EEEN313/ECEN405

Electromagnetics

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What?

- Electromagnetics has ‘electro’ in it but we cant feel it
- Perfect for controversies – 5G, Covid; Covid from 5G ☺
- So why study electromagnetics (EM)?
  - Basis for everything that converts mechanical to electrical and vice versa
  - From Motors to relays, all apply EM
- For this course: We don’t go into detail; no Maxwell Equations (new 4XX course next year)
- Our focus is the understand the principles so that we can work in power systems design.
- We use scalar product in our formulas than integrals of dot and cross products (simplify them).
- There is a lot in EM – important to focus!

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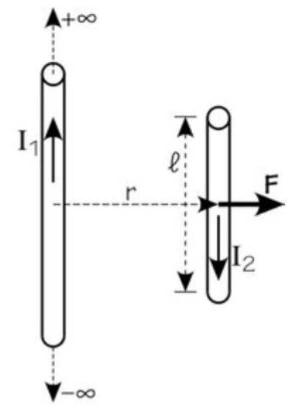
Ampere's Law

- Ampere developed a lot of laws. Our focus is Ampere's Force Law (AFL)
- Two conductors parallel to one another so that the force is maximum – something we all use right from transmission lines to winding inductors and transformers
- AFL says there is a force F acting outward between the conductors



$$F = \frac{\mu I_1}{2\pi r} I_2 \ell \ \text{ newtons (N)}$$

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AFL

- What we learn:
- Force depends on the strength of the two currents
- Force diminishes as the distance between the conductors increase
- Most involve a physical constant that relates to a material properties - µ (permeability) – always relates to permeability of free space.

$$F = \frac{\mu I_1}{2\pi r} I_2 \ell \ \text{ newtons (N)}$$

$$\mu_0 = 4\pi \times 10^{-7} \ \text{ newtons/ampere}^2 \ \ (\text{N/A}^2)$$

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Example 1 – Force between Busbars

- Busbars are aluminium and copper 'bars' that carry large currents.
- Used instead of round wires that occupy large space than busbars
- Mounted on insulators and enclosed in a bus duct for support and isolation

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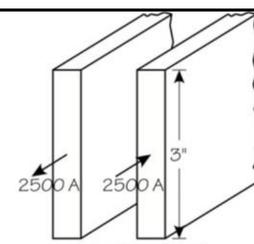
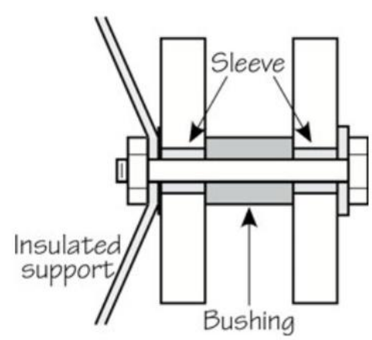
Example 1

- Two busbars are mounted parallel to each other
- The bars are held in place by a bolt through both bars into an insulating block
- The bars are held apart by a bushing on the bolt.
- Bolts are installed at one-foot spacing along the busbars in the bus duct.
- These bars are to be built to carry 2,500 A d-c.
- We have to find the force on the bolts.





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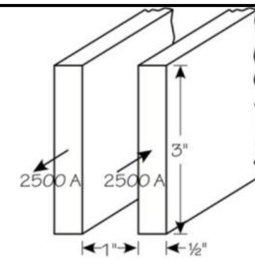
Solution

- To complete the circuit, the currents are in opposite directions
- The forces are trying the sperate the bars which tensions the bolts
- Lets assume length being 12 inches
- Conductor distance r from is 1 and a half inches (how?)
- 2.25 pounds per bolt is not much.



$$F = \frac{4\pi \times 10^{-7}(2500)}{2\pi\left(1.5 \times 2.54 \times 10^{-2}\right)}(2500)\left(12 \times 2.54 \times 10^{-2}\right)$$
$$= 10 \text{ N/ft}$$

$$F = 10 \div 9.8 \times 2.2 = 2.25 \text{ lb/bolt}$$

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Fault

- But what if there's a fault?
- Say 100000 A (40 times the current)

$$F_{fault} = 2.25\frac{100000^2}{2500^2} = 3600 \text{ lb/bolt}$$

- This is the sheer force that is exerted on the bolt on a fault
- Regular maintenance is important.

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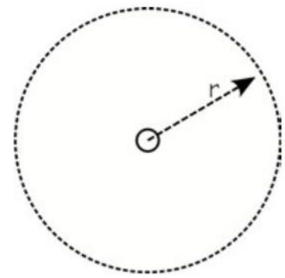
Magnetic Fields in a conductor

- Much like gravity, MF is always around a conductor.
- If I place a second conductor closer to the dotted line, I will feel a force pushing outward.
- The force is related to distance between the conductors.



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Magnetic Flux Density

- The field created by the first conductor is independent of the second one.
- The field is described as B or magnetic flux density.
- Official unit for it is Tesla or T.
- It has a direction stated by 'Right hand rule'

$$B = \frac{\mu I_1}{2\pi r} \quad \text{webers/m}^2 \quad (\text{Wb/m}^2)$$

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Magnetic Flux ϕ

- Flux is B by an area

$$\Phi = \int_A B \bullet dA \quad \text{webers (Wb)}$$

- If flux density is uniform and perpendicular to the area, then

$$\Phi = BA \quad \text{webers (Wb)}$$

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Magnetic Field Intensity H

- H is basically a ‘push’ to create field in a material
- The unit has Ampere Turns – as it involves coils. So if a coil has 100 turns and carries a current of 50mA, then its 5 Ampere-turns – equivalent to a single wire carrying 5 Amps.

$$H = \frac{B}{\mu} = \frac{I_1}{2\pi r} \quad \frac{\text{ampere-turns}}{\text{meter}} \quad \text{(A-turns/m)}$$

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Magneto Motive Force MMF

- Like voltage provides EMF, current provides MMF
- Come from Ampere's Circuital Law

Formal $\mathfrak{F} = \oint H \bullet d\ell$ ampere-turns (A-turns)

For a closed path l $\mathfrak{F} = H\ell$ ampere-turns (A-turns)

With number of coils $\mathfrak{F} = Ni$ ampere-turns (A-turns)

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All this related?

- A current flowing through the wire creates MMF; and that provides magnetic field.
- From MMF, and the length of magnetic field, we get magnetic field intensity H.
- The magnetic flux density, B, is H related to the material used.
- Total flux is BA, A being the cross sectional area of the magnetic path.
- The above relations are used in designing inductance and transformers.

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Reluctance and Inductance

- Similar to resistance
- ‘I am reluctant to go to pub tonight as I have an assignment due’
- Reluctance provides relationship between MMF and magnetic flux.

$$\Re = \frac{\ell}{\mu A} \quad \text{ampere-turns/weber}$$

- Ohm’s law of magnetic circuits: $\mathfrak{F} = \Phi\Re$

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Inductance

- What happens if we wind a coil of wire around a magnetic structure?
- Inductance is defined as flux per unit current.

$$L = N\frac{\Phi}{i} \quad \text{henries (H)}$$

- If we use magnetic ‘Ohm’s law’ equation

$$\mathfrak{F} = Ni = \Phi\Re \qquad L = N\frac{Ni/\Re}{i} = \frac{N^2}{\Re}$$

$$L = \frac{N^2}{\Re} = N^2\frac{\mu A}{\ell} \quad \text{henries (H)}$$

Important for designing inductors

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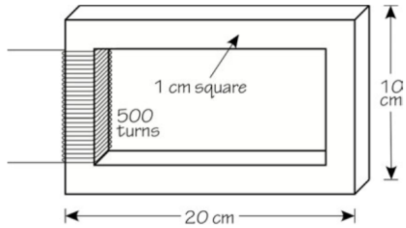
Example 2 – Reluctance of a core



Core is made of alloy whose relative permeability is 900

$$\Re = \frac{\ell}{\mu_r \mu_0 A}$$

$\mu_r = 900$

$\mu_0 = 4\pi \times 10^{-7} \text{ N/A}^2$

$A = (0.01)^2 = 10^{-4} \text{ m}^2$

For path length, choose mean path length

$$\ell = \left[2(20-0.5-0.5)+2(10-0.5-0.5)\right]\times 10^{-2}$$
$$= 0.56 \text{ m}$$

$$\Re = \frac{0.56}{(900)(4\pi\times 10^{-7})(10^{-4})}$$
$$= 4.952\times 10^{6} \text{ A-turns/Wb}$$

$$L = \frac{500^2}{4.952\times 10^6} = 50.5 \text{ mH}$$

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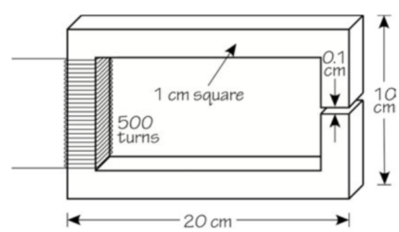
Air Gaps

- What happens if there is a gap in the loop?
- This is called 'air gap'
- Since permeability of the air gap is smaller than iron core, reluctance will be larger.
- Iron core with air gap would be like resistors in series



$$\mathfrak{F} = \Phi(\Re_i + \Re_a)$$

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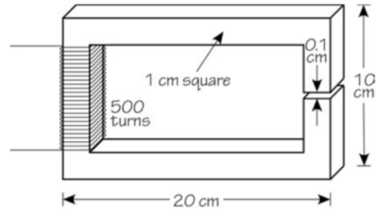
Example with Air Gap



Path length is little shorter now

$$\ell_i = \left[2(20-0.5-0.5)+2(10-0.5-0.5)-0.1\right]\times 10^{-2}$$
$$= 0.559 \;\; \text{m}$$

$$\Re_i = \frac{0.559}{(900)(4\pi\times10^{-7})(10^{-4})}$$
$$= 4.943\times10^{6} \;\; \text{A-turns/Wb}$$

$$\Re_a = \frac{10^{-3}}{(1)(4\pi\times10^{-7})(10^{-4})}$$
$$= 7.958\times10^{6} \;\; \text{A-turns/Wb}$$

$$\Re = 4.943\times10^{6} + 7.958\times10^{6}$$
$$= 12.90\times10^{6} \;\; \text{A-turns/Wb}$$

$$L = \frac{500^2}{12.90\times10^{6}} = 19.4 \;\; \text{mH}$$

The small gap sliced through the iron cut the inductance by more than 60%.

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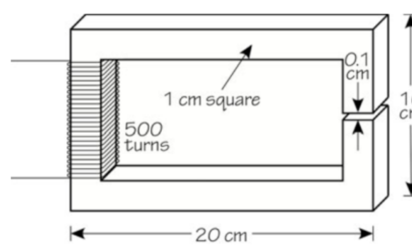
Force in the air gap



- Magnetic force in the iron core will try to close the air gap – since both ends attract each other
- Force in the air gap (ignoring the lengthy derivation):

$$F = \left(-0.5i^2\right)\left(-\frac{\mu AN^2}{x^2}\right)$$
$$= \frac{\mu_r \mu_0 A(Ni)^2}{2x^2} \;\; \text{newtons (N)}$$

- Doubling the current, quadruples the force F.

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Tomorrow

- A design example involving buried distribution power lines
- Designing Inductors