is now $Z_{\mathrm{base,L}} = 266^2/(75 \times 10^3) = 0.943\ \Omega$ and thus $X_{\mathrm{L}} = 0.943 \times 0.075 = 70.8\mathrm{m}\Omega$

Problem 2-51

Part (a): 500 V at the high-voltage terminals is equal to $500/13.8 \times 10^3 = 0.0362$ per unit. Thus the per-unit short-circuit current will be

$$I_{\mathrm{sc}} = \frac{0.0363}{0.075} = 0.48 \text{ perunit}$$

(i) The base current on the high-voltage side is

$$I_{\mathrm{base,L}} = \frac{75 \times 10^3}{\sqrt{3}} = 3.14\ A$$

$3 \times 13.8 \times 10$

$-$

and thus the short-circuit current at the high-voltage terminals will equal

$$I_{\mathrm{sc,H}} = 0.48 \times 3.14 = 1.51 \text{ A}$$

(ii) The base current on the low-voltage side is

$$I_{\mathrm{base,L}} = \frac{75 \times 10^3}{\sqrt{3} \times 460} = 94.1\ A$$

and thus the short-circuit current at the low-voltage terminals will equal

$$I_{\mathrm{sc,L}} = 0.48 \times 94.1 = 45.4 \text{ A}$$

Part (b): The per-unit short-circuit current as well as the short-circuit current at the high-voltage terminals remains the same as for Part (a). The base current on the low-voltage side is now

$$I_{\mathrm{base,L}} = \frac{75 \times 10^3}{\sqrt{3} \times 266} = 163\ A$$

and thus the short-circuit current at the low-voltage terminals will equal

$$I_{\mathrm{sc,L}} = 0.48 \times 163 = 78.6 \text{ A}$$

Problem 2-52

Part (a): On the transformer 26-kV base, the transformer base impedance is

$$Z_{\mathrm{base,t}} = \frac{26^2}{850} = 0.795\ \Omega$$

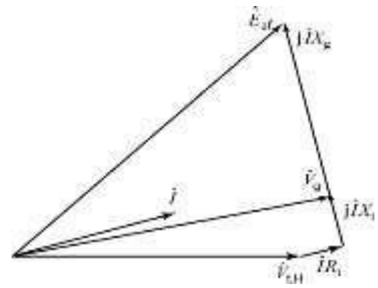
and on the same voltage base, the generator base impedance is

$$Z_{\mathrm{base,g}} = \frac{26^2}{800} = 0.845\ \Omega$$

Thus, on the transformer base, the per-unit generator reactance is

$$X_{\mathrm{g}} = 1.28 \left(\frac{Z_{\mathrm{base,g}}}{Z_{\mathrm{base,t}}}\right) = 1.36 \text{ perunit}$$

Part (b):



Part (c): In per-unit on the transformer base,

$$V_{t,H} = 1.0 \text{ per unit} \quad P = \frac{750}{850} = 0.882 \text{ per unit} \quad S = \frac{P}{0.9} = 0.980 \text{ per unit}$$

and thus

$$\hat{I} = 0.98e^{j\varphi}$$

where $\varphi = \cos^{-1}(0.9) = 25.8^\circ$

Thus, the per-unit generator terminal voltage on the transformer voltage base is

$$\hat{V}_g = V_{t,H} + (R_t + jX_t)\hat{I} = 0.979 \angle 3.01^\circ \text{ per} - \text{unit}$$

which corresponds to a terminal voltage of 0.979×26 kV = 25.4 kV.

The per-unit generator internal terminal voltage on the transformer voltage base is

$$\hat{E}_{af} = V_{t,H} + (R_t + jX_t + jX_g)\hat{I} = 1.31 \angle 72.4^\circ \text{ per} - \text{unit}$$

which corresponds to a terminal voltage of 1.31×26 kV = 34.1 kV.

In per unit, the generator complex output power is

$$S = \hat{V}_g\hat{I}^* = 0.884 - j0.373 \text{ per unit}$$

and thus the generator output power is $P_{gen} = 0.884 \times 850 = 751.4$ MW. The generator power factor is

$$\text{pf} = \frac{P}{|S|} = 0.92$$

and it is leading.