1(a) The back emf is related to the flux and number of turns in the winding

30A is related to the current density in the winding and the cooling.

42A for 60s is related to the specific heat capacity and winding resistance

7-10 cells gives the rated speed via the back emf. 4

An "outrunner" has an easy bobbin like winding so cheap to manufacture.

No endwindings to deal with

Magnets retained centrifugally by steel 3

(b) $S = VA \propto Vol . \bar{B} . \bar{J} \frac{\omega}{p}$ (1)

With all else the same, the voltage and the torque will scale with the length of the machine.

The torque is produced in and around the airgap, with $\bar{B}$ and $\bar{J}$ referring to the mean flux per pole and $\bar{J}$ referring to the effective current around the airgap.

Force $F \propto B \times J$ gives a $F \propto Vol \times$ length

1(b) continued

The 'extra' dimension is the depth of the slots and the three-phase vector sum giving a coefficient.

So Force is per unit length of the airgap periphery and per unit length of the rotor.

All together

$$T\frac{\omega}{p} = F \times \frac{d}{2} \cdot \frac{\omega}{p}$$

$$= B J \frac{d}{2} \frac{\omega}{p} . \pi d l.$$ 4

compare with ①

With modern P.M. machines B is roughly fixed. Similarly J is fixed by use of copper and the maximum temperature rise (for the magnets). But the use of gearboxes allows ω to go up making smaller, cost effective and compact motors possible. This is opening up new applications or improving existing ones like window winders. Linear motion is also a gearbox issue ~ rack and pinion. 3

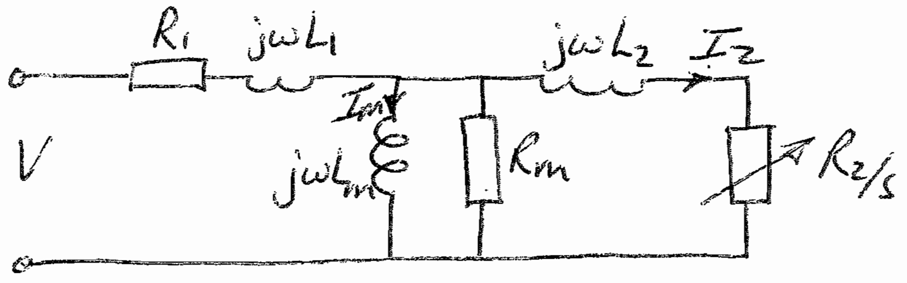
1 (c) HTS wires could be used in place of any of the wires in a machine. They would offer low resistance and much higher efficiency.

Cooling the stator has some problems and the stator losses may be difficult to deal with as the iron losses would remain.

The rotor could be contained in a can and cooled, and operated as a synchronous or "brushless dc" machine there would be no (0) rotor losses making the low temperatures easy to maintain. (6)

Induction motors require rotor losses to work. If $R_2 \rightarrow 0$ then $s \rightarrow 0$ synchronous!

2(a) For a voltage to be induced on the rotor, the rotor must move at a different speed to the rotation of the magnetic field. 2



Neglect R_1, $j\omega L_1$, $j\omega L_2$, R_m.

$$T\omega_s = 3 I_2^2 R_2/s = 3 \frac{V^2}{R_2/s}$$

$$T = 3\frac{V}{\omega_s} \cdot \frac{V}{R_2/s} \qquad I_m = \frac{V}{\omega L_m}$$

$$T = 3 I_m L_m V \cdot \frac{s}{R_2}$$ 6

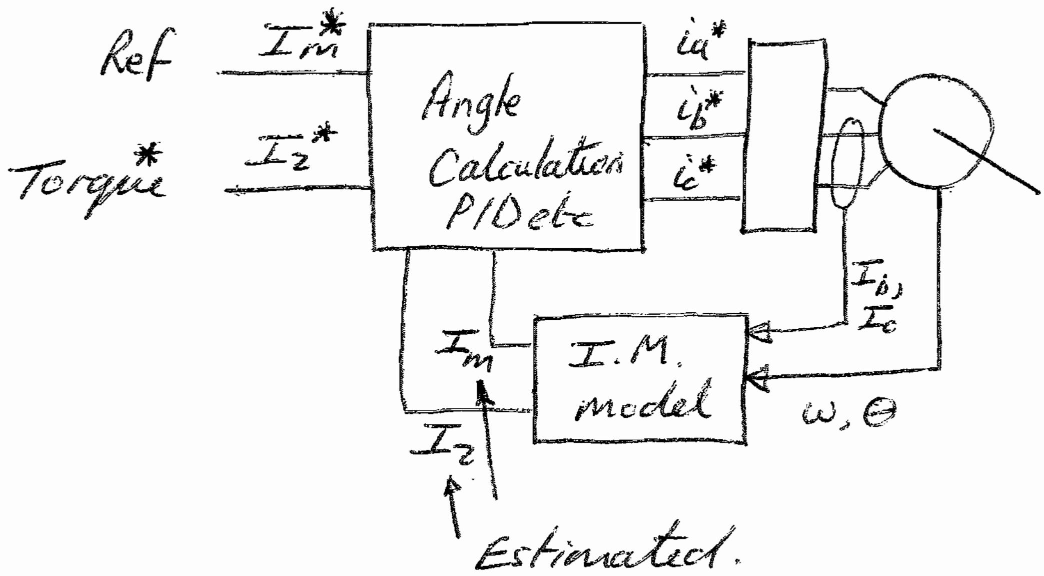
$I_m L_m$ is related to the flux (factor of $\frac{3}{2}$)

$T \propto$ flux. I_2 Orthogonal as ωL_2 neglected.

The flux cannot change fast; $dI_m = \frac{1}{L}\int V dt$

But I_2 can change rapidly if s is changed quickly. This requires feedback and a "model". 2

2(a) cont.

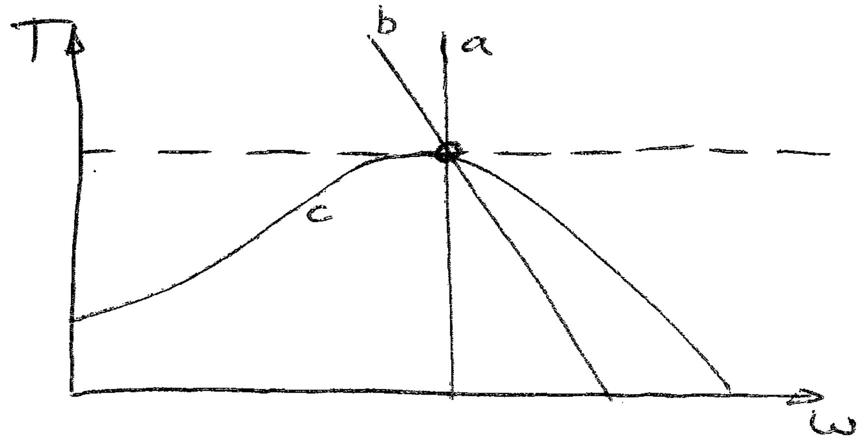


4

The model is necessary to calculate the state of the machine prior to any change requested.

In the nature of feedback loops the model could be in the forward path. Often the model is little more than L_2/R_2 to account for the lag in the rise of I_2 (neglected earlier).

2(b)



2

a ~ normal rated flux small slip

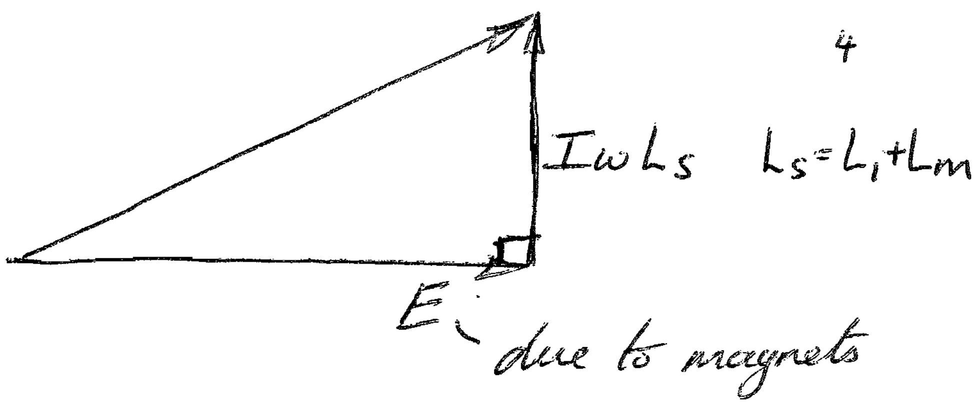
$$T = 3V \frac{s}{R_2} I_{m_{rated}} \ldots$$

efficient in terms of I^2R losses, but needs full flux and maybe inefficient in terms of iron losses. Ready for increased torque 2

b ~ reduced flux - efficient (better than a above), but not ready for increased torque. 2

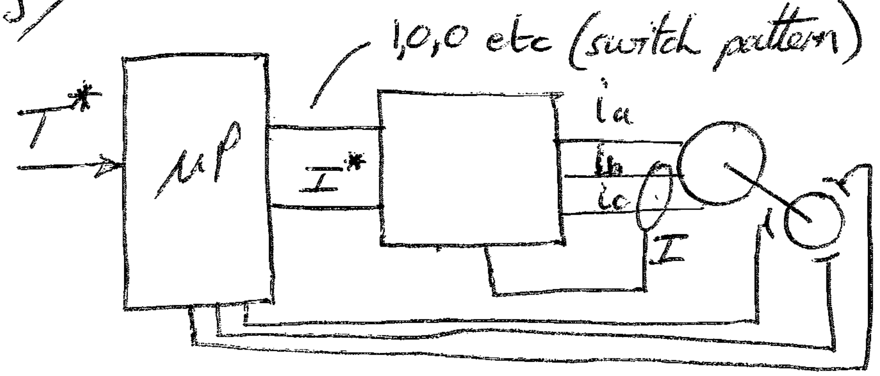
[c ~ inefficient in I^2R losses and dangerous]

3(a) Brushless dc motor drives are based on synchrous motors run in such a way that they behave as dc motors. To effect this, the motor must be run closed loop with regard to position. The current can then be injected at an appropriate angle with respect to the magnet flux. A "Torque" angle of 90° maximises torque per amp and given the small value of synchronous reactance, the fixed angle of the current in the stator and the control of that current also mean that the machine iron does not become saturated. Best illustrated by a phasor diagram.



4

eg./

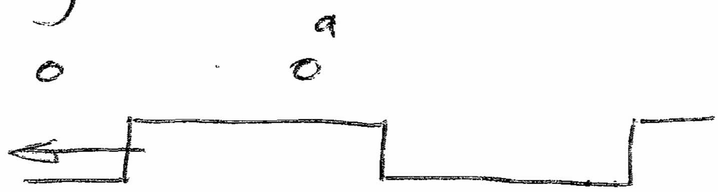


4

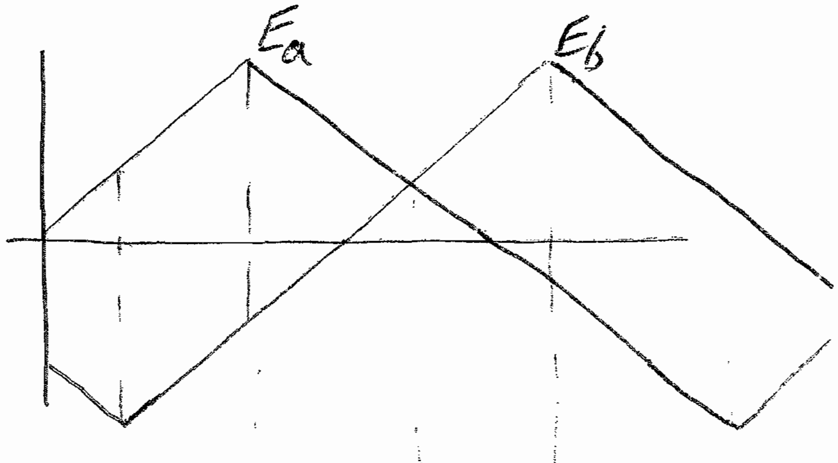
(Sinewaves need a sine prom) in μP.

3 (b) Considering the energy gives an immediate answer. Trapezoidal motors are run with blocks of dc current and produce smooth torque (except around transitions). So the back emf must be constant in those periods. Furthermore the torque profile is found by measurement or calculation when 2 phases are excited with a dc current, so the argument above fills in the whole curve. It's not so satisfactory as $E \propto \omega$ and $\omega = 0$ for the tests!

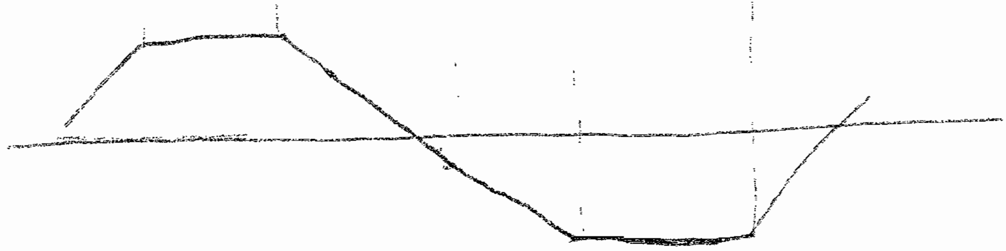
OR/ Squarewave flux and a concentrated winding :-



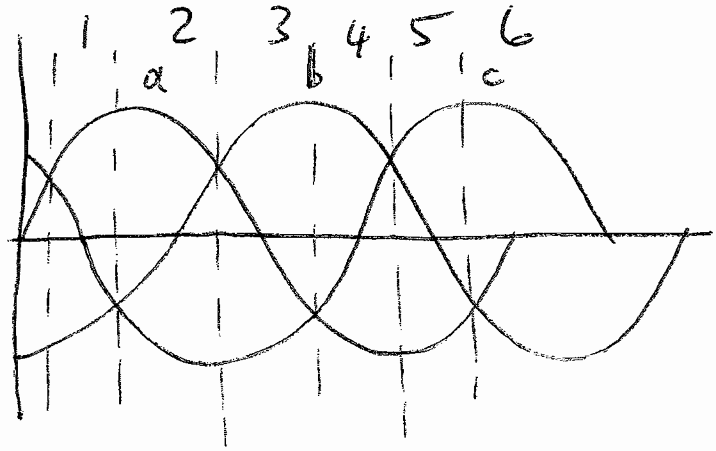
gives:



Voltage is $E_a - E_b$ ~ just like T-θ



3(c) Start with the back emf waveforms



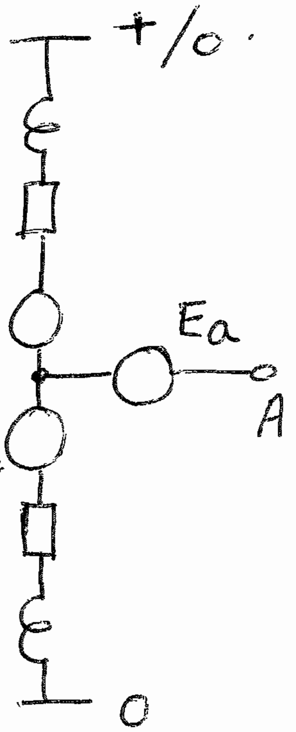
6 periods from lectures or above

ab, $\boxed{ac, bc, ba}$, ca, cb,

So one phase is high and one low. (with modulation)

eg

Period 3



Switch when $E_b = E_a$

Voltage at A w.r.t. O is $E_a - E_c$ neglecting $L\frac{di}{dt} + Ri$.

Note that L_b, L_c, R_b, R_c form a potential divider — so look for $|E_b| = |E_c|$ and $E_a = 0$!

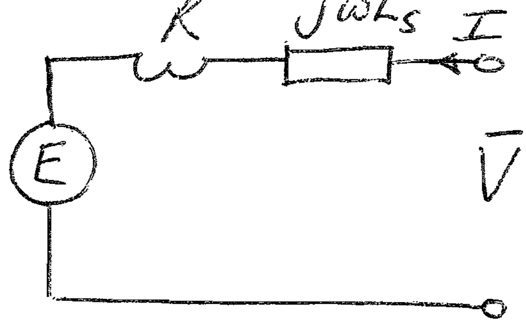
3(c) cont.

Clearly at standstill there is no back-emf so the motor has to start open loop. This is not without its problems. Similarly when slowing down the emfs will be reducing while the pwm 'noise' is increased per cycle so 'lock' can be lost. With sensors these problems are avoided. 2

4(a) The brushless dc motor is a synchronous motor run in closed loop. The hybrid stepper is also a synchronous machine, but run open loop with a axial flux design and castellations giving it many poles and a detent torque. 3

BLDC	Stepper	5
Closed Loop	Open Loop	
High Speed (few poles)	Low speed (Many poles)	
No unexcited detent	Positive detent.	
Cannot pull out	May "step out"	
3 phase	2 phase	
Upto high powers	Low powers $< 3kW$	

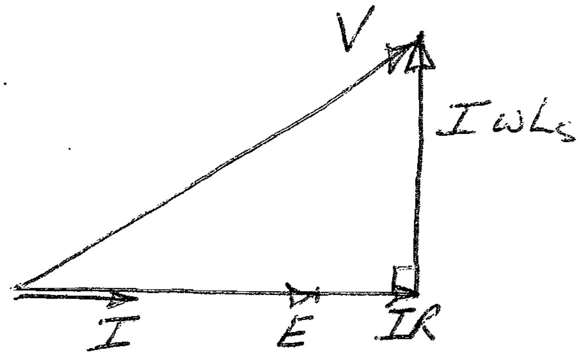
4(b)



$$\bar{V} = \bar{E} + \bar{I}R + j\omega L_s \bar{I}$$

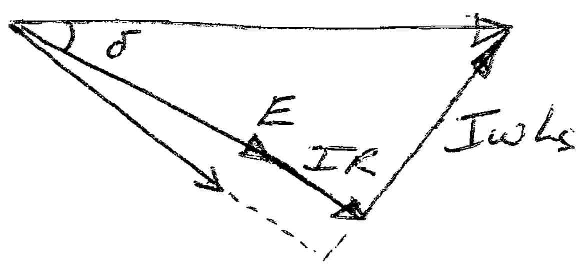
2

BLDC



2

Stepper

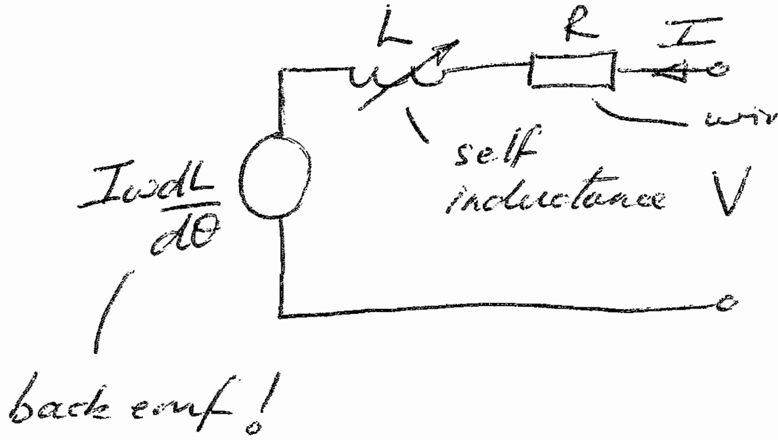


2

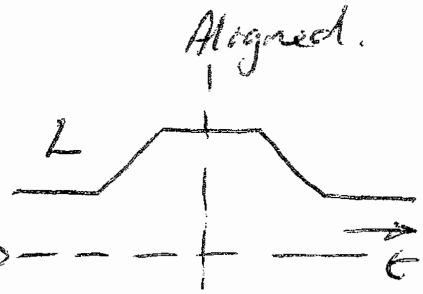
4 (c) $$V = IR + \frac{dLI}{dt}$$

$$= IR + I\frac{dL}{dt} + L\frac{dI}{dt}$$

$$= IR + I\frac{dL}{d\theta}\cdot\underbrace{\frac{d\theta}{dt}}_{\omega} + L\frac{dI}{dt}$$



4



The model works on instantaneous values.

To do serious work we need I to be a maximum when $\frac{dL}{d\theta}$ starts. Otherwise the L term impedes the current rise and the current will not be high for good torque.

2