1

G. Çakal

Part-I

a) First, let's find core reluctance.

$$R_{core} = \frac{l_{core}}{\mu_0 \mu_r A_{core}} \quad ; \quad l_{core} = 2\pi \times 10cm = 20\pi cm$$

$$A_{core} = 4cm^2$$

$$R_{core} = \frac{20\pi \times 10^{-2}}{\mu_0 \times 1400 \times 4 \times 10^{-4}} \cong 893k \ (1/H)$$

$$L = \frac{N^2}{R} \Rightarrow N = \sqrt{L \times R_{core}} = \sqrt{10m \times 893k}$$

$$\boxed{N \cong 95 \text{ turns}}$$

b) $\oint H dl = NI = B \cdot A_{core} \cdot R_{core} \Rightarrow I_{max} = \frac{\hat{B} \cdot A_{core} \cdot R_{core}}{N}$

$$= \frac{1.6 \times 4cm^2 \times 893k}{95}$$

$$\boxed{I_{max} = 6A}$$

c) Say $J = 4A/mm^2$

$$A_{wire} = I/J = 6/4 = 1.5mm^2$$

$$A_{wire-total} = 1.5mm^2 \times 95 \cong 143 \ mm^2$$

$$A_{window} = \pi (r_{in}^2) = \pi (90mm)^2 \cong 25k \ mm^2$$

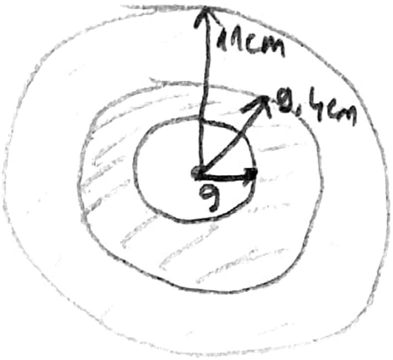
$$k_{fill-factor} = \frac{143}{25k} \Rightarrow k_{ff} = 0.56\%$$

$\Rightarrow$ quite feasible ✓

G. Çakal

Part - II

d) More accurate solutions can be obtained using Matlab. But let's assume that flux is concentrated at 20% of the inner radius



$A_{core} = 0{,}4 \times 2 = 0.8\,cm^2$

$l_{core} = 2\pi \times 9{,}2 = 18{,}4\pi\ cm$

$$R_{core} = \frac{18{,}4\pi\ cm}{\mu_0\, 1400 \times 0{,}8\,cm^2}$$

$R_{core} = 411k\ (1/H)$

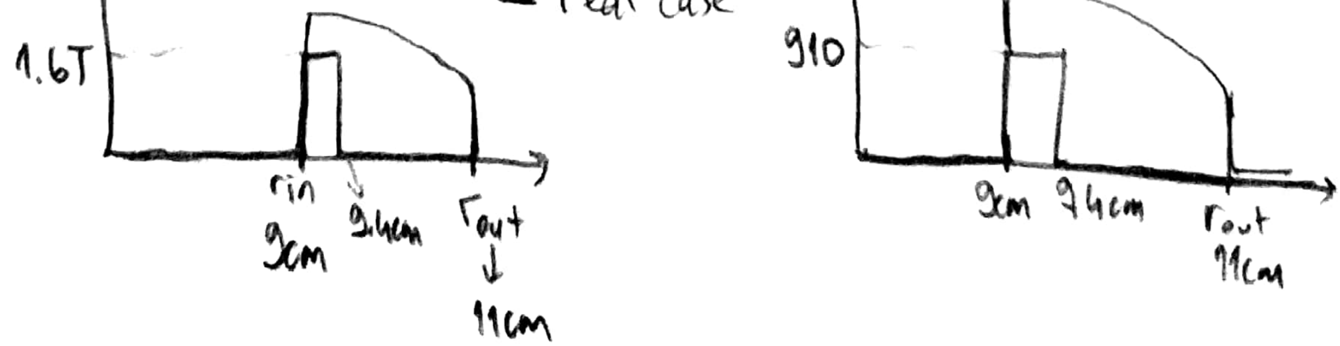
$$N = \sqrt{L \cdot R} = \sqrt{10m \times 411k}$$

$$\boxed{N \cong 203 \text{ turns}}$$

$$I_{max} = \frac{\hat{B} \cdot A_{core} \cdot R_{core}}{N} = \frac{1{,}6 \times 0{,}8 \times 10^{-4} \times 411 \times 10^{3}}{203}$$

$$\boxed{I_{max} = 0{,}26\ A}$$

e) case: $I = I_{max}$, non-homogenous distribution.



G. Çakal

Q2)

$F = B \cdot I \cdot l$

$B = 1.5T$ (assumed uniform and constant

$I = \dfrac{V}{|R + j\omega L|} = \dfrac{12}{0.5} = 24A$

↳ $f=0$ (assumed stationary, on stall)

$l = ?$ $\quad l_{1\text{-turn}} = 2\pi r = 20\pi$ cm

$l_{30\text{turn}} = 600\pi$ cm $= 6\pi$ m.

$\Rightarrow \quad F = 1.5 \times 24 \times 6\pi \Rightarrow \boxed{F \overset{N}{=} 680\ N}$

$F = kx \Rightarrow \boxed{x = 6.8\ cm}$

↑ 100 N/cm

G. Galeal

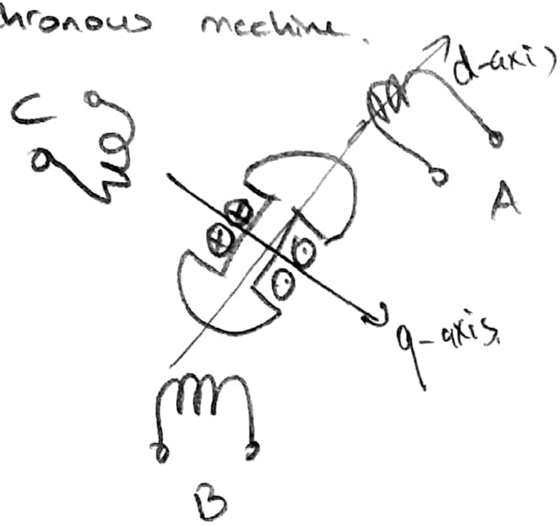
Q3) a) N42H → max. operating temp of 120°C
N42UH → " " " " 180°C

i) They have same remanence flux density. So, the two machines have the same magnetic loading.
For electrical loading, I guess, it depends. If the maximum operating temperature of the machine is limited by the operating temperature of PMs, then electrical loading of the machine with N42UH can be increased further. However, if maximum operating temperature of the machine is limited by an another factor such as maximum operating temperature of windings, then two machines should have the same electrical loading.

ii) The operating temperature of the machines may or may not be the same depending on the case mentioned above. Again, insulation temperature classes are also depends on the case above. I would use Class H (180°C) insulation for N42UH machine and class B (130°C) insulation for N42H machine.

G. Fakal

b) D-axis is aligned with main flux passing direction. For example, it is aligned with magnetization direction of PM in PM machines. Q-axis is aligned with 90° electrically ahead of d-axis. Say you have a salient pole sychronous machine.



Ld is the $\frac{2}{3}$ of the inductance when d-axis is aligned with phase-A as shown above. Lq can also be measured similarly when q-axis is aligned with phase-A.

<u>Addition</u>: Ld and Lq results from saliency in the magnetic model. Due to this saliency, reluctance torque can be created (such as in IPMSM), increasing torque density.

G. Cakal

c) Torque of the IPMSM can be written as follows

$$T = \frac{3}{2} pp \left(\lambda_{pm} - (L_q - L_d) i_d \right) i_q$$

$$\uparrow$$

$$0$$

when PMs are demagnetized $\lambda_{pm} \to 0$. However, the machine is still capable of producing torque due to saliency.

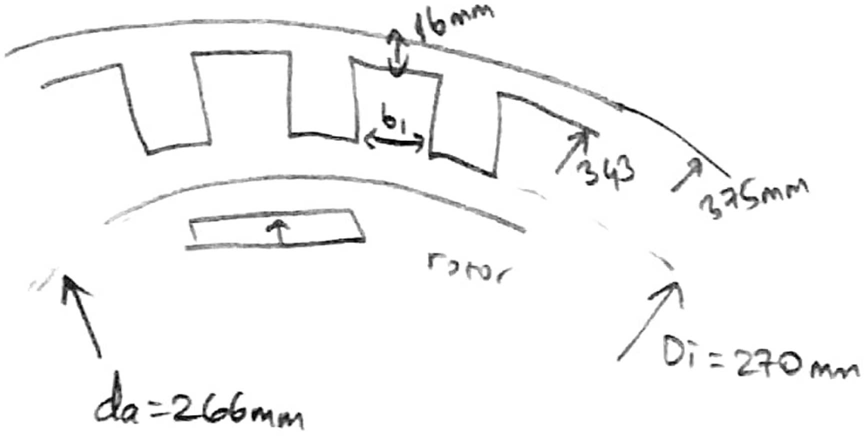
d) Fractional pitched windings

+	−
• End windings can be reduced. (Decreasing losses and increasing efficiency.)	• Can be implemented only for double layer structure.
• High frequency harmonics are reduced	• Subharmonics
• Cogging torque can be limited.	

G. Çakal

Q4) a) Number of poles, $P = 12$.

b) I will use cylindrical stator approximation by Carter's coefficient.



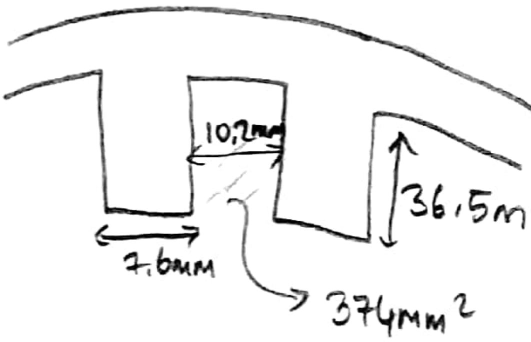
$\delta = 2mm$ (air gap)

$\delta_{eff} = \delta \cdot k_c$

$$k_c = \frac{\tau_u}{\tau_u - K \cdot b_1}$$

$$K = \frac{b_1/\delta}{b_1/\delta + 5}$$

Slot drawing:



$\Rightarrow b_1 = 10.2mm$

$\tau_u = ?$ (slot pitch)

$$\tau_u = \frac{\pi \cdot D_i}{N} = \frac{\pi \times 270mm}{54} = 15,7mm$$

Then, carter's coefficient can be calculated as

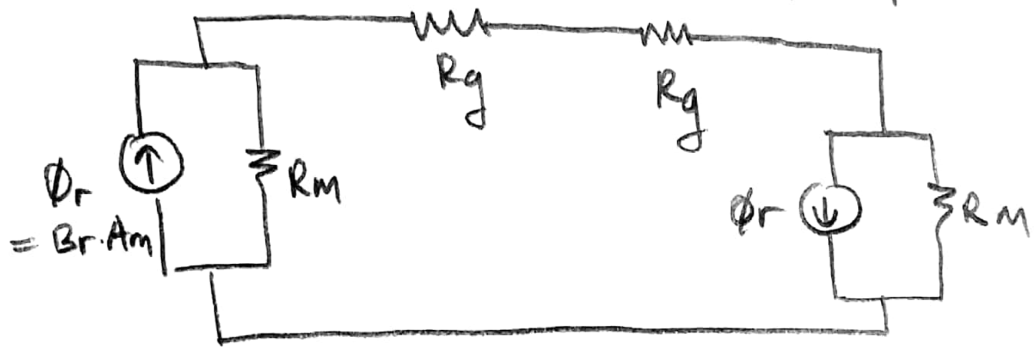
$$K = \frac{10.2/2}{10.2/2 + 5} \cong 0.5 \quad , \quad k_c = \frac{\tau_u}{\tau_u - K \cdot b_1} = \frac{15,7}{15,7 - 0,5 \times 10,2} = 1,48$$

$\Rightarrow \delta_{eff} = 1,48 \times 2mm = 2.96 \Rightarrow \boxed{\delta_{eff} \cong 3mm}$ effective air gap.

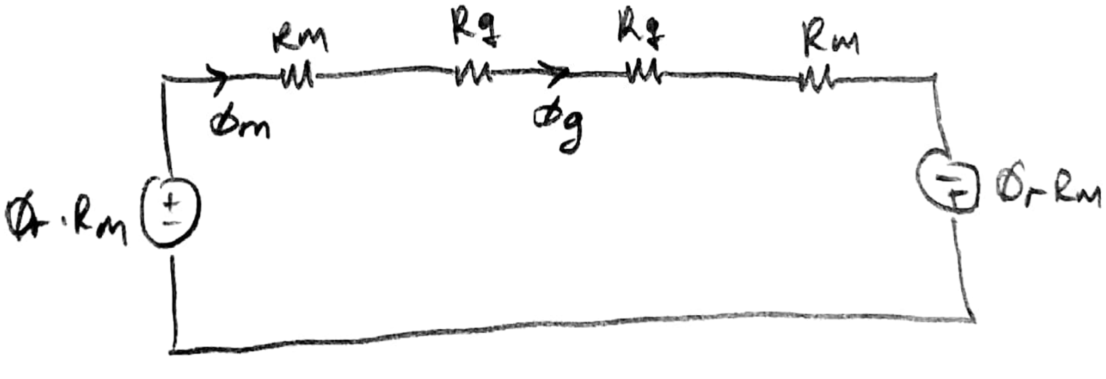
G. Şokel

Then;

I assume two magnets are combined in a pole.
Assuming that the core is infinitely permeable, the magnetic equivalent circuit under one pole-pair is as



OR



$$\cancel{2}\phi_r \cdot R_m = \cancel{2}(R_m + R_g)\cdot \phi_m \quad , \quad \phi_m = \phi_g$$

$$\Rightarrow \phi_m = \frac{\phi_r \cdot R_m}{R_m + R_g} = \frac{B_r \cdot A_m \cdot R_m}{R_m + R_g}$$

G. Gokal.

what is R_m, R_g? $\quad R = \dfrac{l}{\mu_0 \mu_r A}$

(say $\mu_r = 1.05$ for magnet)

$$R_m = \frac{4mm}{\mu_0 \times 1.05 \times 54mm \cdot l_{ax}}$$

l_{ax}: axial length of mach.

$$= \frac{4}{54 \times 1.05} \times \frac{1}{\mu_0 l_{ax}}$$

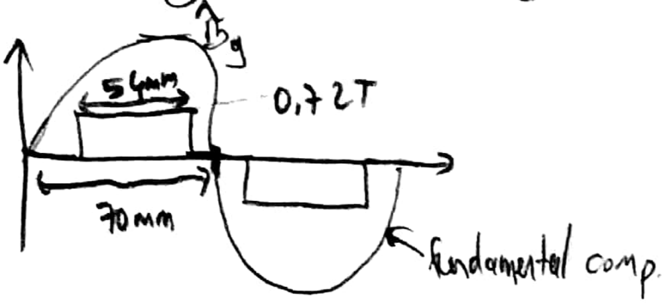
$$R_g = \frac{3mm}{\mu_0 \times 54mm \times l_{ax}} = \frac{3}{54} \times \frac{1}{\mu_0 l_{ax}}$$

Then, $\dfrac{R_m}{R_m + R_g} = 0.56$

Then, $\phi_g = B_g \times A_g = \underset{\substack{\uparrow \\ 1.29T}}{B_r} \times A_m \times 0.56$

$$B_g = \frac{1.29T \times \cancel{l_{ax}} \times \cancel{54mm} \times 0.56}{\cancel{54mm} \times \cancel{l_{ax}}} \Rightarrow B_g = 0.72T$$

Here, we assumed that there is a square wave-shaped flux density in the air gap as follows



$$\hat{B}_g = \frac{4}{\pi} \sin\left(90^\circ \times \frac{54}{90}\right) \times 0.72$$

$$\Rightarrow \boxed{\hat{B}_{g_1} = 0.86T}$$

G. Gökal.

we found that $\hat{B}_{g1} = 0.86\,T$

what about peak flux density at the stator teeth?

$$\hat{B}_{teeth} \cong \hat{B}_{g1} \times \frac{l_{teeth} + l_{slot}}{l_{teeth}} = 0.86\ \frac{7.6 + 10.2}{7.6}$$

$$\boxed{\hat{B}_{teeth} = 2\,T}$$

Back-core flux density?

$$\frac{\hat{\phi}_{pp}}{2} = B_{core} \times A_{core} = \hat{B}_{core} \times 16mm \times l_{ax}$$

$$B_{avg} \times A_{pole} = 2\,\hat{B}_{core} \times 16mm \times l_{ax}$$

$$A_{pole} = \frac{\pi \times 268}{12} \times l_{ax} = 70.2\,mm \times l_{ax}$$

$$B_{avg} = \hat{B}_{g1} \times \frac{2}{\pi} \cong 0.55\,T$$

$$\Rightarrow \hat{B}_{core} = \frac{0.55 \times 70.2mm \times \cancel{l_{ax}}}{2 \times 16mm \times \cancel{l_{ax}}} \Rightarrow \boxed{\hat{B}_{core} = 1.2\,T}$$

G. Çakal

c) These are mainly for cooling purposes. Also, it makes manufacturing easier

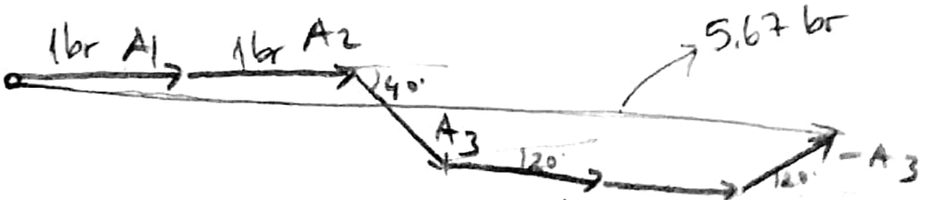
d) Let's model one pole pair, 9 slots.

$$q = \frac{54}{12 \times 3} = 1.5$$ (fractional slot) (assuming 3 phase mach.)

Then, we need to have double-layer winding diagram.

1	2	3	4	5	6	7	8	9
A_1	$-C_1$	B_1	B_2	$-A_2$	C_2	C_3	$-B_3$	A_3
A_2	$-C_2$	$-C_3$	B_3	$-A_1$	$-A_3$	C_1	$-B_1$	$-B_2$
0	40°	80°	120°	160°	200°	240°	280°	320°

1 pole-pair



$$\Rightarrow \boxed{k_{w_1} = \frac{5.67}{6} = 0.945}$$

e) G. Çakal

Assume $L_{ax} = 300\,mm$.

We calculated that $\hat{B}_{g1} = 0.86\,T$

Then, our magnetic loading $= \hat{B}_{g1} \frac{2}{\pi} \Rightarrow \underline{\bar{B} = 0.55\,T}$

Let's pick electrical loading: $\underline{\bar{A} = 45\ kA/m}$

Then, our tangential stress: $\sigma = \frac{\bar{A} \cdot \hat{B}_{g1}}{\sqrt{2}} = \frac{45k \times 0.86}{\sqrt{2}}$

$$\boxed{\sigma = 27.4\ kPa}$$

Then, torque of the machine;

$$T = \underset{\substack{\uparrow \\ 268mm}}{\pi \cdot D_{gap}} \cdot \underset{\substack{\uparrow \\ 300mm}}{l_{ax}} \cdot \sigma \cdot \frac{D_{gap}}{2} \Rightarrow \boxed{T \cong 930\ Nm}$$

Say $n_{rated} = 500\ rpm$

$$\Rightarrow P_{out} = 930 \times \frac{500}{30}\pi \Rightarrow \boxed{P_{out} \cong 48\ kW}$$

G. Çakal

f) Say $V_{line} = 400V$

$\Rightarrow V_{ph} = 230\ V_{rms} = 4.44 \cdot N_{ph} \cdot f \cdot \hat{\Phi}_{pp}$

$f = ?$ $\quad \frac{120 f}{\underset{12}{P}} = 500 \Rightarrow \underline{f = 50 Hz}$

$\hat{\Phi}_{pp} = \underset{\underset{0.55T}{\Downarrow}}{B_{avg}} \times A_{pole} = 0.55 \times \frac{\pi D_{gap}}{P} \times l_{ax}$

$= 0.55 \times \frac{\pi \times 0.268 \times 0.3}{12}$

$\underline{\hat{\Phi}_{pp} = 11.6\, mWb}$

Then, $N_{ph} = \frac{230}{4.44 \times 50 \times 11.6m} \Rightarrow N_{ph} \cong 90$ turns

Assume that all pole-pairs are connected in series

$\Rightarrow N_{pp} = \frac{90}{\underset{6}{pp}} \Rightarrow N_{pp} = 15$ turns

$\boxed{N_{slot} = 15/3 = 5 \text{turns}}$

for single layer!

$I_{ph} = \frac{P_{out}}{400\sqrt{3}} \Rightarrow I_{ph} \cong 70\,A$ $\quad$ Say $J = 4 A/mm^2$

$\Rightarrow A_{wire} = 17.5\ mm^2 \rightarrow$ Chose AWG5 wire ($A_{wire} = 16.8 mm^2$)

($J = 4.2\ A/mm^2$)

$$A_{wire-slot} = A_{wire} \times N_{slot} \times 2$$ ← double layer

G. Sokol

$$= 16.8\,mm^2 \times 5 \times 2 = 168\ mm^2$$

$A_{slot} = 374\ mm^2$ (datasheet)

$$k_{fill-fact} = \frac{168}{374} = 0.45$$ (quite good)

Electrical loading?

$$\bar{A} = \frac{I_{rms} \times N_{slot} \times \#totslots \times 2}{\pi\, D_T} = \frac{70 \times 5 \times 54 \times 2}{\pi \times 0.27}$$

↙ double layer

$\underline{\bar{A} = 45\ kA/m}$

This value is the same as the selection in part (e)