In these problems, use the following formulae:

$$T_{EM} = 3 \cdot k \cdot I_{ph(rms)} \text{ and } E_{ph(rms)} = k \cdot \omega$$

Summer 2009, Summer 2002

Problem 1

A four-pole three-phase permanent-magnet ac motor is used for traction in a hybrid-electric vehicle. The vector-controlled motor is rated at 100 Nm at 6000 rpm, and is powered by a three-phase sinusoidal PWM inverter supplied by a 300 V NiMH battery pack. The motor efficiency and power factor at rated power are 90% and 0.9, respectively. Determine the following drive parameters at rated power and speed:

(i) per-phase voltage, V_{ph},
(ii) per-phase back emf, E_{ph},
(iii) per-phase current, I_{ph},
(iv) per-phase synchronous inductance, L_S,
(v) motor voltage and torque constants, k_E and k_T,
(vi) motor copper loss, given a per-phase series resistance of $R_S = 30\ m\Omega$,
(vii) core, friction and windage losses for the machine.

[Ans. 106.1 V, 95.5 V, 244 A, 150 uH, 0.152 V/rad/s, 2.68 kW, 4.3 kW]

Problem 2

Summer 2008, Summer 2003

(a) A four-pole three-phase permanent-magnet ac motor is used for traction in a hybrid-electric vehicle. The vector-controlled motor is rated at 20 Nm at 6000 rpm, and is powered by a three-phase sinusoidal PWM inverter supplied by a 42 V NiMH battery pack. The motor efficiency and power factor at rated power are 90% and 0.9, respectively. Determine the following drive parameters at rated power and speed:

(i) per-phase voltage, V_{ph},
(ii) per-phase back emf, E_{ph},
(iii) per-phase current, I_{ph},
(iv) per-phase synchronous inductance, L_S,
(v) motor constant k_T.
(vi) motor copper loss, given a per-phase series resistance of $R_S = 1.5\ m\Omega$,
(vii) core, friction and windage losses for the machine.

Wrong ⇒ R_S not accounted for in eq. cct.

[Ans. 14.9 V, 13.4 V, 347 A, 16.5 uH, 0.021 V/rad/s, 542 W, 844 W]

Problem 3

The specification sheet for the TK 164-110-03 permanent magnet motor is attached. Determine the applied per-phase voltage and current, power factor, copper loss, and core-friction loss for the rated power condition under water cooling: 13.92 kW output power at 173.99 rad/s. Note that the specified winding parameters are twice the per-phase parameters.

Technical Data Summary TK 164

High power medium speed spindle motors

Applications:

Direct drive lathes

Swiss type lathes

Speed up to 5000 rpm, 40-200 Nm

Short duty constant power

	Symbol	TK 164-60-04	TK 164-110-03 *	TK 164-250-09	Units
Reference data (winding independent)					
Nominal torque, S1,0 speed, conduction+convection cooled IC 418 1)	Tnc	19	40	106	*Nmrms*
Nominal torque, S1, 0 speed, water cooled 2)	Tnw	37	80	209	*Nmrms*
Peak torque, S6 10% 1)	Tpk	54	114	302	*Nmrms*
Maximum torque 3)	Tul	93	171	389	*Nm*
Maximum structural speed	Pn	500	500	500	*rad/sec*
Critical flux control torque 4)	Pf	86	157	366	*Nm*
Motor constant	Tw	2,33	3,63	6,31	*Nm/sqrt(W)*
Pole number – 6 NORTH, 6 SOUTH	PN	12	12	12	
Connection		Y	Y	Y	
Physical data (winding independent)					
Rotor inertia	Jm	4,30	7,30	16	*mkgm2*
Acceleration at maximum torque	apk	12576	15595	18855	*rad/s2*
Outer diameter	Dout	164	164	164	*mm*
Rotor hole diameter	Din	96	96	96	*mm*
Overall stator length	Stkout	102	152	292	*mm*
Stack length	Stk	60	110	250	*mm*
Stator mass	Msta	4,8	8	17	*kg*
Rotor mass	Mrot	1,3	2,4	5,5	*kg*
Insulation		Class H - F	Class H - F	Class H - F	
Protection		IP 00	IP 00	IP 00	
Thermal data (winding independent)					
Thermal imp. assumed for cond. Cooling 1)	Rthc	0,390	0,214	0,093	*K/W*
Thermal impedance, motor to cooling frame 2)	Rthw	0,092	0,050	0,021	*K/W*
Thermal capacity	Cth	2.016	3.360	7.140	*J/K*
Thermal time constant cond cooling 1)	Tc	786	719	664	*sec*
Thermal time constant, water cooled 2)	Tw	185	168	150	*sec*
Loss at Tnc	LOc	267	491	1.120	*W*
Loss at Tnw	LOw	1.030	1.880	4.380	*W*
Coolant flow, 5 C temp rise, 35 C inlet	Cfl	3,0	5,4	12,6	*lit/min*
Treshold of built-in PTC	PTCt	130	130	130	*oC*
Electrical data (winding dependent)					
Nominal speed (knee speed) 5)	wn	173,29	173,99	52,40	*rad/sec*
Nominal power, water cooling, knee speed 6)	Pnw	6,41	13,92	10,95	*kW*
Back E.M.F. between phases	Ke	1,80	1,76	5,13	*Vs*
Torque constant	Kt	3,13	3,05	8,89	*Nm/Arms*
Temp.coeff. of E.M.F. and Kt	dKe/dT	-0,09	-0,09	-0,09	*%/oC*
Winding resistance, 20oC	Rw	2,69	1,06	2,98	*Ohm*
Winding inductance	Lw	12,63	6,58	24,00	*mH*
Nominal current, zero speed 1)	In0	6,08	13,12	11,92	*Arms*
Nominal current, zero speed, 2)	In	12,46	27,62	24,74	*Arms*
Maximum current 3)	Ipk	37,19	70,12	54,69	*Arms*
Frequency	fn	166	166	50	*Hz*
Efficiency at rated power 6)	n	0,86	0,88	0,71	

Definitions:

1) Motor assembled in light alloy case with outer surface = 500% of

2) Water cooled motor, water inlet temperature = 35 C, copper temp, 120

3) Torque at which magnetic saturation prevents further overloading

4) Knee torque corresponding to unlimited constant power operation

5) Limit of constant torque operation with 400 Vac supply

$P_o = 13.92\,kW \qquad \omega_m = 173.99\ rad/s$

$K_T = 3.05\ \frac{Nm}{A} \Rightarrow k = 1.016\ \frac{Nm}{A}$

$R_{ph} = \frac{R_W}{2} = 0.53\,\Omega \qquad \eta = 88\%$

$L_s = \frac{L_W}{2} = 3.29\,mH$

$P_I = \frac{P_o}{\eta} = 15.818\,kW$

$P_I - P_o = 1880\,W$

$E_{ph\,rms} = K\omega_m = 1.016 \times 173.99$
$\simeq 176.89\ V$

$T_o = \frac{P_o}{\omega_m} = 80\,Nm$

$I_{ph} = \frac{T_o}{3k} = 26.23\,A$

$V_{ph} = R_{ph} I_{ph} + E_{ph} + j\omega_e L_s I_{ph}$

$\omega_e = 2\pi f_e \ , \ f_e = 166\,Hz$

$\boxed{\omega_m = \frac{2\pi f_e}{\text{pole pairs}}} = 173.99\ rad/s$

$V_{ph} = (0.53 \times 26.23) + j(2\pi \times 166 \times 3.29\times10^{-3} \times 26.23) + 176.89$
$= (190.8 + j90.25)\,V = 211\angle 25.31^\circ\,V$

$K_T = 3.05\ Nm/A$

$K = \frac{K_T}{3} \simeq 1.02\ Nm/A$

$E_{L-L,rms} = \sqrt{3}\,K\omega = k_E\omega$

$K_E = 1.76$

$E_{ph,rms} = K\omega$

$PF = \cos\phi$
$= 0.904$

$P_{loss} = P_{cu} + P_{cFW}$

$P_{cu} = 3R_{ph}I_{ph}^2$

$P_{cFW} = P_{loss} - 3R_{ph}I_{ph}^2$
$= 786\,W$

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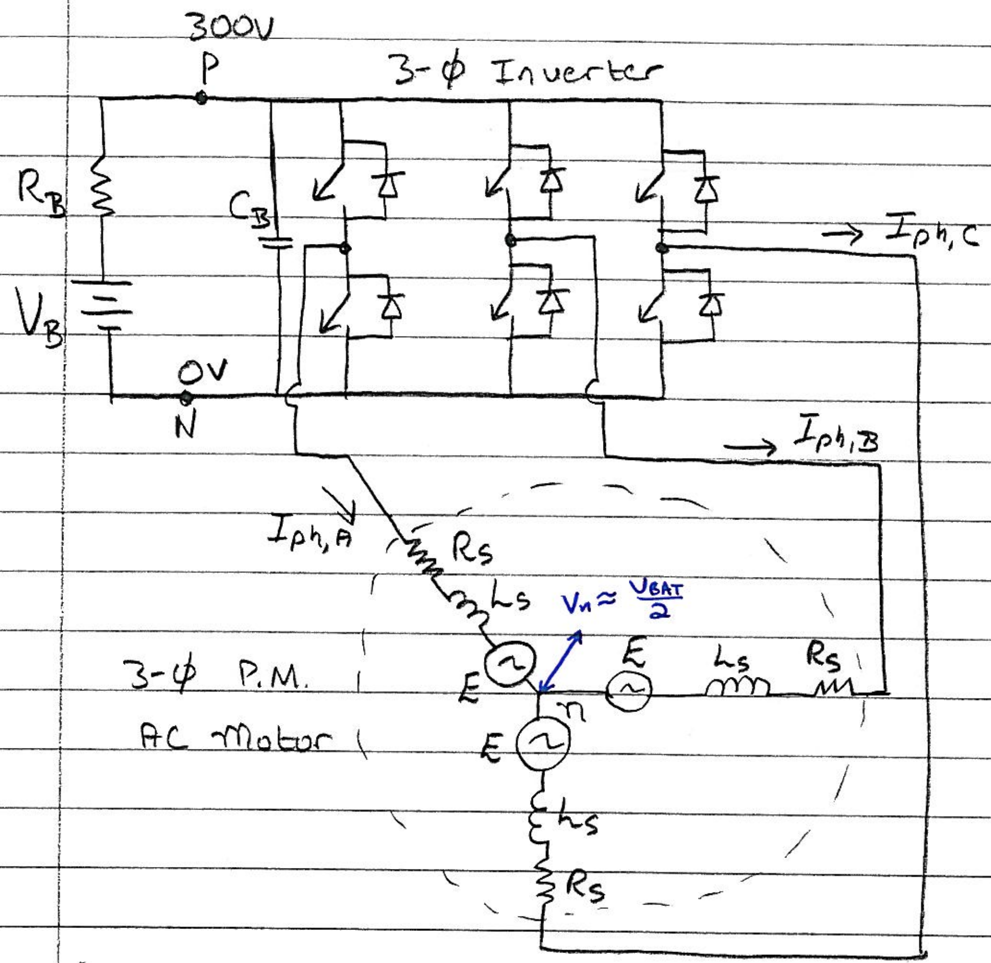


Motor: $\eta_M = 90\%$
$\cos\phi = 0.9$
$R_S = 151 m\Omega$

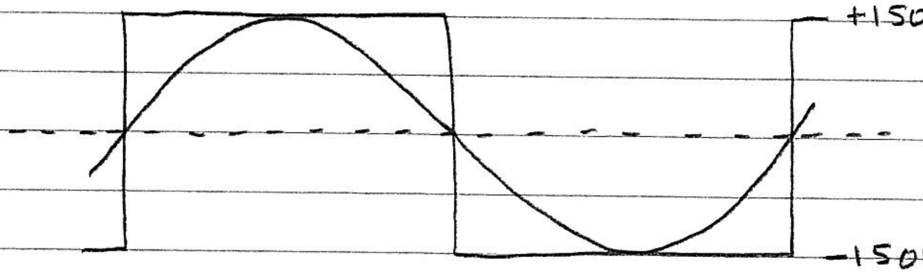
Inv. $\eta_I = 95\%$

Battery: $V_B = 300$ V
$R_B = 0.135 \Omega$

At rated power, the inverter is operating at the limit of sinewave modulation, i.e. $m = 1$

The phase voltage of the inverter and motor is given by

$$v_{ph}(t) = m \cdot \frac{V_B}{2} \cdot \sin \omega t$$



For m = modulation index = 1

$$v_{ph}(t) = \frac{V_B}{2} \cdot \sin \omega t$$

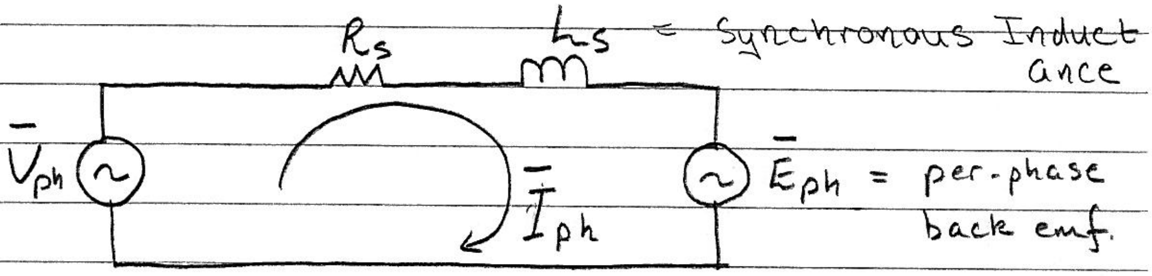
$$V_{ph}(t) = \frac{V_B}{2} \sin \omega t$$

$$\Rightarrow V_{ph} = \frac{V_B}{2\sqrt{2}} = \text{RMS phase voltage}$$

$$= \frac{300V}{2\sqrt{2}}$$

$$= 106.1 \text{ V}$$

(ii) The per-phase equivalent circuit model of the PMAC motor is



$X_{Ls} = \omega L_s = 2\pi f L_s$

NEGLECTING R_s: $\bar{V}_{ph} = \bar{E}_{ph} + j X_{Ls} \bar{I}_{ph}$

{ $\bar{E}_{ph}$ & $\bar{I}_{ph}$ are in phase, max T.

The machine is space-vector controlled for maximum torque. Thus, the space-vector current and rotor flux are 90° out of phase, resulting in $\bar{E}_{ph}$ and $\bar{I}_{ph}$ being colinear.

$$\bar{V}_{ph} = |V_{ph}| \cos\phi + j |V_{ph}| \sin\phi$$

$$= E + j X_{Ls} I_{ph}$$

$\Rightarrow E = V_{ph} \cos\phi$

$= 106.1 \times 0.9$

$E = 95.5 \text{ V}$

$X_{Ls} I_{ph} = V_{ph} \sin\phi$

$= 46.2 \text{ V}$

(iii)

P_o = motor o/p power
$= T \cdot \omega_R$
$= 100 \cdot 628$ W
$= 62.8$ kW

ω_R = motor ang. spe
$= \frac{6000 \text{ rpm} \times 2\pi}{60}$

$\omega_R = 628 \text{ rad s}^{-1}$

$f_R : 100$ Hz

P_I = motor I/P power
$= \frac{P_o}{\eta_M}$
$= \frac{62.8 \text{ kW}}{0.9}$
$= 69.8$ kW

$P_I = 3 \cdot V_{ph} \cdot I_{ph} \cdot \cos\phi$

$\Rightarrow I_{ph} = \frac{P_I}{3 \cdot V_{ph} \cdot \cos\phi}$

$= \frac{69.8e^3}{3 \cdot 106.1 \cdot 0.9}$ A

$I_{ph} = 244$ A_{rms}

(iv) L_s = Synchronous inductance

From (ii) $X_L I_{ph} = V_{ph} \sin\phi$

$X_L I_{ph} = 2\pi f_e L_s I_{ph} = V_{ph} \sin\phi$

4-pole machine $\Rightarrow f_e = f_R \times 2 = 200$ Hz

$\Rightarrow L_s = \frac{V_{ph} \sin\phi}{2\pi f_e \cdot I_{ph}}$

$= \frac{46.2}{2\pi \cdot 200 \cdot 244}$ H $= 0.15$ mH

EE4001 Q6B cont'd

(v) Determine R_E R_T

$$3\,E_{ph}\,I_{ph} = T_{EM}\cdot\omega_R$$

$$E_{ph} \propto \omega_R \qquad\qquad 3\,I_{ph} \propto T_{EM}$$

$$= k\,\omega_R \qquad\qquad T_{EM} = 3k\,I_{ph}$$

$$\Rightarrow k = \frac{E_{ph}}{\omega_R} \qquad\qquad \Rightarrow k = \frac{T_{EM}}{3\,I_{ph}}$$

$$= \frac{95.5\text{ V}}{628\text{ rad s}^{-1}}$$

and $k = 0.152$ Nm/A

(vi) Copper Loss $= 3\,R_s\,I_{ph}^2$

$$P_{cu} = 3 \times 0.015 \times 244^2 \text{ W}$$

$$= 2.68\text{ kW}$$

Total Motor Loss $= P_{cu} + P_{CFW}$

(vii) where P_{CFW} = core, friction and windage loss

$\Rightarrow$ Motor loss $= P_I - P_O = P_{cu} + P_{CFW}$

$$\Rightarrow P_{CFW} = P_I - P_O - P_{cu}$$

$$= (69.8 - 62.8 - 2.7)\text{ kW}$$

$$P_{CFW} = 4.3\text{ kW}$$