DC Machines

Dr Andrew Cruden
Electronic & Electrical Engineering
University of Strathclyde
R: R3.08H
E: a.cruden@eee.strath.ac.uk
T: 0141-548-2991

Overview of Presentation

- Investigate the torque/speed characteristics of series and shunt DC motors and describe typical applications for both types
- Summary

- See accompanying notes entitled ‘19222 DC Machines Theoretical Overview’

Quick Review

- There are two types of DC machine to be considered: *series* and *shunt* connected motors
- Series motors have the armature and field coils connected in series
- Shunt motors have the armature and field coils connected in parallel

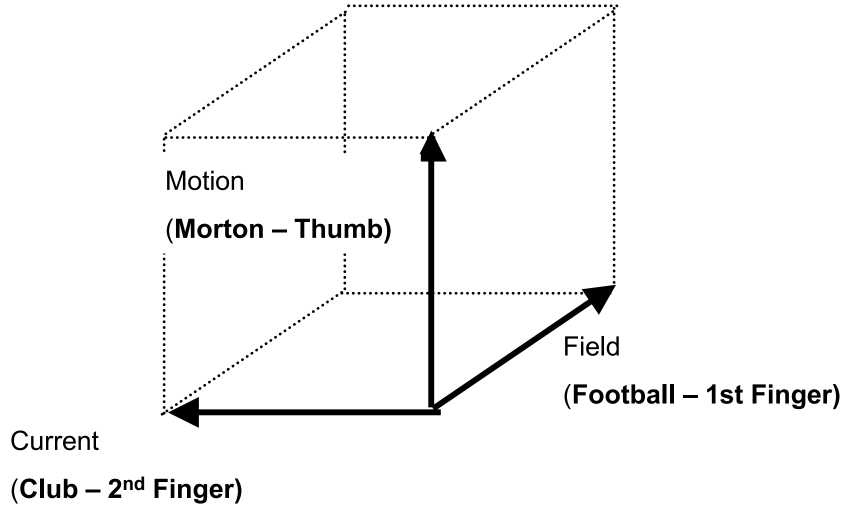
DC Motor Relationships

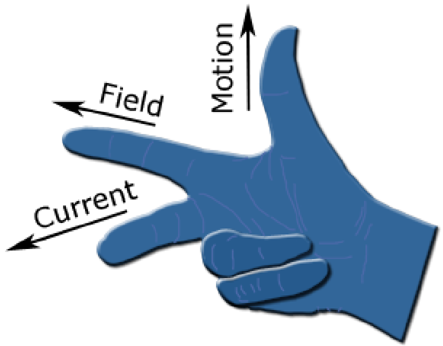
- In the motor armature, the effect of the applied voltage, V_a, is reduced by the influence of an induced emf, the 'back emf', V_{emf} or E, which is established through the process of electromagnetic induction (i.e. Right Hand Rule) in opposition to the applied voltage

- *Note*: the Right Hand Rule illustrates an induced current however it is a voltage (emf) that is induced which in turn causes a current to flow…. talking about a current helps the mnemonic!!

Fleming's Right Hand Rule

- The direction of the induced emf in a circuit can be understood using Fleming's right hand rule
- The first finger of the right hand points in the direction of the magnetic flux (field)
- The thumb is pointed in the direction of motion of the conductor **relative** to the flux
- The second finger then represents the direction of the induced emf (i.e. current flow resulting from the 'back emf')





‘Back emf’ – Faraday’s Law of Electromagnetic Induction

- The concept of a ‘back emf’ can be confusing
- It simply means that whilst we are creating a force on a conductor to produce motor action, the *same* conductor is moving through a magnetic field and therefore has a voltage (emf) induced in it
- This means that even whilst we are driving a machine as a motor, part of it is still working as a generator (i.e. inducing an emf)
- The underlying principle is Faraday’s Law of electromagnetic induction – see Transformer notes

DC Motor Relationships

- Therefore the equivalent applied voltage, V_{eq}, equals

$$V_{eq} = V_a - V_{emf}$$

- The 'back emf', $V_{emf} = E$, is only present when the motor armature is turning.
- If the motor is stopped then there is no induced emf, as no lines of flux are being cut, and the armature current will be a maximum (as $V_{eq} = V_a$). Note that the induced emf can never be equal to or higher than the applied voltage

DC Motor Relationships - contd

- As V_a is 'regulated' by the induced emf, the armature current is regulated, i.e. if no emf was induced the armature current flowing would be much higher and the speed of motor operation would be much higher
- The value of induced emf, $V_{emf} \propto$ rate of change of flux, or

$$V_{emf} = \Phi \omega K_e$$

- where Φ is the motor flux, ω is the rotational speed of the motor in rads/sec and K_e is a constant relating motor parameters such as number of poles etc and is specific for a particular motor
- The flux, Φ, is established by the field current I_f

DC Motor Relationships - contd

- The torque output of the motor is proportional to the force on the conductors and from $F = BI_aL = (\Phi/A)I_aL$ then, $T = F.r$,

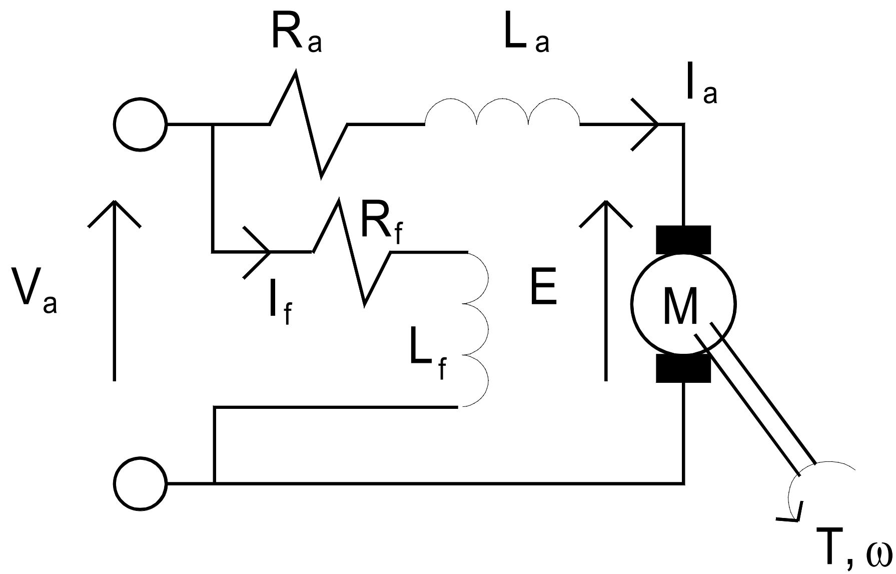
$$T = \Phi I_a K_t$$

- where Φ is as before, I_a is the armature current and K_t is the torque constant of the motor.

DC Shunt Motor

- For a shunt connected motor if the applied voltage is constant then the field current, I_f, and therefore the flux, Φ, is constant
- $E \propto \omega \;\; (E = V_{emf} = \Phi \omega K_e)$
- So when a load is applied to the shunt motor the speed decreases, and therefore so does E
- As E decreases then the armature current, I_a, starts to increase and the torque, $T = I_f I_a K_t$, starts to increase
- $V_a = I_a R_a + E \Rightarrow \omega = \dfrac{V_a - I_a R_a}{I_f K_e}$

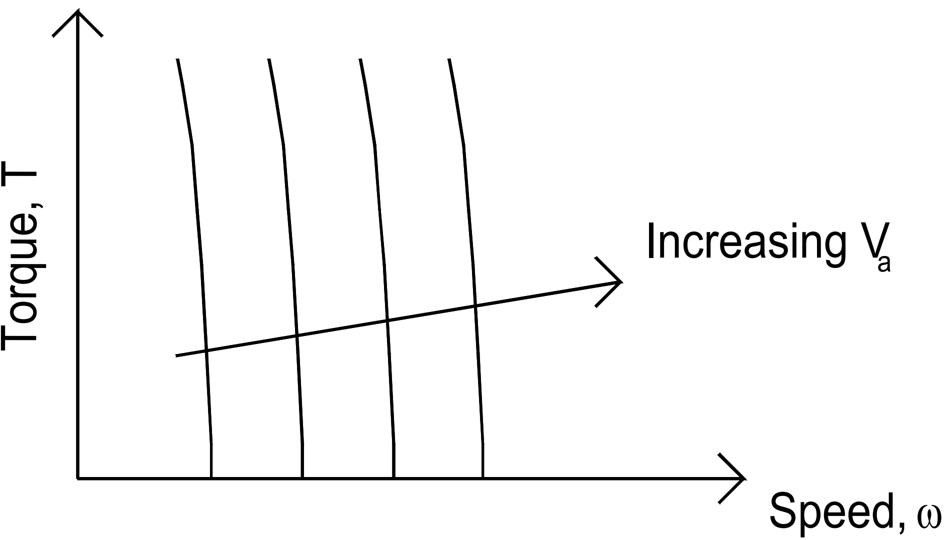
<u>Equivalent Circuit for DC Shunt Motor</u>



Inductors L_a and L_f are shown for completeness. For tutorials/exams, the inductors should be neglected (i.e. omitted)

DC Shunt Motor

Torque vs Speed Characteristics
for a DC Shunt Motor



- The motor torque will increase until it matches the applied load torque
- For typical values of I_a, and R_a, it is normal to assume $V_{emf} \sim V_a$
- Hence as V_a is varied so does E and ω
- Practically, at no-load ($T \sim 0$), I_a is small and $E \sim V_a$, and as the load torque increases then I_a increases and causes E to fall slightly relative to V_a.
- Therefore the speed does fall slightly as torque increases but in general for a shunt motor the speed is considered constant

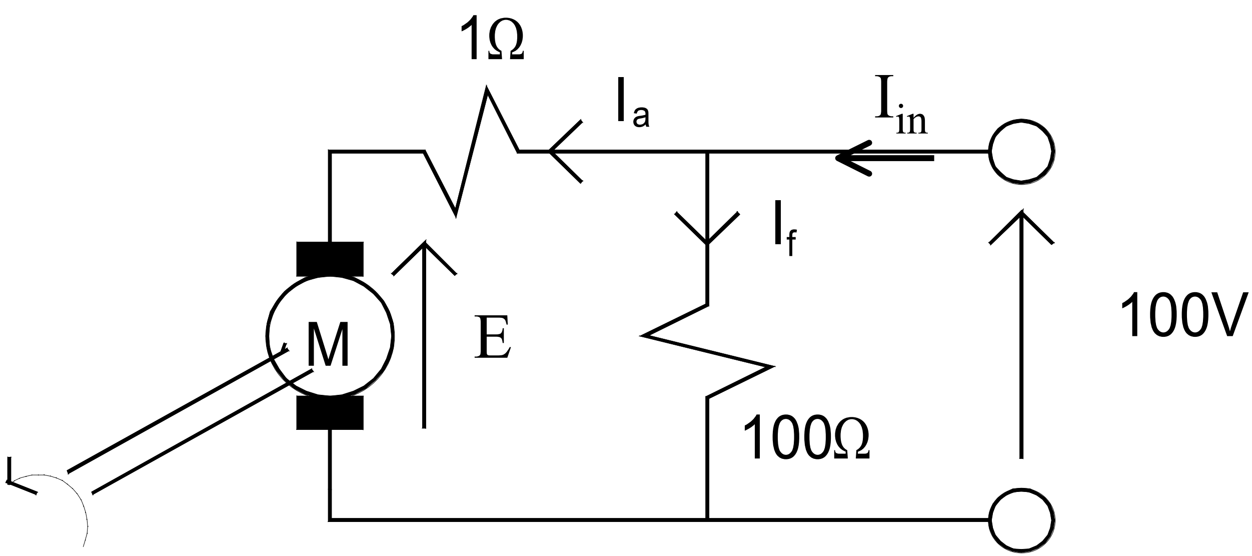
w.r.t Torque

Practical Concerns: Shunt Motor

- Field Weakening: Examine the earlier equation $\omega = \dfrac{V_a - I_a R_a}{I_f K_e}$
- The speed could be varied by varying I_f
- This is known as field weakening - however there is a danger if the field current is reduced to much - the motor could overspeed!!
- Some motors sense any decrease in field current and operate a protective relay trip i.e. disconnect the power
- I_f would typically be varied by changing the field resistance R_f

Example: Shunt Motor

- Assume that the shunt motor is supplied from a 100V supply, and has an armature resistance of 1Ω and a field resistance of 100Ω, torque of 0.949Nm at a speed of 990rpm and $K_e = 0.955$ V/(A.rad/s).
- Calculate the power output of this motor, the efficiency at this load and the new speed if the field resistance is changed to 125Ω?



Example: Shunt Motor - contd

- Power Output, $P = T\omega = T*(2\pi/60)*n$, where T is the motor torque and n is the motor speed in rpm
- $P = 0.949*(2\pi/60)*990 = 98.4$ W
- Power input $= I_{in}*V_{in} = (I_a+I_f)*V_{in}$. The field current can be calculated easily from the circuit diagram $I_f = 100V/100\Omega = 1A$.
- $E=\phi\omega K_e=I_f\omega K_e=1*(2\pi/60)*990*0.955= 99V$
- $V_a=I_a.R_a+E \Rightarrow I_a=(100-99)/1= 1A$
- Therefore Power input = (1+1)*100 = 200W
- The motor efficiency is $\eta=P_o/P_{in}*100\% = 98.4/200*100 = 49.2\%$

Example: Shunt Motor - contd

- From previous it was shown that the torque for a shunt motor is proportional to the armature current, which has not changed, therefore the motor torque is still = 0.949Nm
- The new field current, I_f = 100/125 =0.8A
- From $T = I_f I_a K_t$, for I_f = 1A then K_t= 0.949/(1*1) = 0.949Nm/A^2
- For the new value of I_f , the corresponding new value of the armature current can be calculated

$$I_a = 0.949/(0.8*0.949) = 1.25A$$

- Therefore, $\omega = \frac{V_a - I_a R_a}{I_f K_e} = \frac{100-(1.25*1)}{0.8*0.955} = 129.25 \, rad/s = 1234 \, rpm$

Example: Shunt Motor - contd

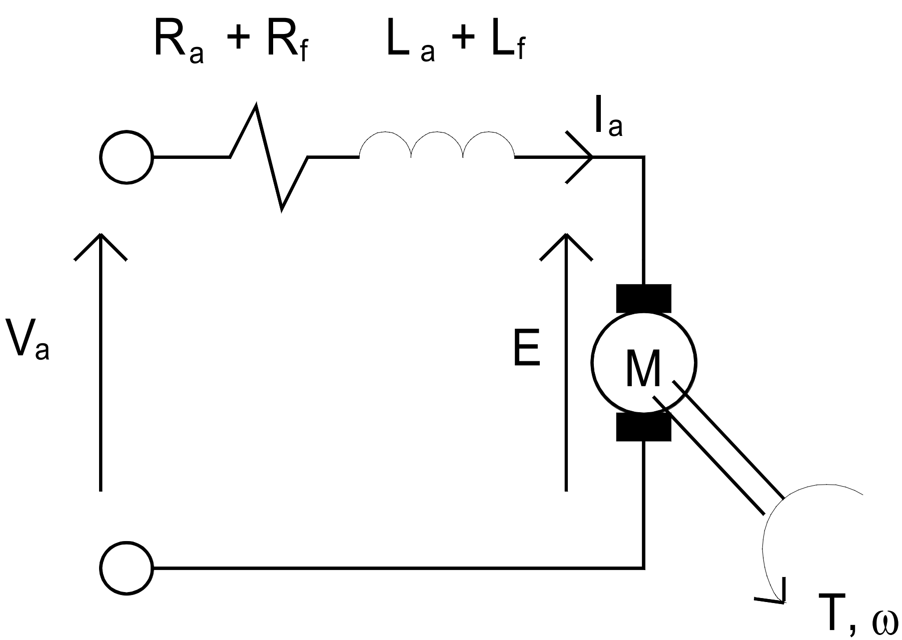
- Say the load torque on the motor was trebled on sudden application of a new load. Investigate the effect on the motor speed for constant field current (with $R_f = 100\Omega$) .
- New torque, T = 3*0.949 = 2.847Nm = $I_f I_a K_t$
- Therefore new I_a = 2.847/(1*0.949) = 3A (This is intuitively correct as torque α I_a if the field current is constant)
- From

$$\omega = \frac{V_a - I_a R_a}{I_f K_e} = \frac{100 - (3*1)}{1*0.955} = 101.57 rad/s = 970 rpm$$

- Therefore for a trebling of motor load the speed has changed by ((990-970)/990)*100% = 2% i.e. almost constant speed with changing load
- Shunt motors are good for conveyors and machine tools which must operate at constant speed with varying loads

Series DC Motor

<u>Equivalent Circuit for DC Series Motor</u>



Inductors L_a and L_f are shown for completeness. For tutorials/exams, the inductors should be neglected (i.e. omitted)

- The flux, Φ, of the motor is directly proportional to the field current, I_f, flowing to establish the magnetic field.
- For a series motor the current in the field and armature coils is exactly the same

$$T = I_f I_a K_t$$
$$= I_a^2 K_t$$

- From the circuit diagram,

$$V_a = I_a(R_a+R_f) + E,$$

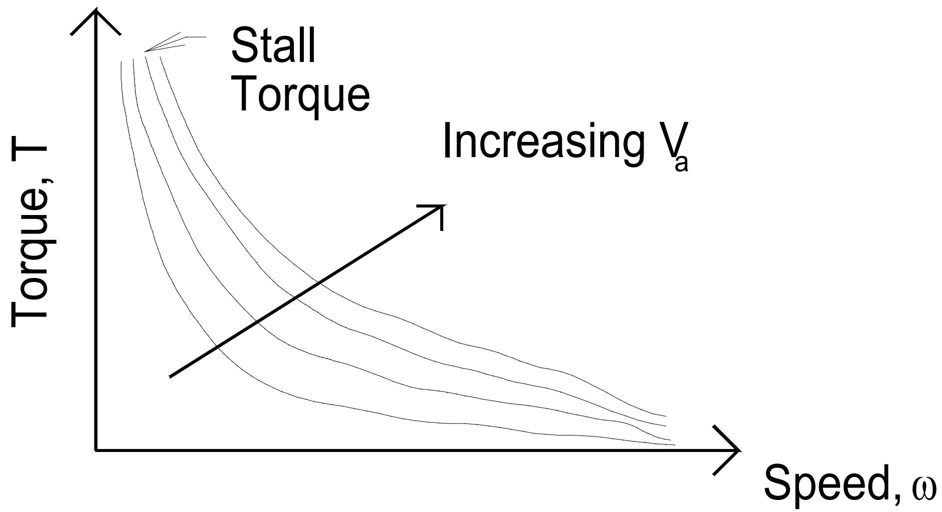
where V_a and I_a are average values and $E = V_{emf} = \Phi\omega K_e$

- $E = I_a \omega K_e$

Series DC Motor - contd

- At no load, T~0, I_a is minimal and E~V_a, and hence ω is a maximum as $E=I_a\omega K_e$
- As the load torque increases, I_a rises to the square power ($T\alpha I_a^2$)
- As I_a increases E falls relative to V_a, however the speed falls according to $E=I_a\omega K_e$
- Therefore as the torque increases the speed of a series motor decreases quite rapidly ($\omega\sqrt{T}$ = constant)

Torque vs Speed Characteristics of a Series DC Motor



Practical Concerns: Series Motors

- From the torque vs speed characteristic it is clear that as the torque is decreased the motor speed increases - and will keep on increasing into overspeed (similar to potential field weakening run away for the shunt motor)
- It is good practice therefore to always have a load connected to a series DC motor before it is turned on to prevent overspeed. (generally this only applies to large DC motors as small motors tend to have enough friction to prevent this naturally)

Speed Regulation

- Speed regulation determines the ability of the motor armature to maintain its speed when a changing load is applied
- (Analogous to transformer voltage regulation)
- Speed regulation is a ratio of **no-load** to **full-load** speed

$$\%\,speed\ regulation = \frac{n_{nl} - n_{fl}}{n_{fl}} \times 100\%$$

where n_{nl} is the no-load speed and n_{fl} is the full load speed in rpm

- The lower the speed regulation the more constant the motor speed will be over a range of applied loads

Example: Series Motor

- Say the torque a series motor produces is 4Nm with 5A flowing in the armature. Calculate the value of the stall torque if the supply voltage to the motor is 100V and $R_a = R_f = 1\Omega$?
- From previous it was shown that: $T = I_a^2 K_t$

$$K_t = T/I_a^2 = 4/25 = 0.16 \text{ Nm/A}^2$$

- The armature current can be calculated by analysing the equivalent circuit: $$I_a = \frac{V_a - V_{emf}}{R_a + R_f} = \frac{100 - 0}{1 + 1} = 50A$$

Note: $V_{emf} = 0$ at stall i.e. zero speed

- Therefore the stall torque $T_s = 50^2 * (0.16) = 400$ Nm

Example: Series Motor - contd

- From previous it was shown: $V_a = I_a(R_a+R_f) + E$ and $E=I_a\omega K_e$
- This can be rearranged to give: $K_e = \dfrac{V_e - I_a * (R_a + R_f)}{I_a \omega}$
- From previous, if the motor were turning at 900rpm, with a current of 5A then the emf constant, K_e, is

$$K_e = \frac{100 - 5 * (1 + 1)}{5 * (\frac{900}{60} * 2 * \pi)} = 0.19 (V / A.rad / s)$$

- If the motor now takes 20A calculate the new torque and motor speed?
- $T = I_a^2 K_t = 20^2 * 0.16 = 64$Nm

$$\omega = \frac{V_a - I_a * (R_a + R_f)}{I_a K_e} = \frac{100 - 20 * (1 + 1)}{20 * 0.19} = 15.8 rad / s = 150.1 rpm$$

Example: Series Motor - contd

- The speed regulation of the series motor is difficult to calculate as at full-load the motor is virtually stalling and at no-load it could overspeed.
- Most applications for DC series motors are traction drives for locomotives or for cranes, where a high starting torque, high accelerating torque and high speed at light load is required
- These applications need high starting torque to overcome the inertia of the load and the train requires to run at high speed once moving
- The series motor 'self-adjusts' to protect itself from overloads i.e. it will reduce speed as the load increases and then stall

Summary of Presentation

Motor	Shunt	Series
Torque	$T=I_f I_a K_T$	$T=I^2{}_a K_T$
Back emf	$E=I_f \omega K_e$	$E=I_a \omega K_e$
Circuit Eqn	$V_a=I_a R_a+E$	$V_a=I_a(R_a+R_f)+E$
Mechanical Power o/p	$P=T\omega$	$P=T\omega$
Electrical Power i/p	$P=V_a(I_f+I_a)$	$P=V_a I_a$