Revision of Electromagnetism – MANDER Notes 2013

Current in a straight wire causes a circular magnetic field around the wire to form.
Current in a coil of wire causes a straight magnetic field to form inside the coil.
Changing a magnetic field near a wire causes a current to flow in the wire.

Diagrams:
Use the right hand grip rule.

The formula for calculating the magnetic field strength at a certain distance from a wire is…

$B = kI / d$

where k is $2x10^{-7}$ NA^{-2}
note that B is directly proportional to the current but
inversely proportional to the distance.

Coils
Use the right hand grip rule again with fingers showing direction of current this time.
Note that inside the coil the field goes S→N
Outside the coil the field goes N→S
ie. the **field exits at the North end**.

The coil with current is a **electro magnet** and interacts with other magnets (similar poles repel).
w/s q1-3

Motor Effect
A current in a wire **induces** a magnetic field which results in **motion** if the wire is already resting in a magnetic field (similar poles repel, different attract).

Use the Right Hand Slap Rule (RHSR) to remember which direction this force is towards.
Fingers = direction of magnetic field
Palm = direction of force, ***effect*** of the current, out of palm
Thumb = direction of current, ***cause*** of the force

The current carrying wire only experiences a force if it **crosses the magnetic field lines**.

F=BIL where F is force, B is magnetic field strength, I is current, and L is the length of the wire resting in the magnetic field. $B = F/IL$

Coils
These can be used as electromagnets.
- can be turned on and off
- can be made stronger or weaker
- can be reversed

Electromagnets are made stronger by:
- higher voltage, higher current
- more turns of wire in the coil
- having a soft iron core

Generator Effect
When we move a wire in a magnetic field a force acts on the charges within the wire causing a current to flow.

RHSL also applies.
Fingers = direction of magnetic field
Palm = direction of force on charges, ***effect***, out of palm
Thumb = direction of wire, ***cause*** of the force

If we use a unconnected length of wire the charges will move and produce a voltage across the wire. The electric field in the wire will oppose the induced magnetic force so eventually the charges will stop moving as the two balance.

As the wire exits the magnetic field the electric field in the wire will move the charges back again.

V=BvL where induced voltage (V) equals the magnetic field strength x velocity of the wire x the length of wire.

Q. A wire 0.40m long, at right angles to a magnetic field of strength 6.0T is moved at 5.0m/s.

a) which end becomes + … need diagram
b) what is the voltage…12V

Magnetic Field Strength
At a point from a straight wire   B = kI / d   where $k = 2x10^{-7}$ NA^{-2}

At a point inside a solenoid (coil) $B = \mu_0 NI / L$
where $\mu_0 = 1.26x10^{-6}$ TmA^{-1} and is the *permeability of free space.*
N is the number of turns in the coil
L is the length of the coil
I is the current

At the end of the coil the field strength decreases and is half the maximum value.

Fun with Fields
For individual charges or for many charges in a wire, a force is experienced and a current induced only when the charge is crossing magnetic field lines.

For a loop this means only one side of the loop. If both sides cross then the forces will cancel each other out.

Induction
As a charge moves through a magnetic field it experiences a force at right angles to its motion. Use the RHSR to work out which direction this is in.

The motor effect is about the generation of movement from electrical energy.
The generator effect, or induction, is about the generation of electrical energy from movement.

eg. A magnet moving into a coil of wire induces a current in the coil. This is because each charge in the wire experiences a force as it crosses magnetic field lines. You don't get something for nothing, however, so now for…

LENZ’s Law
This is based on the conservation of energy.
An induced current causes a force to oppose the change that caused it.

3 examples (coil in field, magnets moving towards coil, coil moving towards magnets)
If this didn’t happen then we could just give a magnet or coil a single push then get electricity out of it forever.

“Negative point” energy motors on the internet are ALL FAKES because they don’t take Lenz’s law into account. You can NOT get more energy out than you put in.

FLUX and Induction
A *changing* magnetic field is required to generate a current in a coil.

You can do this by moving the magnet or by changing the strength of the magnet.

Magnetic Flux is the strength of the magnetic field in a certain area and has unit φ.

$\varphi = B \times A$

Changing flux results in a voltage in the coil, eg. you only notice the wind/air when you are moving through it.

$V = -\Delta\varphi / \Delta t$

The **negative sign** is a reminder of Lenz’s law. The induced voltage opposes the change that caused it.
As a coil rotates **in a motor** we can use a commutator (switch) to swap the direction of the current over. This means an electric motor can keep spinning in one direction.
In a generator the commutator does not need to swap the current direction. Brushes are still used because otherwise the rotating coil will get all wound up.

Both the torque and the voltage is dependent on the orientation of the coil in the field.

$V = V_{max} \sin \omega t$ where $V_{max} = BAN\omega$

B is magnetic field strength
A is area of coil
N is number of turns of wire in coil
ω is angular velocity = $2\pi f$
No brushes or commutator are needed if the magnet is rotated inside the coil.

RMS
AC RMS is the equivalent DC value of voltage or current which would produce the same amount of power as the AC value.

Root mean square or RMS voltage is the voltage used for determining the amount of power that a sinusoidal signal is capable of providing. RMS voltage is defined as follows, where V_P is the peak voltage in the AC or sinusoidal signal.
$V_{RMS} = V_P / \sqrt{2}$

Note that this equation is only valid for sinusoidal signals. Using the RMS voltage of a sinusoidal signal, you can determine the power provided by that signal using the following equation.

$P = V_{RMS}^2 / R$

For example, standard North American wall outlets provide 120 VAC, which refers to the RMS voltage of the signal. Following the conversion, the peak voltage of the wall outlet is approximately 170 V.

Transformers
Two coils on one iron core.
A *changing* current (AC) into *the primary coil* produces a changing magnetic field in the iron core. This changing field also goes through the other coil and thus induces a voltage in the *secondary coil*.

The voltages in the secondary coil depends on how many turns of wire there are in the coils.

$V_s / V_p = N_s / N_p$
ie. ratio of voltages = ratio of number of turns

Three ways to make a better transformer:
1. Use a soft iron core
2. Low resistance wire, lots of turns
3. Thin laminated sheets in iron core rather than solid.

Reduces eddy currents in the iron core. Electrons in the core will try to move under the changing magnetic field and we don't want them doing that because any magnetic field they produce will oppose the force that made them move and make our transformer less efficient.

Why use a transformer:
1. The voltage we generate may not be the voltage we want to use.
2. Transmission efficiency

All wires have some resistance. Some voltage will be lost as heat to this internal resistance. V = IR

If we decrease the current (I) in the power line then the voltage lost (V) to the internal resistance (R) will be less.

P = IV we can keep the same amount of power by decreasing current while increasing the voltage in the wire.
This is why we have 220,000V power lines and transformers to change the voltage back and forth.

Inductance

Mutual inductance
This uses two coils. Changing voltage in one coil induces a voltage in another coil.

$V = -M \Delta I / \Delta t$

Where M is the value for mutual inductance, unit *henry* (H)
1 henry is when 1 amp per second in one coil causes 1 volt in the second coil.

Self inductance
This uses one coil. A changing current induces a voltage in the *same* coil. Because the induced voltage opposes the change that caused it the change in current will be opposed.

ie. If you have a coil in a circuit the current will take *longer* to build up to maximum or to fall to minimum.

$V = -L \Delta I / \Delta t$

The negative sign in the equation shows that the induced voltage opposes the change of current (Lenz's Law).

Energy Stored
Inductors store energy in their magnetic field.
If you turn the current off the field collapses.
But a changing magnetic field causes a voltage that opposes the change.
$E = ½ LI^2$
L is the inductance, I current

eg. A circuit has a battery, switch, lightbulb, and a coil. When turned on the light bulb comes on slowly. When switched off the lightbulb dims slowly as the energy in the coil's magnetic field gets used up.

The decay curve for inductors is similar in shape to capacitors.
The time for the current to rise to 63% is $\tau = L / R$

Rectification and current smoothing
Making AC only positive by flipping any negative current around. Use a diode bridge rectifier so the current ends up only moving in one direction.

Reactance
V = IR compares with $V_c = IX_c$
A similar property to resistance but it is also affected by the *frequency* of the AC supply. Think of the difference between how a capacitor behaves in DC and AC.

Capacitors block low frequencies and DC.
$X_c = ½ \pi f C$
eg. 100μF cap with a $250V_{rms}$ 50 Hz AC supply
At this frequency the reactance is 32Ω

The rms current in the circuit is I=V/X = 250/32 = 7.8A

Phase
The voltage on the capacitor follows that of the resistor by 90 degrees.
Diagrams can show us the Supply voltage.

When the capacitor is first connected there is no charge on it. This results in a voltage difference on the two sides of the resistor.

When the capacitor is fully charged there will be no voltage difference between it's plates and the power supply so there will be no voltage on the resistor when there is full voltage on the capacitor.

Use Pythagoras to work out the supply voltage from the voltage phasors for the capacitor and the resistor.
ie. take a reading of the RMS voltage on the resistor, and the capacitor that are in series with each other. The voltages don't just add up as they are at 90 degrees to each other.

Impedence
Combined resistance in a circuit due to a capacitor and a resistor.
$Z = V_s / I$

So after a whole lot of substituting you end up with: $Z = \sqrt{R^2 + (X_C)^2}$ Which is just using Pythagoras.

Reactance and Inductors
$V = IR$ compares with $V_L = IX_L$
A similar property to resistance but it is also affected by the *frequency* of the AC supply. Think of the difference between how an inductor behaves in DC and AC.

$X_L = 2\pi f L$

In DC circuit at first connection:
Current starts to flow. The changing current in the coil induces a changing magnetic field that creates a voltage that opposes the change that caused it. High reactance.

No voltage drop over the resistor.

In DC circuit after current has stabilised:
No changing magnetic field means no reactance in coil.
Maximum voltage drop across resistor.

In AC circuit
We see the voltage across the coil leading the voltage on the resistor by 90 degrees. Use Pythagoras to calculate the voltage of the supply from the two voltage phasors.

LCR circuits – mixing them all together
Voltage on the coil will be 180 degrees out of phase from the voltage on the capacitor.

Total resistance in such a circuit is made up of the resistance from the three different components and is called **Impedance**.

Total impedance = V_s / I

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

Two points:
1) Capacitors and inductors react to *frequency* differently.
   For capacitors higher frequency = lower reactance.
   For inductors higher frequency = higher reactance.

2) At a specific frequency the reactance of the inductor and capacitor will be equal but opposite. This is the *resonant frequency.* The only remaining resistance in the circuit will be from the resistor. At this frequency the circuit is said to be in *resonance*.

Equation for resonant frequency

$$f = \frac{1}{2\pi\sqrt{LC}}$$

Summary of this summary
DC electrical circuits involve V=IR and P=IV. There are series and parallel circuits. There are power supplies and power converters. Some power supplies are hiding power converters inside them and you have to work out how that internal resistance is affecting the circuit. This is Kirchoff's Laws.

In DC circuits you can put capacitors and inductors.
Capacitors (C) will tend to block DC as they charge up and reach a maximum. AC will allow them to keep charging and discharging.

Inductors (L) allow DC to flow but tend to block AC as AC is a changing current. A changing current produces a changing magnetic field around the wire which in turn produces a force on the charges in the wire so that a magnetic force is created that opposes (resists) the thing that caused it. This is Lenz's Law.

Capacitors block DC
Inductors block AC

Reactance is the capacitor and inductor equivalent of resistance in a resistor.
Inductance is the combined reactance of the capacitor and inductor. This is interesting as the reactance of each is 180 degrees out of phase with each other and 90 degrees out of phase with any resistor hanging around. Yes, this talk of phase and angles means we are back talking about circles again.

LCR circuits include a resistor. Resonance is really handy for tuning your radio to your favourite station while ignoring all those other stations on nearby frequencies.