Modelling of machines

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Course structure and history

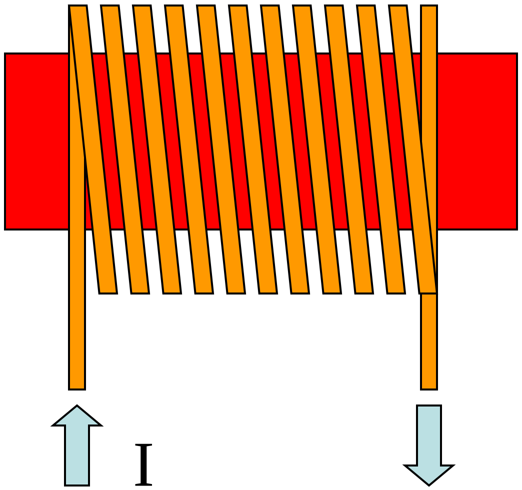
- Essentially two ‘halves’ to course:
  - – Modelling of devices using ψ-i techniques
  - – Generalised machine theory
- Detailed syllabus on EEE web-pages
- Examination papers back to 1994 (2001-2005 not entirely representative)
  - – Several minor changes mean that a few section of past questions (not many) are outside the scope of the current course

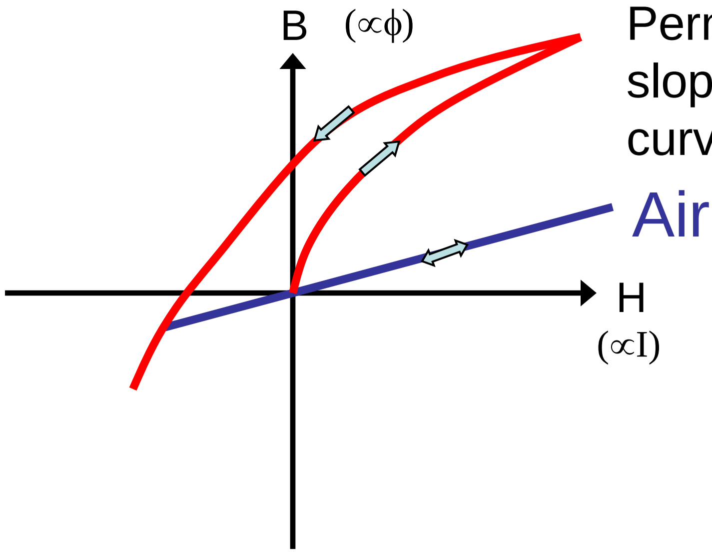
ψ-i modelling of electromagnetic devices

- Based on flux-linkage (ψ) versus current characteristics
- Captures variation of coil flux-linkage with current and position
- Powerful technique for handling magnetic non-linearity and complex spatial variations
- In principle, could be used for all electromagnetic devices – but use tends to be limited to particular types of rotating machines (notably switched reluctance) and many linear actuators
- Reliant on complex calculation / experimental measurements to derive starting characteristics for the analysis

Magnetic Materials

Magnetic Materials



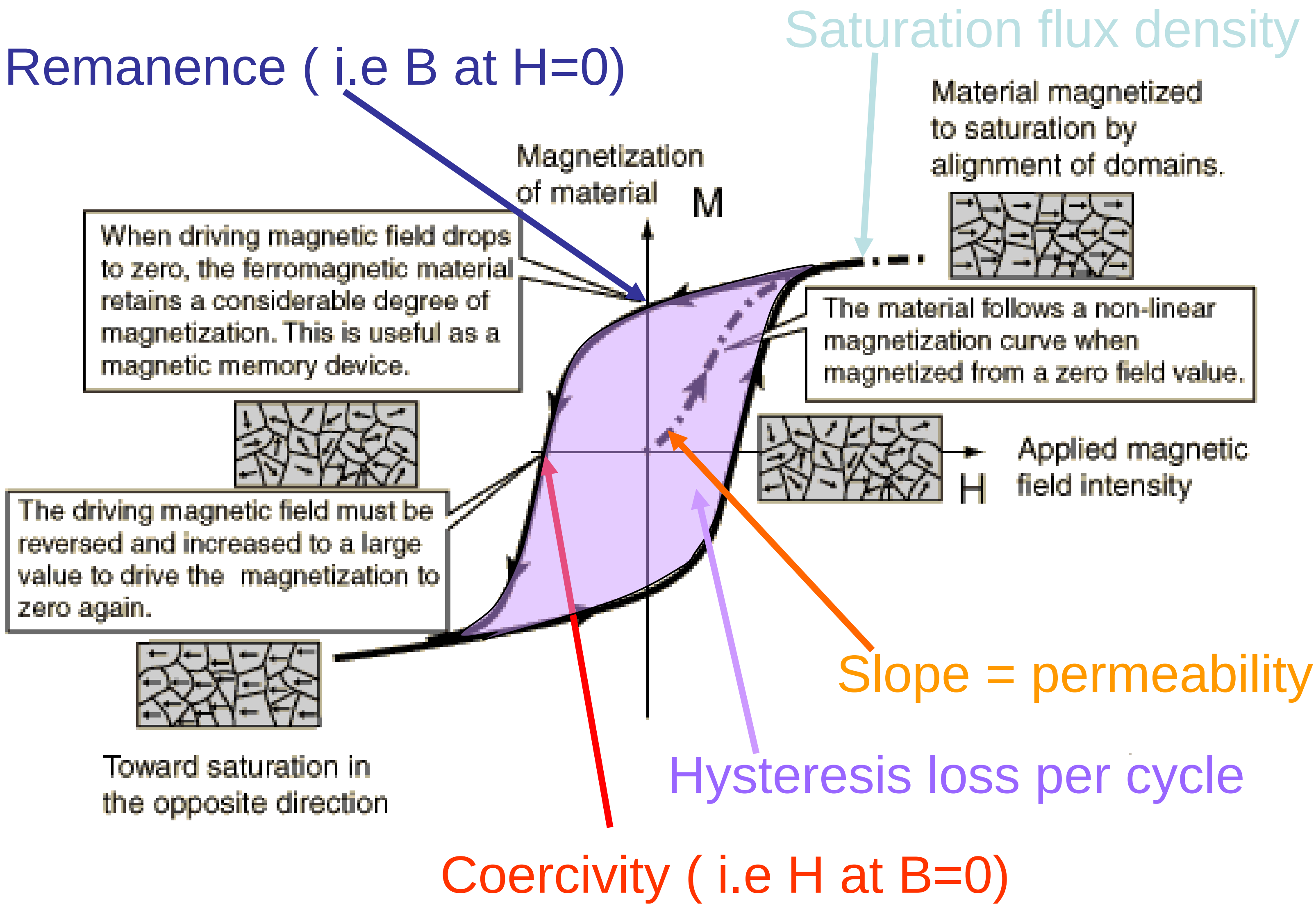


Permeability – slope of B/H curve

Some applications (e.g transformers) require materials that are easy to magnetise and de-magnetise - **soft magnetic materials** (e.g Iron, Silicon Iron, Nickel Iron, Cobalt Iron)

Others require materials that are difficult to de-magnetise and remain essentially permanently magnetised - hard or **permanent magnets**

Magnetic hysteresis



Desirable properties of soft magnetic material

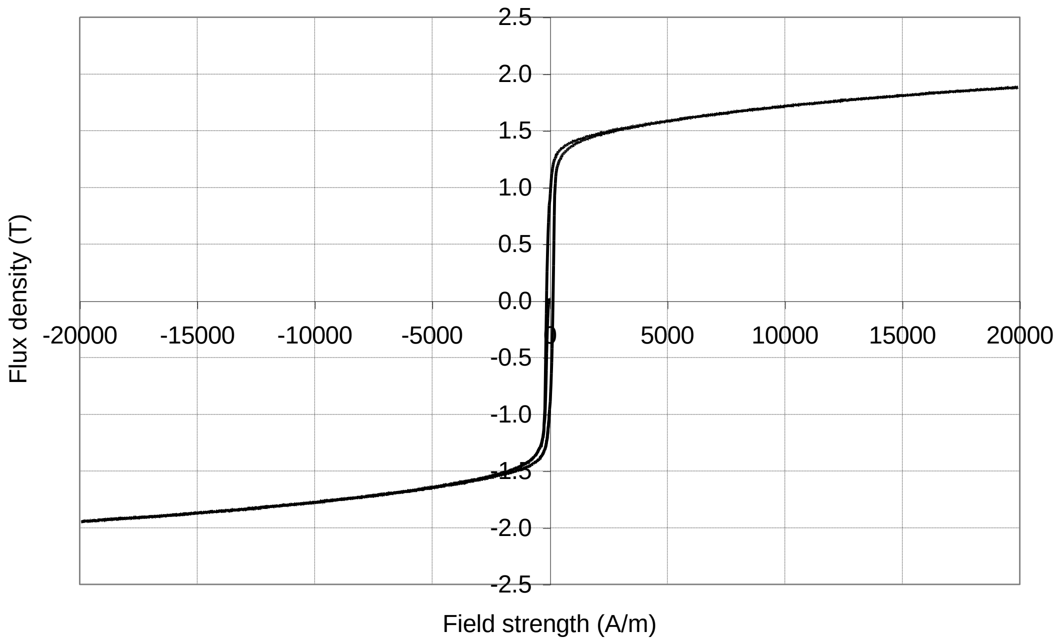
•High saturation flux density

- increased flux carrying capability

•High permeability

- reduced mmf (Ampere turns) to achieve a given flux

Typical BH characteristic for 3.5% Silicon Iron



Very high permeability up to flux densities of 1.5T (several 1000)

Gradually diminishing permeability beyond 1.5T – onset of significant magnetic saturation

Eventually saturates such that slope = μ_0 (permeability of free space) – 'physics' defintion

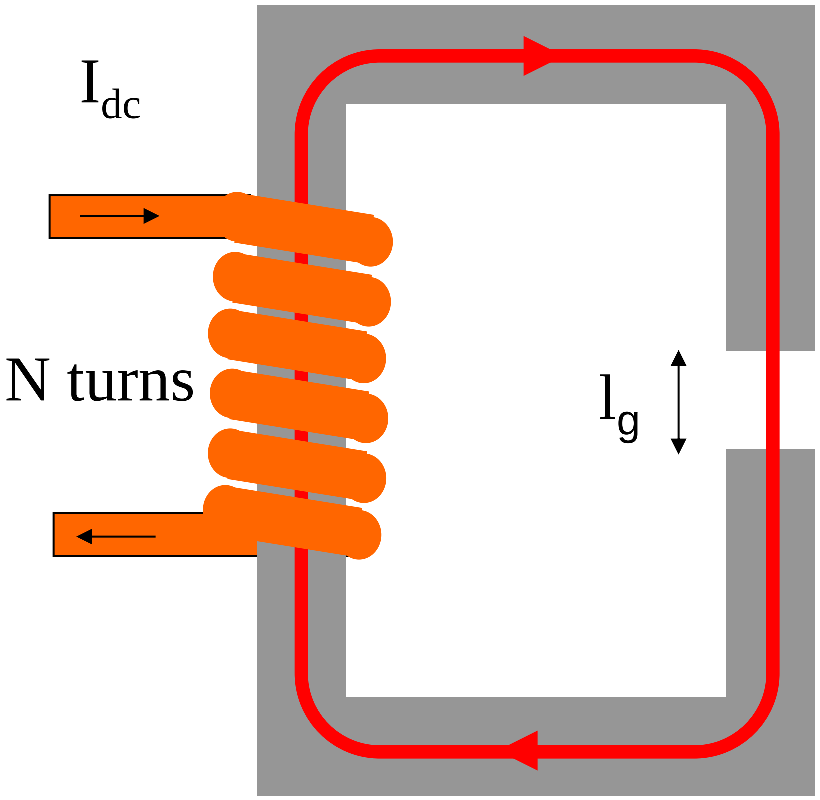
ψ-I characteristics

Consider a simple magnetic circuit which consists of a c-shaped iron yoke with a small airgap of length lg.

A coil with N turns carrying a current I_{dc} is wound around the yoke.

When the level of flux in the iron yoke is low, then its relative permeability will be several 1000s, and the reluctance of the magnetic circuit (analogous to electrical resistance) will be dominated by the airgap

Under these conditions, the flux in the magnetic circuit (ϕ is given by:

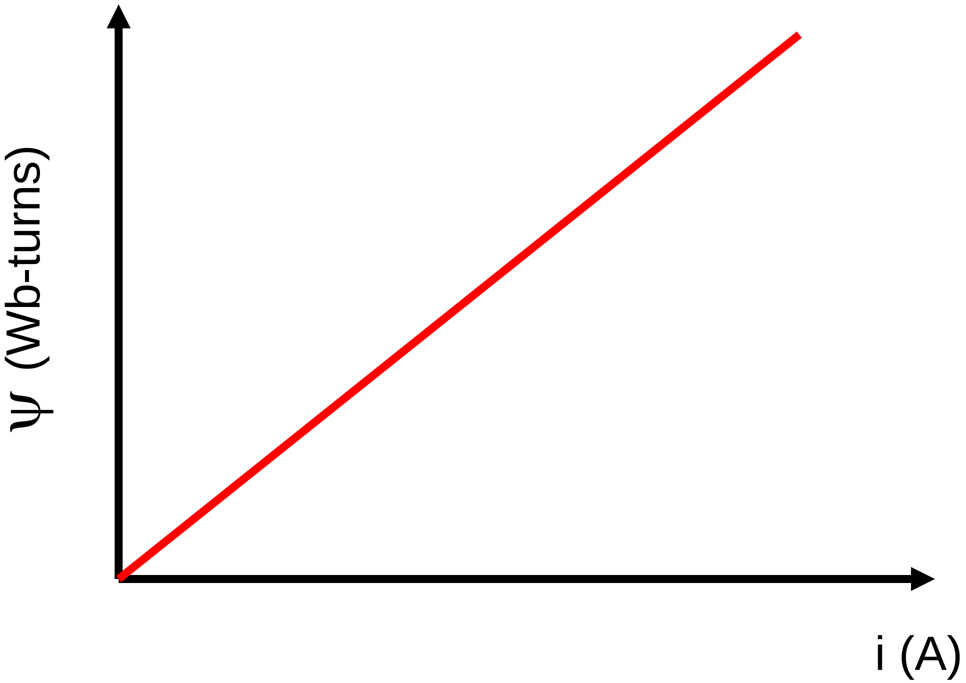


$$\phi = \frac{NI}{S} = \frac{NIA\mu_0}{l_g}$$

$$S = \frac{l_g}{\mu_0 A}$$

where A is gap and yoke cross-sectional

- Demonstrates that providing the iron permeability is high (several 100s to 1000s) then the flux (ϕ) is proportional to the magnitude of the current
- For these conditions, the variation in the flux-linkage ($\psi=N\phi$) with current is simply a straight line as shown on the ψ-i characteristic below



Note: Strictly, the units of flux-linkage are Webers (Wb). However, it is common practice to use Wb-turns to draw attention to the fact that the number of turns are already factor into the quantity (very similar case to the use of Ampere-turns for mmf)

This linear relationship will eventually breakdown with the onset of magnetic saturation in the yoke at higher currents

In a magnetic circuit which exhibits significant saturation, the net reluctance S, is no longer dominated by the airgap. In such cases the flux can be estimated in principle using the following:

$$S = \frac{1}{A}\left(\frac{l_g}{\mu_0} + \frac{l_i}{\mu_i} \right)$$

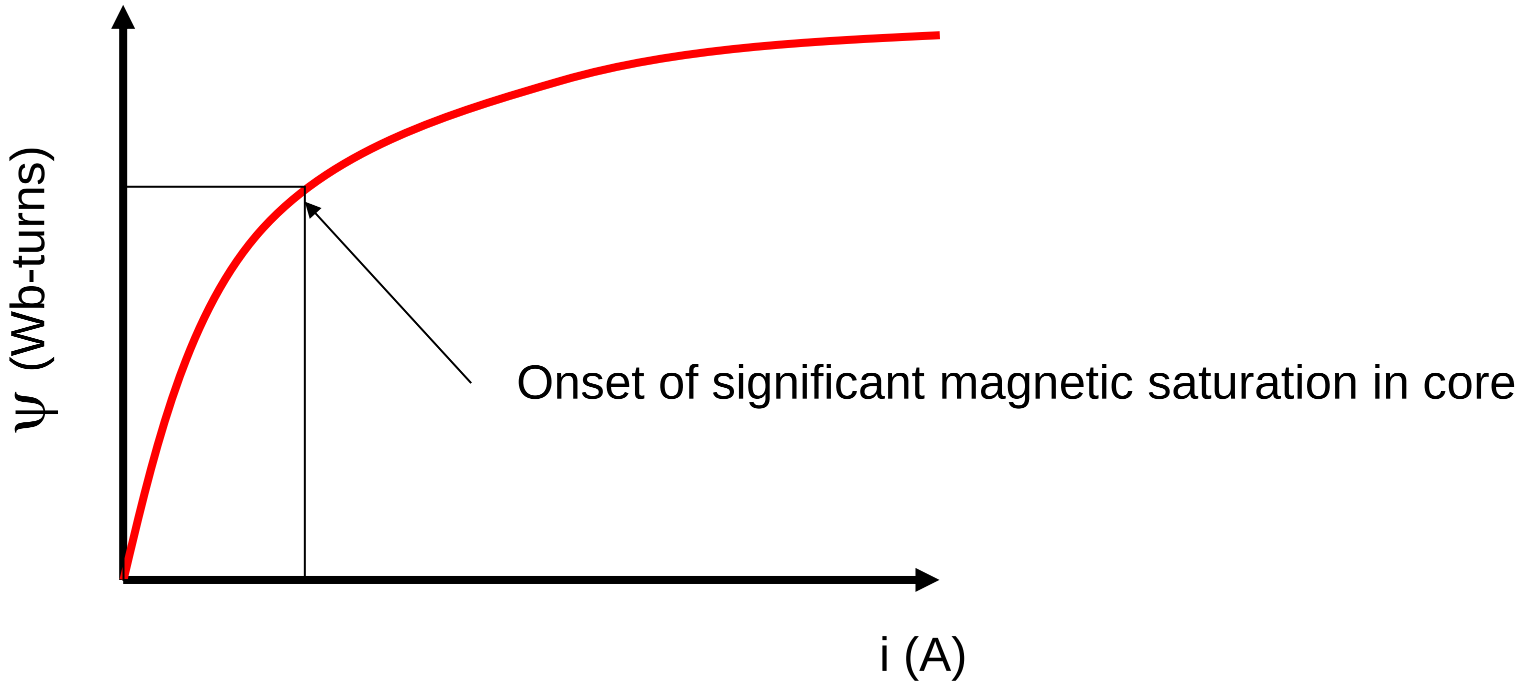
The equation above assumes that the net cross-section through which flux passes remains constant around the circuit and the flux density in all regions is uniform – gross simplification for all but very short aspect ratio gaps

In practice, the yoke is subjected to region of greater localised saturation and leakage which changes the effective cross-sectional area through which flux passes

Even if the above equation held, it is still a non-linear problem since the permeability of the iron (μ_i) depends on the flux density (B) in the iron, which is turn depends on the reluctance which in turn depends on μ_i !

Such problems can, and are on occasions solved iteratively, but non-linear magnetic circuits are not well suited to direct algebraic methods – hence the graphical method of ψ-i is often used

Typical non-linear ψ-I characteristic



Notes:

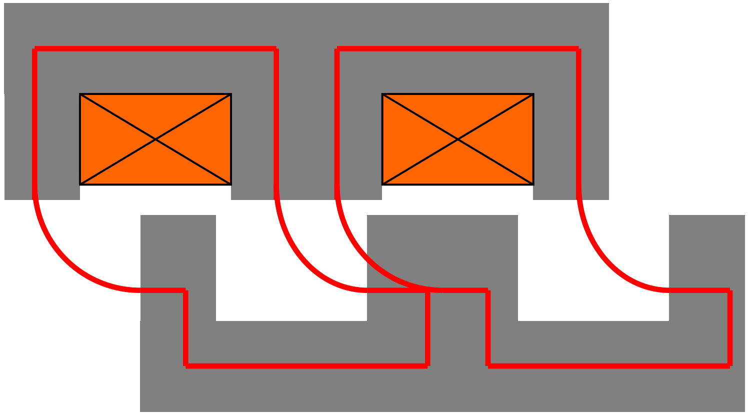
Magnetic saturation is a gradual process – slightly subjective decision as to when characterisitc is showing evidence of ***practically significant*** saturation

Flux-linkage always increases with increasing current – even under extreme levels of saturation. It is just that the rate of increase of flux-linkage with current approaches that exhibited by air

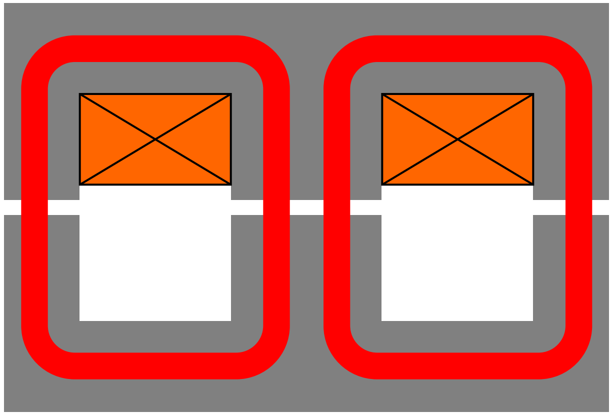
Consider a very elementary electromagnetic actuator
The stationary elements consists on a so-called iron E-core with a coil wound around the central tooth
The moving element consists of a matching iron E-core

If the armature is in the so-called unaligned position – the reluctance is relatively high and the flux is low for a given current. However as the moving element draws itself into the aligned position, the flux increases significantly for the same current

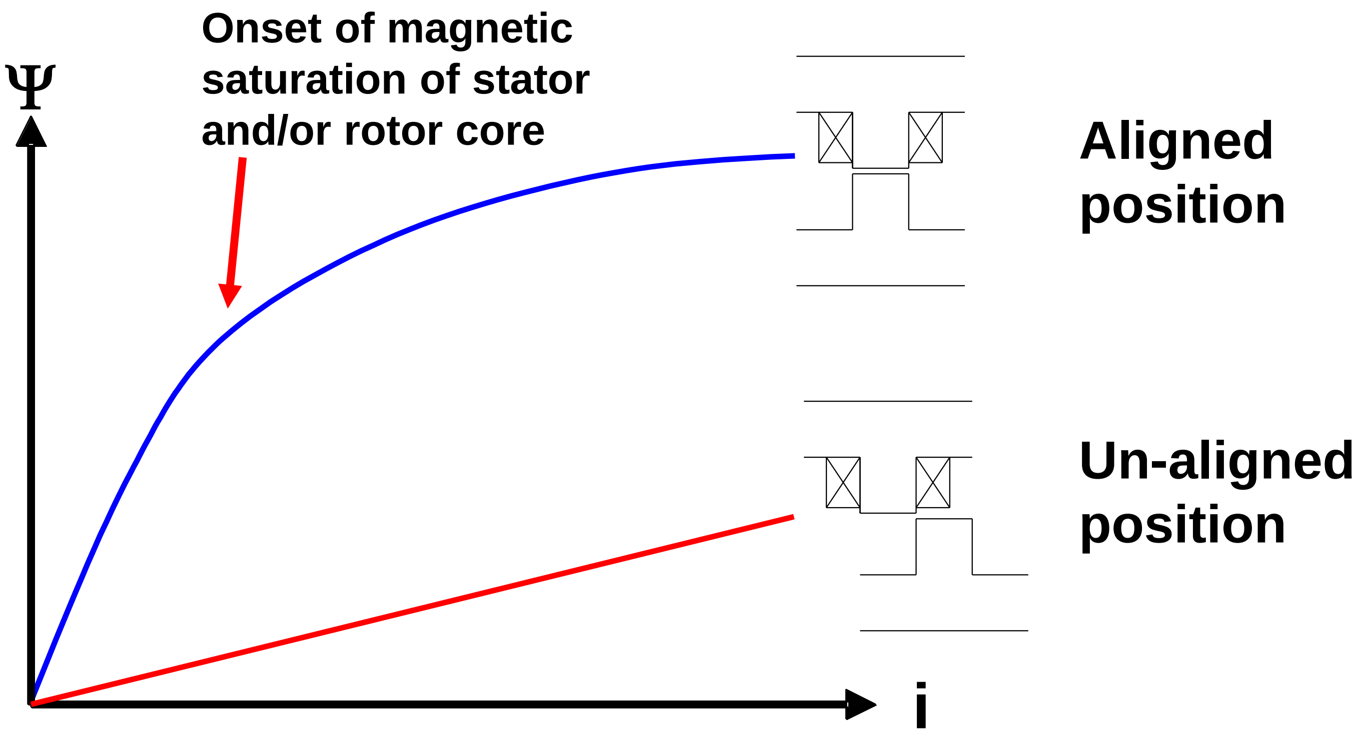
Unaligned



Aligned



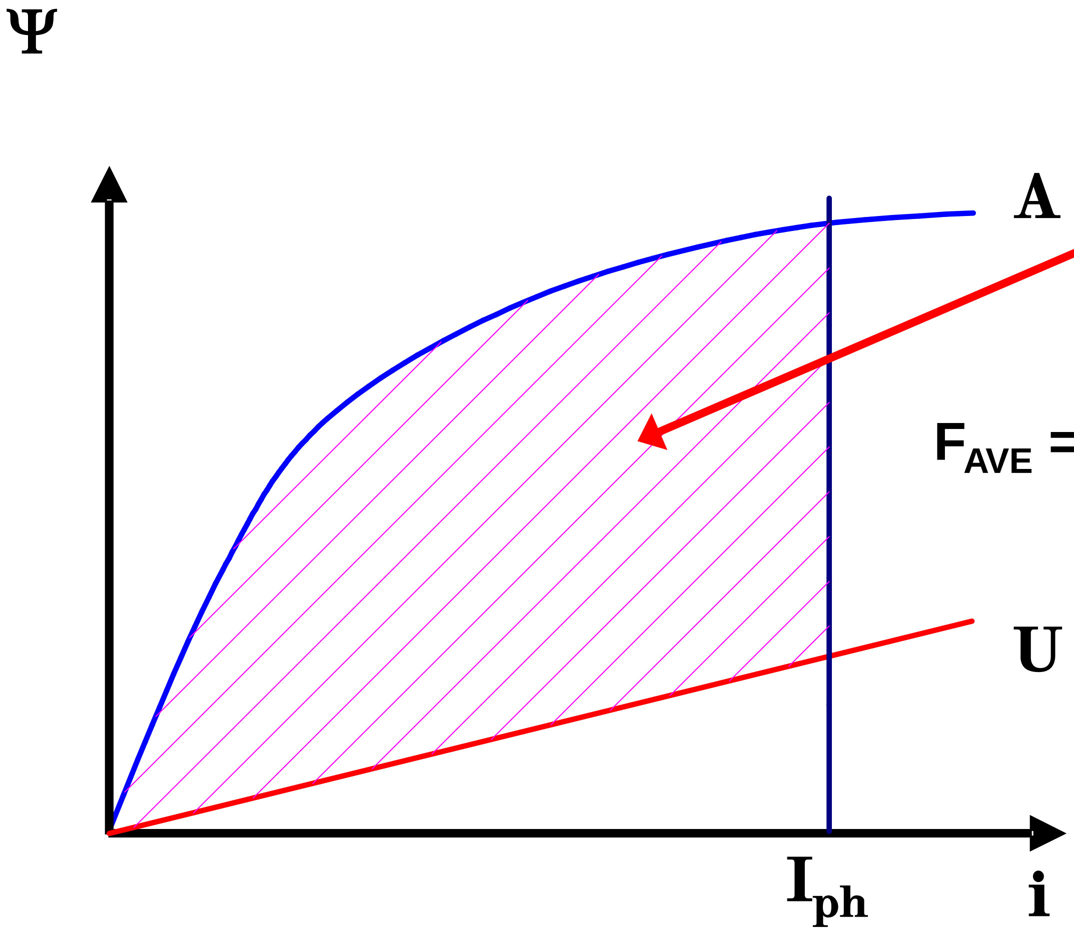
The resulting ψ-i characteristic would have the form



Once the ψ-i characteristic has been obtained (by experiment, finite element modelling or from some other analysis methods) it provides the basis for calculating various aspects of device performance, notably forces (in linear machines) and torque (in rotating machines)

Average force calculation for previously shown linear device

Force produced by drawing moving element into alignment at a fixed current

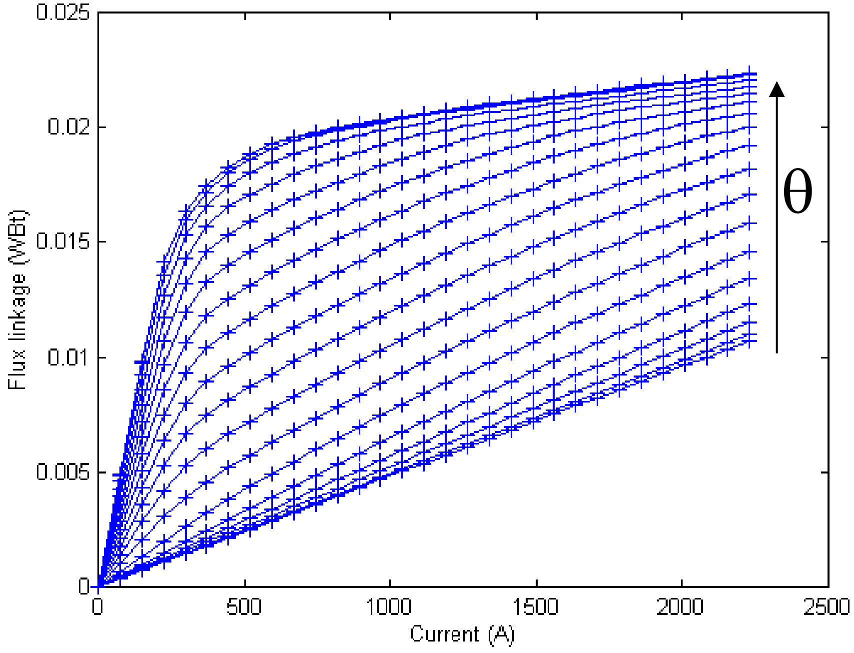


Shaded area is change in co-energy

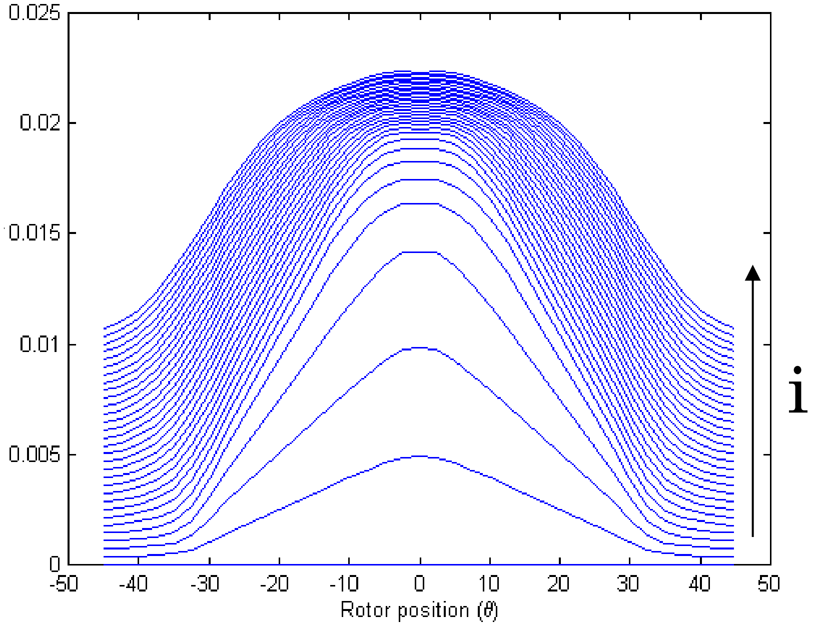
$$F_{AVE} = \frac{\text{Change in co-energy}}{\text{Linear displacement}}$$

In practice, many curves at intermediate between un-aligned and aligned positions are used

Ψ-i



Ψ-θ



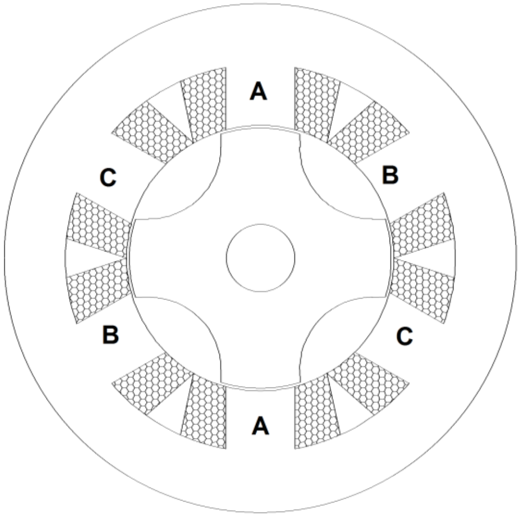
Same data: plotted in two different ways

- Most machines are considerably more complex that the simple E-core device shown earlier
- One important category of machine for which ψ/I modelling is widely used are so-called ‘Switched reluctance’ machines -often referred to as simply SR machines

Basic construction

Doubly salient, singly excited machine

3-phase 6/4



Salient iron rotor

- Laminated
- Contains no magnets or coils
- Simple robust structure

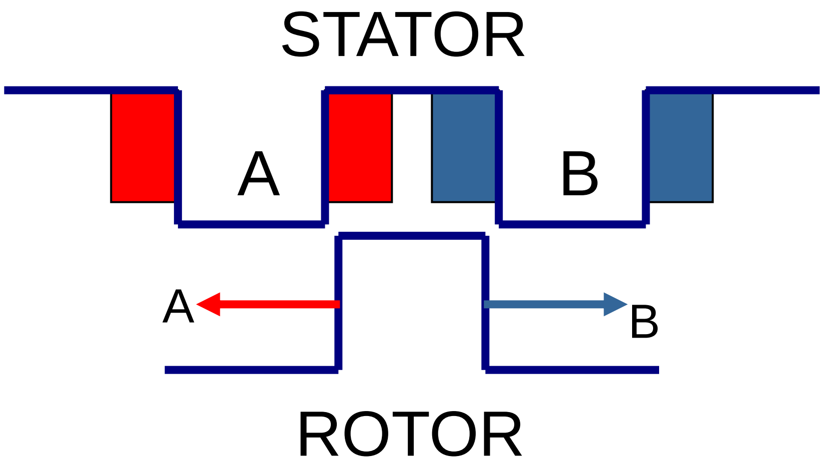
Salient iron stator

- Laminated
- Incorporates multi-phase winding

Common features

- Different numbers of stator and rotor teeth
- Operated with power electronic converter
- Tend to require small airgaps (<0.5mm common)

Torque production mechanism



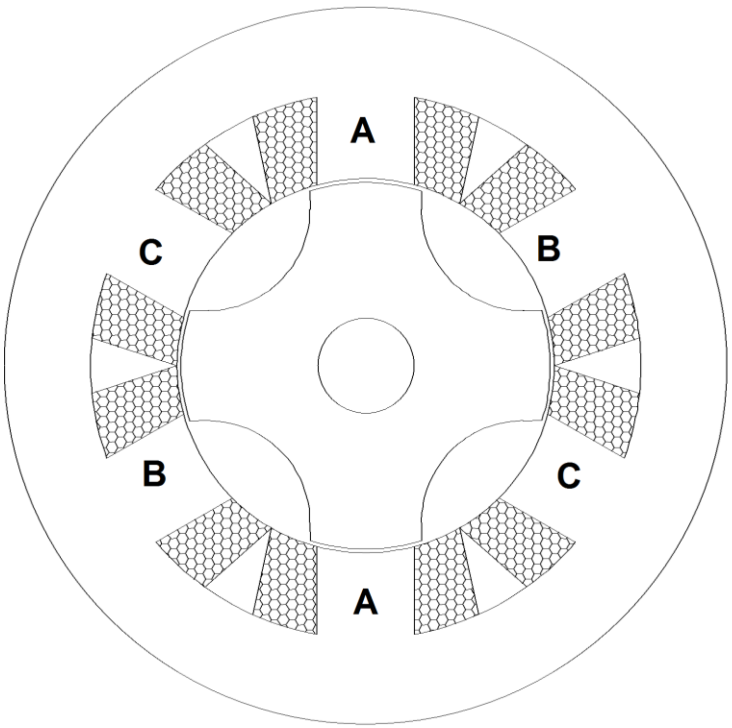
Based on pure reluctance torque
- rotor attracted to a position of minimum reluctance (maximise flux)

Torque independent of polarity of current

Direction of rotation determined by sequence not current polarity

Continuous rotation achieved by sequential attraction of rotor teeth
- requirements on rotor and stator pole number combinations

Basic motoring operation – 3 phase example



Shown aligned with phase A

Current into phase B would draw rotor anti-clockwise

Current into phase C would draw rotor clockwise

Direction determined by phase sequence

Continuous motion produced by sequence of separate torque pulses

Commutated as a function of rotor position (and not time per se)

Comparison with other machines

Claimed advantages

- Simple rotor and stator construction
- Low rotor moment of inertia
- Potential for very high speed operation
- Potential for high temperature operation
- Simple concentrated coil
- Pre-formed (high packing factor) coils
- Unipolar drives
- Inherently fault-tolerant
- High starting torque capability

Claimed disadvantages

- Pulsed nature of torque
- Large torque ripple
- Relatively poor drive VA utilisation
- High levels of acoustic noise and virbation
- Lower specific power than brushless permanent magnet
- Very large unbalanced magnetic pull
- Drives formats not well suited to standard power modules
- Require very accurate position measurement / **estimation**

Phase and pole combinations

Need phases to sequentially come into and out of alignment

Higher phase numbers tend to give smoother torque

Higher phases have better winding utilisation

Phases	Stator teeth	Rotor teeth	Strokes /rev
2*	4	2	4
2*	8	4	8
3	6	4	12
3	6	8	24
3	12	8	24
3	18	12	36
3	24	16	48
4	8	6	24
4	16	12	48
4	24	18	72
5	10	4	18
5	10	6	30
5	10	8	40

*** not inherently self-starting**