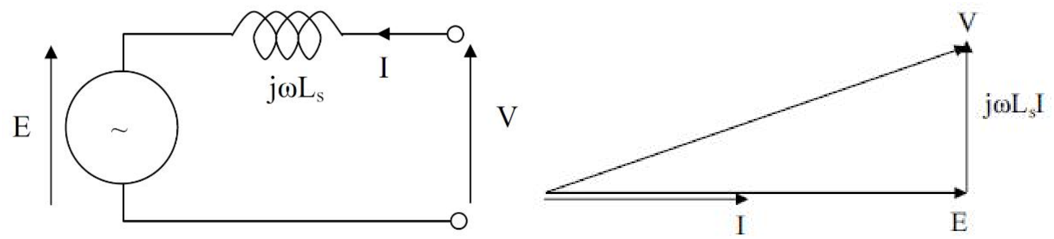
3B4 Electric Drive Systems Crib 2019 Mark Ainslie and Teng Long

1(a)

Commutator and brush wear and inefficiency due to field winding losses and friction at the brushes are two problems for brushed DC motors. Replacing the commutator by a power electronic circuit capable of switching armature currents and the field winding with PMs, the need for brushes is removed, efficiency is improved and a higher power/torque density can be achieved.

1(b)

The sinusoidal BLDCM consists of a rotor (rotating) with radially magnetised PMs of opposite polarity (i.e., N-S-N-S) and a stator (stationary) consisting of a sinusoidal three-phase winding (similar to the synchronous machine seen in Part IB).



Rated speed is the maximum speed up to which the rated torque can be sustained. The rated torque is related to the rated current (proportional in a fixed field DC motor), which is the maximum current the motor can sustain indefinitely without it overheating, which is determined by the ability to remove heat from the stator windings. Above the rated speed, the available torque falls linearly with speed.

The phasors E and jwL_s both increase in proportion to the motor's angular speed, so the magnitude and frequency of the voltage V must be controlled appropriately to maintain a torque angle of 90 degrees and hence obtain rated torque at different speeds up to the rated speed.

1(c)(i)

$T_{rated} = 3kI_{rated} = 3 \times 2.2 \times 200 = 1320$ Nm

$V_{rated}^2 = E^2 + (\omega L_s I_{rated})^2 = (k\omega/p)^2 + (\omega L_s I_{rated})^2$

$(415/\sqrt{3})^2 = (2.2\omega/2)^2 + (\omega \times 3.2 \times 10^{-3} * 200)^2$

$\omega \approx 188$ rad/s $\rightarrow \omega_s = \omega/p \approx 900$ rpm

1(c)(ii)

Field weakening allows higher speeds than the rated one by allowing the torque angle to be reduced from 90 degrees with the motor operating at rated voltage/current. In this case, the rotor and stator fluxes are no longer at 90 degrees with respect to each other and a component of the stator flux now directly opposes the rotor flux, reducing the total air gap field.

For max. speed, $V = V_{rated}$, $I = I_{rated}$, $T = 0.5T_{rated} = 660$ Nm $\rightarrow \sin\beta = 0.5 \rightarrow \beta = 150$ degrees

Cosine rule: $V_{rated}^2 = (k\omega/p)^2 + (\omega L_s I_{rated})^2 - 2(k\omega/p)(\omega L_s I_{rated})\cos 30$

$(415/\sqrt{3})^2 = (2.2\omega/2)^2 + (\omega \times 3.2 \times 10^{-3} * 200)^2 - 2(2.2\omega/2)(\omega \times 3.2 \times 10^{-3} * 200)\cos 30$

$(415/\sqrt{3})^2 = \omega^2[1.21 + 0.4096 - 2*1.1*0.64*\cos 30] = \omega^2[1.21 + 0.4096 - 1.2194]$

$\omega = 378.75$ rad/s $\rightarrow \omega_s = \omega/p \approx 1808$ rpm

$P = T\omega_s = 660*378.75/2 \approx 125$ kW

Cosine rule: $(\omega L_s I_{rated})^2 = V_{rated}^2 + (k\omega/p)^2 - 2*V_{rated}*(k\omega/p)\cos\delta$

$\cos\delta = [V_{rated}^2 + (k\omega/p)^2 - (\omega L_s I_{rated})^2]/[2*V_{rated}*(k\omega/p)] = 0.863$

$\delta = 30.3$ degrees

$\varphi + \delta = \beta - 90 \rightarrow \varphi = 150 - 90 - 30.3 = 29.7$ degrees

Power factor $\cos\varphi = 0.869$ leading

1(d)

Neglect mmf drop in soft iron magnetic circuit, so only consider air gap and PM (ignoring any curvature of the pole pieces)

$L_{air} = 1$ mm, $L_{PM} = 1.5$ mm

$H_{air}L_{air} + H_{PM}L_{PM} = 0$, $B_{air} = B_{PM}$

We want to operate at $B_r/2$, $H_c/2$ to achieve BH_{max}, corresponding to $H_{PM} = -1030/2$ kA/m

$H_{air} \times 1e\text{-}3 - 515e3 \times 1.5e\text{-}3 = 0$

$H_{air} = 772500$ A/m $\rightarrow B_{air} = 0.97$ T

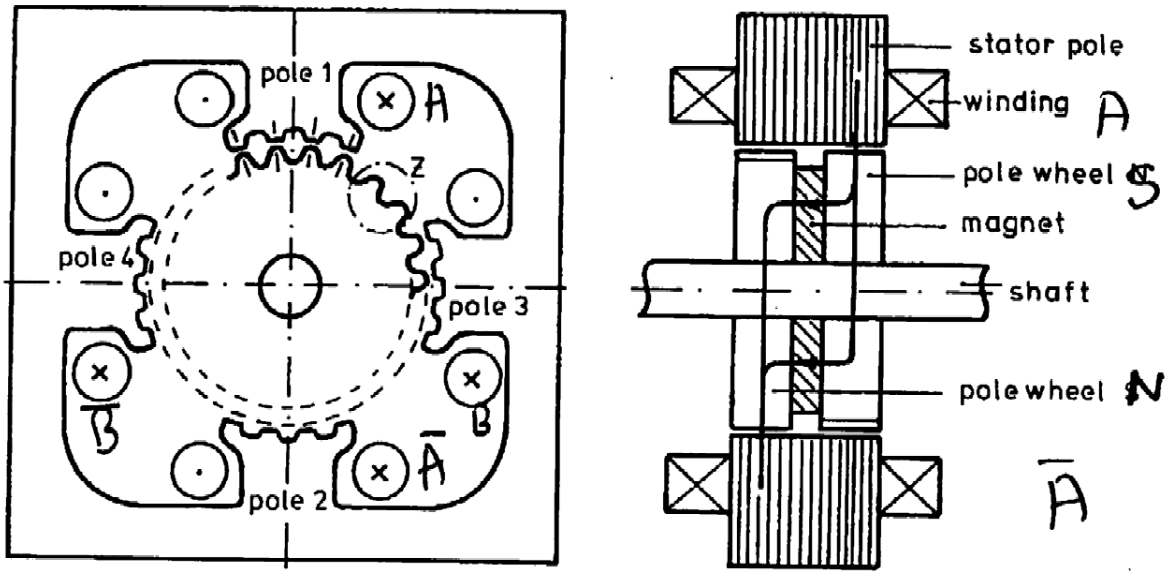
1(e)

Rotor has no iron losses as it rotates in synchronism with the stator-driven field. Hence, stator iron losses only. Use specific loss curves, scaling by frequency^2 if necessary, multiplied by total mass of stator (e.g., teeth + core). If VVVF operation at rated flux, but 50% rated speed, losses scaled by 1/4.

Assessor's comments:

A reasonably popular question. 1(c) Many candidates confused ω and $\omega_s = \omega/p$ when dealing with $E = k\omega_s$ and $j\omega L_s I_{rated}$ terms. Most candidates forgot to describe power factor as leading or lagging. 1(d) Many candidates did not refer to maximum energy product, BH_{max}, of PM corresponding to $B_r/2$, $H_c/2$. 1(e) Only a small number of candidates correctly referred to specific loss curves and no candidate discussed rotor/stator loss differences.

2(a)



Rotor: soft magnetic material with 50 equally-spaced teeth, with an axially-magnetised PM sandwiched between. Rotor wheels offset from each other by exactly 1/2 tooth pitch. Stator: coils wound on each pole, coils making up each phase connected in series.

Hybrid stepper motors utilise two types of torque production: 1) reluctance torque, due to reluctance variations in the magnetic circuit, which enables precise positioning; 2) holding/detent torque, even at zero current, due to stator/rotor teeth-PM interaction.

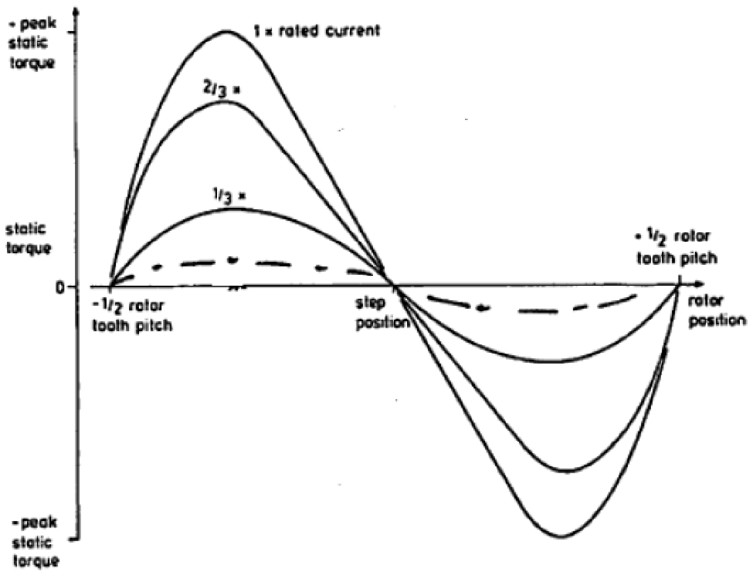
Excite phase A, phase B off. Pole 1 becomes S pole, pole 2 N; N wheel aligns with S pole, S wheel aligns with N pole. Teeth of N wheel completely misaligned with N pole; misaligned with pole 3 (B phase) by 1/4 tooth pitch. If phase A turned off and B excited such that pole 3 becomes S pole → new equilibrium position is alignment of N wheel with pole 3, rotor moves 1/4 tooth pitch.

Step angle in full-stepping mode: $360/4/N_t = 360/4/50 = 1.8$ degrees

2(b)(i)

A holding/detent torque, even at zero current, due to the stator/rotor teeth-PM interaction. This is useful where the rotor positions needs to be remembered, e.g., power supply failure.

2(b)(ii)



Irated → 220 mNm

0.5Irated → 120 mNm

I = 0 → 20 mNm

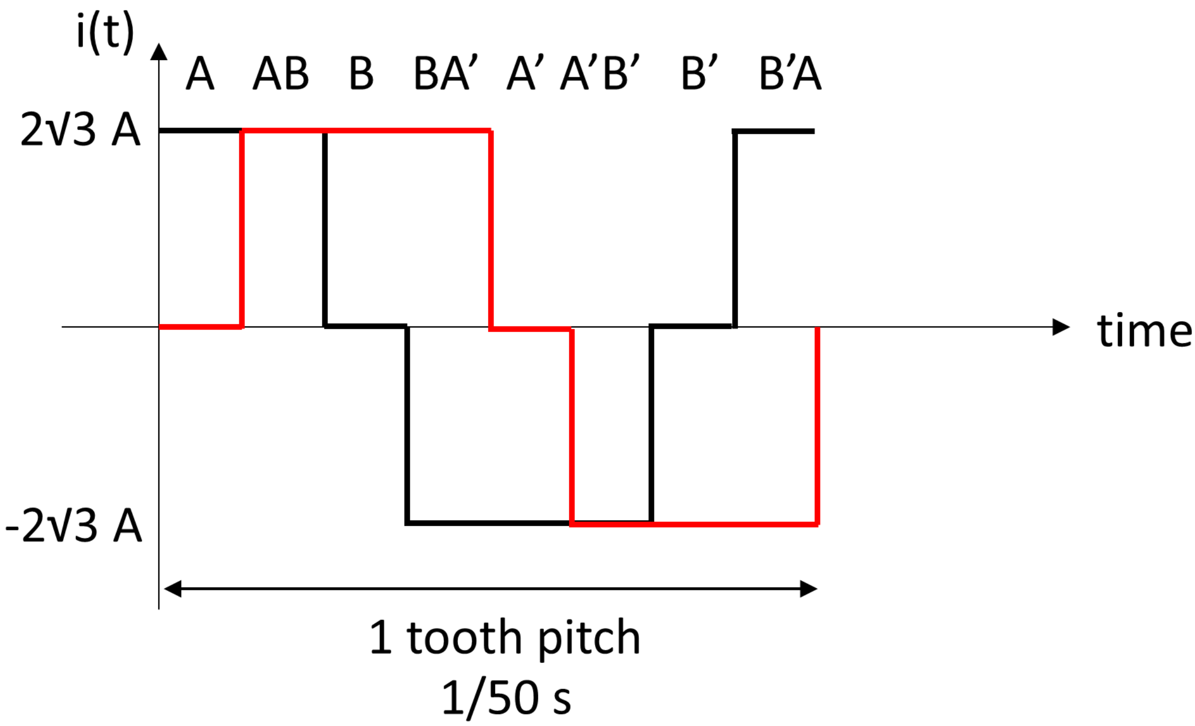
2(c)

Full-stepping: phases are sequentially excited A, B, -A, -B, A, etc. Alternatively, two phases at a time for higher torque AB, BA-, A-B-, B-A, AB, etc.

Half-stepping: A, AB, B, BA-, A-, A-B-, B-, etc. 8 distinct states, 1/8 tooth pitch movement.

Micro-stepping: Extension of half-stepping, but phases are excited with different proportions of current, making the steps even smaller.

In half-stepping mode, $I_{rms} = I_{rated} = \sqrt{(3/4)}I_{peak} = 4 \rightarrow I_{peak} = 8/\sqrt{3} = 4.62$ A



2(d)

See Fig. 8.9a in lecture notes; replace T1-T4 with MOSFETs (a complete solution will include the diodes). T1/T2 switched on as pair, so current in winding flows one way; to reverse direction, T1/T2 switched off, T3/T4 switched on. In the case of full-stepping, 200 steps per second for 60 rpm, 100 times per second switching between T1/T2 and T3/T4.

$P = 2*I^2R = 2*4^2*0.1 = 3.2$ W (ignoring MOSFET losses)

In this mode, each phase is excited only half the time, so peak value of current in MOSFETs is $\sqrt{2}I_{rated} = 4\sqrt{2}$ A.

2(e)

See Fig. 8.9b; bifilar winding is simpler and applying a voltage to one of the parallel strands results in a current that flows in the opposite direction to the other strand for a similar voltage. Hence, the full H-bridge is unnecessary → unipolar drive.

$P = 2*I^2R = 2*4^2*0.1*(0.6/0.4) = 1.5*3.2$ W $= 4.8$ W (again ignoring MOSFET losses)

Examiner's comments:

The least popular question, attempted by less than half of all candidates. Explanations of the hybrid stepper motor were generally good, but lacked explanation of the methods of torque production. In addition, many candidates confused reluctance torque and detent torque. Some candidates forgot single phase excitation during half-stepping (i.e., A, AB, B, BA-, etc.) and many confused rated current and peak current.

Q3. (a) - Better use of the space
- Reduce the harmonic content of the air gap flux
- Short pitching further reduces harmonic contents of the air gap flux.
- Less harmonic content of the flux gives smoother torque
- Short pitching also reduces the length of endwinding hence the winding resistance can be reduced.

(b) 36 slots. 2 pairs of poles, 3 phases.

'phase band' $m = \frac{36}{3 \times 2 \times 2} = 3$, 3 slots occupied by per phase per pole.

Two slots short pitched, double layered, the winding arrangement then becomes:

pole pair 1 N	pole pair 1 S	pole pair 2 N	pole pair 2S
$AAA\ \bar{C}\bar{C}\bar{C}\ BBB$	$\bar{A}\bar{A}\bar{A}\ CCC\ \bar{B}\bar{B}\bar{B}$	$AAA\ \bar{C}\bar{C}\bar{C}\ BBB$	$\bar{A}\bar{A}\bar{A}\ CCC\ \bar{B}\bar{B}\bar{B}$
$AAA\ \bar{C}\bar{C}\bar{C}\ BBB$	$\bar{A}\bar{A}\bar{A}\ CCC\ \bar{B}\bar{B}\bar{B}$	$AAA\ \bar{C}\bar{C}\bar{C}\ BBB$	$\bar{A}\bar{A}\bar{A}\ CCC\ \bar{B}\bar{B}\bar{B}$

short pitching:

P1 N	P1S	P2 N	P2S
$AAA\ \bar{C}\bar{C}\bar{C}\ BBB$	$\bar{A}\bar{A}\bar{A}\ CCC\bar{B}\bar{B}\bar{B}$	$AAA\ \bar{C}\bar{C}\bar{C}\ BBB$	$\bar{A}\bar{A}\bar{A}\ CCC\ \bar{B}\bar{B}\bar{B}$
$A\bar{C}\bar{C}\ \bar{C}BB\ B\bar{A}\bar{A}$	$\bar{A}CC\ C\bar{B}\bar{B}\bar{B}AA$	$A\bar{C}\bar{C}\ \bar{C}BB\ B\bar{A}\bar{A}$	$\bar{A}CC\ C\bar{B}\bar{B}\ \bar{B}AA$

$\beta = 360/36 = 10^\circ$

$\alpha = 2\beta = 20^\circ$

No. Q3②
Date 9.1.19

$$k_w = \frac{\sin(m p\beta/2)}{m \sin(p\beta/2)} \cos(p\alpha/2)$$

$$= \frac{\sin(3\times 2\times 10^\circ/2)}{3\sin(2\times 10^\circ/2)} \cos(2\times 20^\circ/2) = 0.902$$

Assume $E_{ph} = V_{ph} = 400/\sqrt{3}$. Using $E_{rms} = \frac{l\omega}{p} d N_{ph} k_w B_{rms}$

$$N_{ph} = \frac{E_{rms}\cdot p}{l\omega d k_w B_{rms}} = 25.47.$$

Double-layer winding, at per phase, there are $36/3 = 12$ coils.

The turns of per coil is: $N_{coil} = \frac{25.47}{12} = 2.12$

Using larger integer, $N_{coil} = 3$.

Then, $N_{ph} = 3\times 12 = 36.$

(c) $T\cdot \omega_r = T\cdot\omega_s - 3I_2'^2R_2'$

$s T\omega_s = 3I_2'^2 R_2$, $T = \frac{3I_2'^2R_2'}{s\omega_s}$. $\omega_s = \frac{2\pi f_1}{p}$

$|I_2'|^2 = \frac{V_1^2}{(\frac{R_2'}{s})^2 + X_2'^2}$, $T = \frac{3V_1^2R_2'}{s\omega_s\left[(\frac{R_2'}{s})^2 + X_2'^2\right]}$

T: electromagnetic torque, ω_s: syn speed

ω_r: mechanical speed, I_2': rotor current (phase, referred value)

R_2' : rotor resistance (referred value)
V_1 : stator phase voltage
X_2' : rotor reactance (referred value)
s : slip
P : pole pair.

(d) (i) when VVF operation, the motor is operated at small s. then:

$$\frac{R_2'}{s} \gg X_2', \quad T \approx \frac{3V_1^2 s}{\omega_s R_2'^2} = \frac{3V_1^2(\omega_s-\omega_r)}{\omega_s^2 R_2'^2}$$

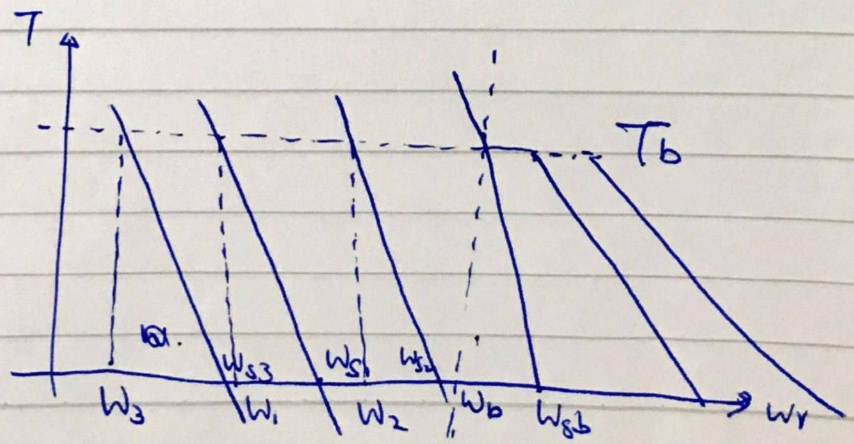
To keep the torque fixed, $\frac{V_1^2}{\omega_s^2}$ is constant, i.e. $\frac{V_1}{\omega_s}$ is constant.

To keep the power fixed.

$$P = T\cdot\omega_s = \frac{3V_1^2(\omega_s-\omega_r)}{\omega_s R_2'^2}$$

$\frac{V_1^2}{\omega_s}$ is constant.

(ii)



No. Q3④
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to change the speed from ω_1 to ω_2 or ω_3

the syn speed ω_s is changed, the torque is fixed. the slip is also fixed. to the linear region. It is equivalent to have a group of lines shifting due to the change of ω_s.

When the supply voltage is over than the rated voltage, the V/ω_s is constant rule has to be broken and V/ω_s becomes smaller, i.e. the magnetic field has to be weakened. The torque will also be reduced due to the weakened field.

Assessor's comments

Q3 AC machine stator winding and induction machine operation: 37 Attempts, Mean 13.21/20

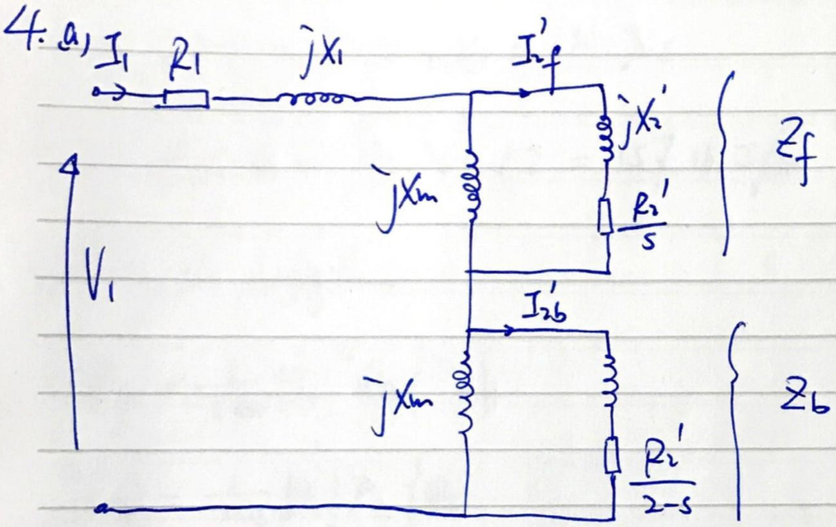
About half of candidates were able to fully and correctly answer this part. The common mistake for the other half of candidates was the incorrect sequence of winding arrangement. Candidates incorrectly put ABC rather than ACB as the sequence. Most of candidates were able to find out the number of slots per phase per pole. About half of candidates were able to calculate the number of turns.

Most of candidates were able to draw the equivalent circuit of three-phase induction machines and the torque expression. However, only a few candidates were able to correctly find the condition of constant output power. The common mistake came from confusion between the constant torque and constant power.

No. Q4 ①

Date 9.1.19

4. (a)



V_1 : single phase stator voltage

I_1 : stator current.

X_m : magnetising reactance.

X_2' : ~~ref~~ referred rotor reactance

R_2' : referred rotor resistance.

S : slip.

I_{2f}' : forward ~~ret~~ component of rotor current. (referred value)

I_{2b}' : backforward component of rotor current (referred value)

Z_f : Forward impedance of the rotor

Z_b : Backward impedance of the rotor.

(b) During the rest period, the loss of the motor is zero. $P_{loss} = 0$,

$\theta = \theta_0 e^{-\frac{t}{\tau}}$, the initial temperature of this period is:

$70 - 20 = 50°C$ the final temperature of this period is:

$40 - 20 = 20°C$

Hence: $(40-20) = (70-20)e^{-\frac{120}{\tau}}$.

$\Rightarrow \tau = -120/\ln(2/5) = 130.96s$

$C = \tau \cdot k = 130.96 \times 1.2 = 157.16\ J/k$

(c) R_1, X_1 negligible,

$T_f = \frac{1}{\omega_s}|I_1|^2 Re\{Z_f\}$

$T_b = \frac{1}{\omega_s}|I_1|^2 Re\{Z_b\}$

$T_{total} = T_f - T_b = \frac{1}{\omega_s}|I_1|^2\left[Re\{Z_f\} - Re\{Z_b\}\right]$

As $X_m >> |jX_2' + \frac{R_2'}{s}|$,
$X_m >> |jX_2' + \frac{R_2'}{2-s}|$,

$$\left.\begin{array}{l} Re\{Z_f\} \approx \frac{R_2'}{s} \\ Re\{Z_b\} \approx \frac{R_2'}{2-s} \end{array}\right\} \longrightarrow T_{total} \approx \frac{1}{\omega_s}|I_1|^2\left(\frac{R_2'}{s} - \frac{R_2'}{2-s}\right)$$

The mechanical power, $P_{mech} = T_{total} \cdot \omega_r$

$= \frac{\omega_r}{\omega_s}|I_2|^2 R_2'\left(\frac{1}{s} - \frac{1}{2-s}\right)$

$= (1-s)|I_2|^2 R_2' \frac{2(1-s)}{s(2-s)}$

$= 2|I_2|^2 R_2' \frac{(1-s)^2}{s(2-s)}$

No. Q4 ③
Date 9 . 1 . 19

Power dissipated in windings = $P_{diss} = 2|I_1|^2 R_r'$

(d) when full load.

$$(80-40) = (T_{2m}-40)\cdot\left(1-e^{-\frac{180}{130.96}}\right) \Rightarrow T_{2m} = 93.54°C$$

$$P_{diss} = k \cdot T_{2m} = 1.2 \times (93.54-20) = 88.25\,W.$$

from (c). $P_{mech} = 2|I_2|^2 R_r' \cdot \frac{(1-s)^2}{s(2-s)}$

$$= P_{diss}\cdot\left(\frac{(1-s)^2}{s(2-s)}\right)$$

$$\Rightarrow \quad 1500 = 88.26 \times \frac{(1-s)^2}{s(2-s)}$$

$$17\cdot s(2-s) = (1-s)^2$$

$$18s^2 - 36s + 1 = 0$$

$$\Rightarrow s = 0.028.$$

Assessor's comments

Q4 Single phase induction machine and duty cycle analysis: 32 Attempts, Mean 12.52/20

Most of candidates were able to fully and correctly answer the first part of this question on drawing the equivalent circuit of single phase induction machine and the torque expression.

In Part b, the temperature equation derivation was answered well and more than half candidates could give correct numerical answer of the temperature coefficient. Candidates have shown good understandings of temperature characteristics. However, only a few candidates were able to clearly differentiate the initial thermal conditions at different cycles. It has been observed that many candidates rushed at this second part of the question due to the time limit.