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Magnetic Components in Power Supplies

Introduction

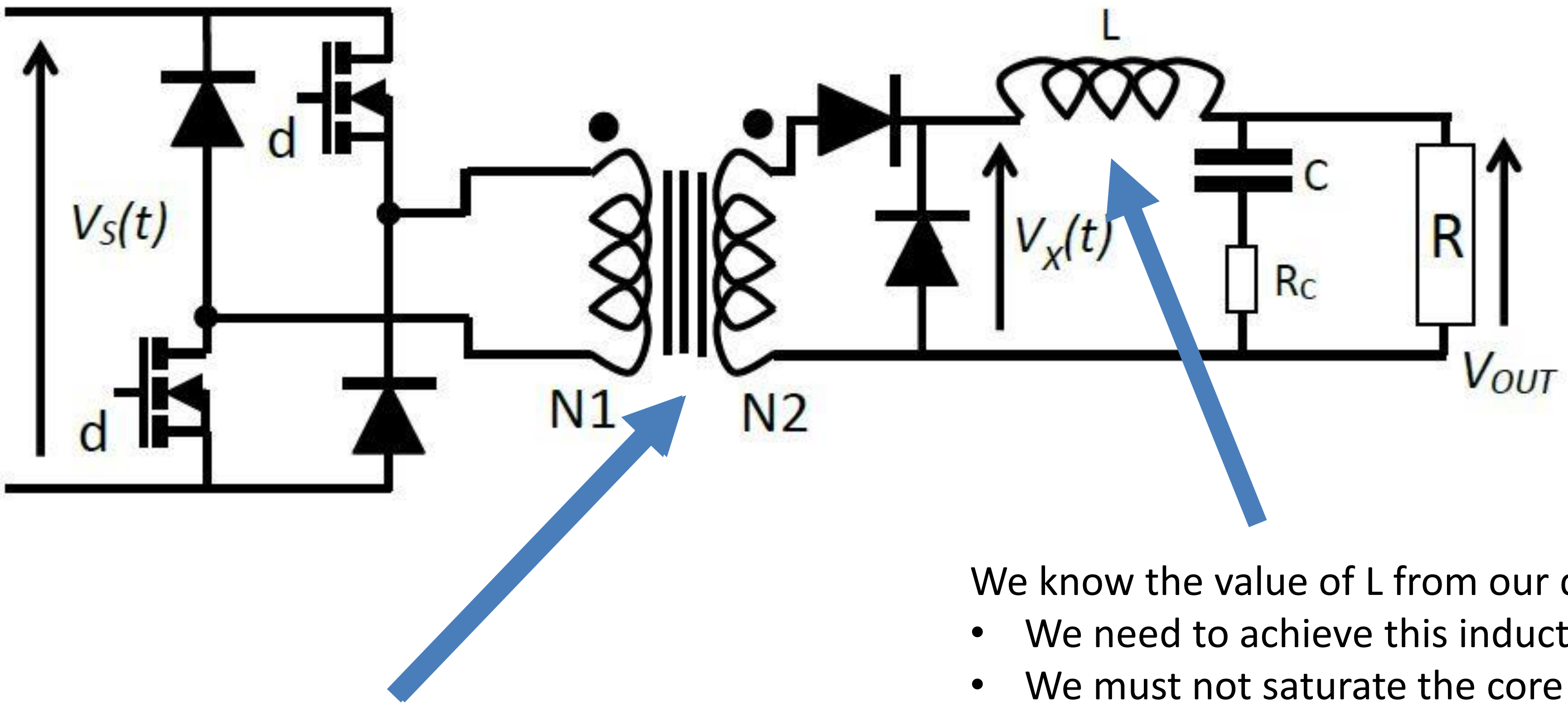
- Magnetic components are used frequently in power electronics circuits to transfer or store and release energy or as part of a filter

- Next week, in the project you will have calculated:
  - The inductance of the inductor in the output filter (the LC part)
  - The turns ratio of the transformer

- In the next part of the project you will go through the design process for these two (+1 more) magnetic components to determine:
  - How to achieve the specified inductance
  - How can we be sure that our maximum circuit current will not saturate the magnetic core (See later)?
  - How do we make sure that we don't have too much loss in our magnetic component?
    - Remember, we want an efficient power supply
  - What about the inductor air gap? How big is big enough?
  - Etc.

- This presentation, and a number of handouts on Moodle will help answer these questions- these are not complete guides… you may have to do some research

Where are the magnetics in our design?



We know the value of L from our design process:

- We need to achieve this inductance
- We must not saturate the core when the converter operates

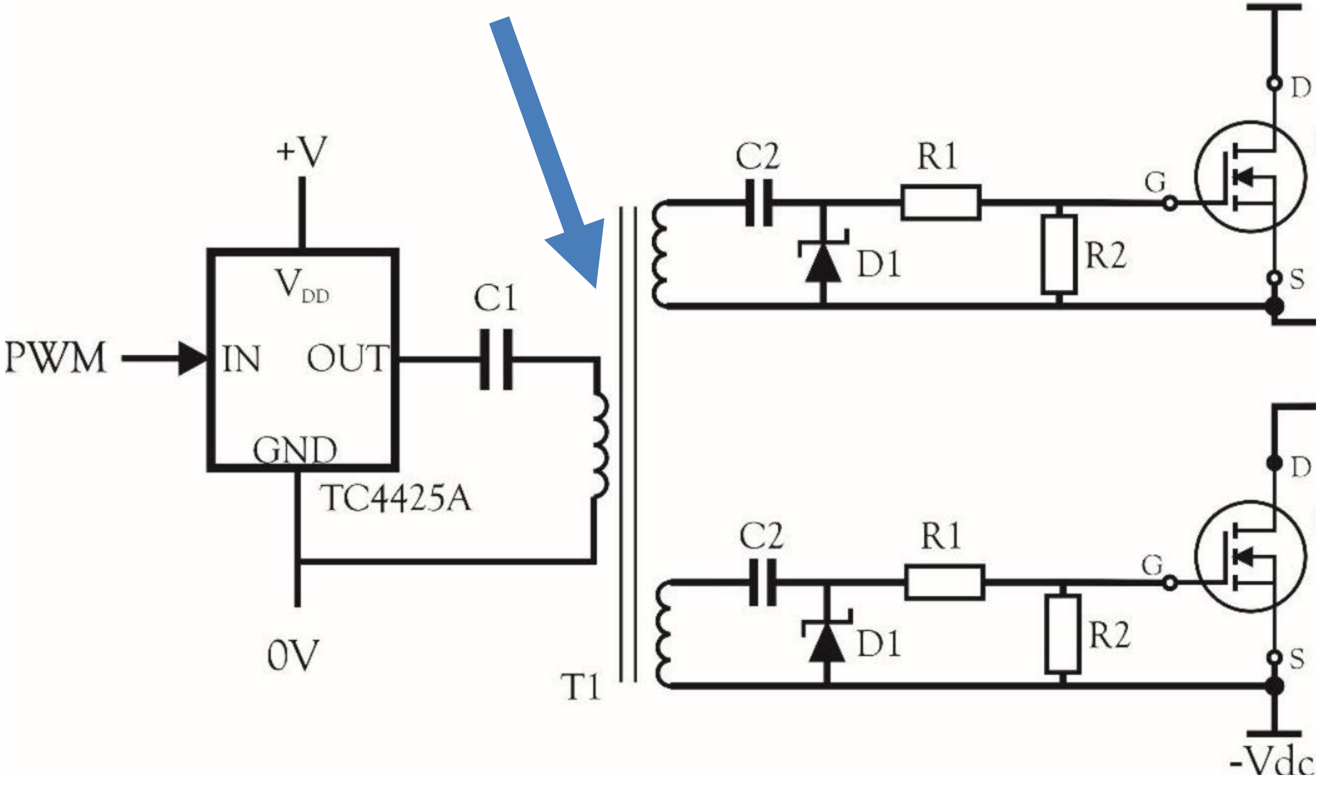
We know the N2/N1 (ratio) from our design process

- We need to calculate the actual number for N1
- We can then get N2 from the ratio N2/N1
- We must not saturate the core

Where are the magnetics in our design?

- This will be the circuit which “drives” the MOSFETs in the actual circuit
- We will go through the details of why it’s needed and how it works next week
- Note, that there is another transformer in this circuit- this time with three windings
- This circuit is a relatively low power compared to the main Forward Converter circuit
  - As a result, the transformer core is very small (about the size of a penny) and is toroidal
  - How it is constructed has quite a large impact on how the circuit operates

3 winding, high frequency gate drive transformer

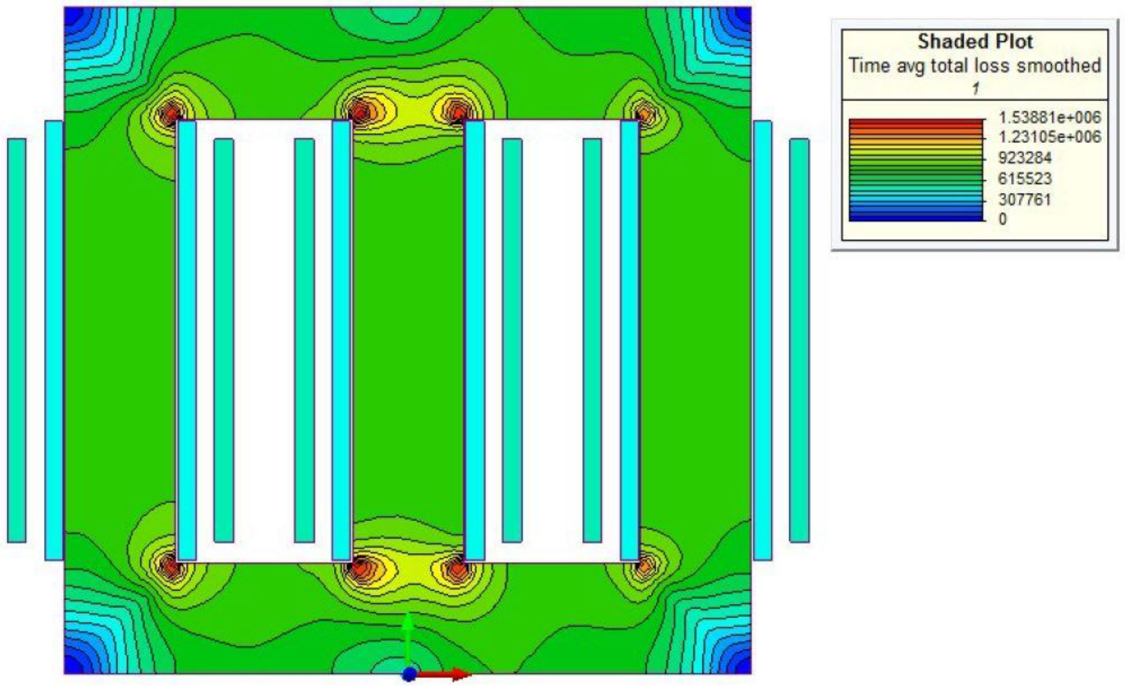


Electromagnetic Basics I

- I don't intend to go through all of the basics of electro-magnetic theory and derivation of basic relationships for the components

- If you need to re-familiarise your self with some of these concepts- I will take a copy of the Year 1 "Power and Energy" notes on magnetics and put them on our Moodle page

- There are also some references at the back of this presentation- give them a read if you're interested in furthering your knowledge



Electromagnetic: Common relationships/equations

N- Number of Turns
i- Current [A]
MMF- Magneto Motive Force- NI [A-turns]
l- Magnetic path length [m]
l_c- Core Magnetic Path Length [m]
H- Magnetic Field- Ni/l (Am^{-1})
ϕ- Flux [Weber]

μ_r- Relative Permeability [Dimensionless]
μ_0- Permeability of free space = $4\pi \times 10^{-7}$ [Crazy Dimensions]
μ_e- Effective Permeability = $\mu_r\mu_0$

B- Flux Density= $\mu_e H$ [T- Tesla]

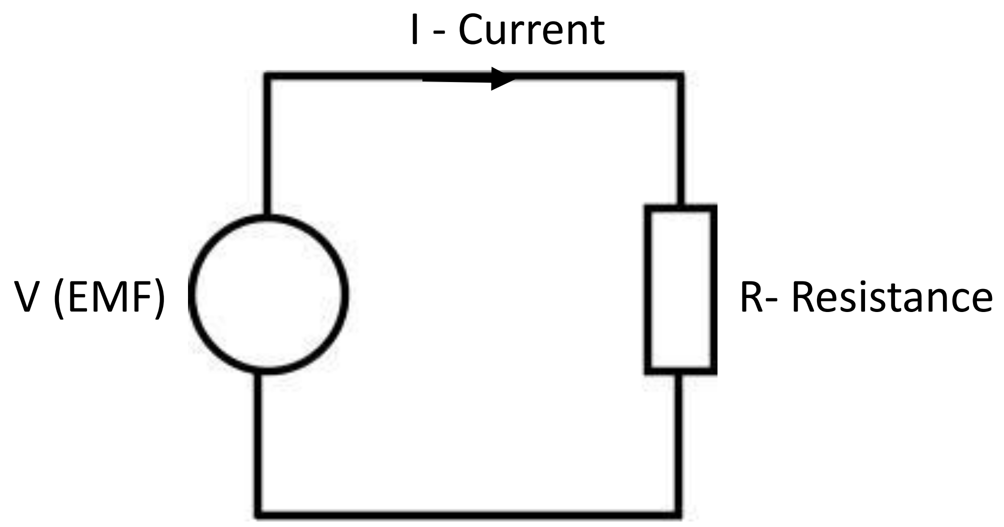
A_c= Core Cross Sectional Area [m^2]
A_g- Air Gap Cross Sectional Area [m^2]
g or l_g= Air Gap Length [m]
R= Magnetic Reluctance- $\mu l_c/A_c$ (for example)

This might seem a lot- however, once you've applied them to a design, and considered their "Electrical Counterparts" (next slide) you will eventually get used to them

Magnetic Circuits

- Analysis using "Magnetic Circuits" makes design (and understanding) a little easier for Engineers

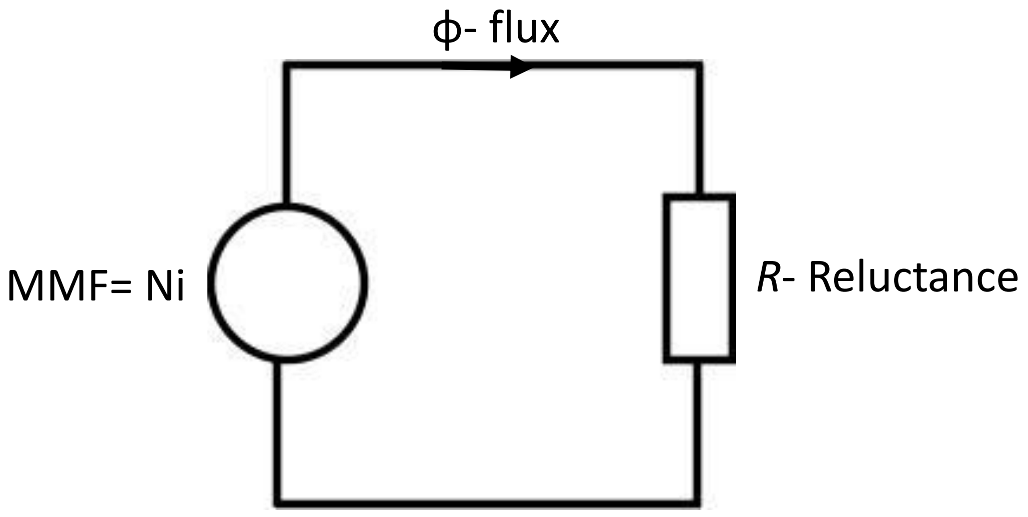
Electrical Circuit



$$R = \frac{\rho l}{A}$$

ρ =Resistivity

Magnetic Circuit



$$R = \frac{l}{\mu A}$$

μ =Permeability

Magnetic Materials for Power Electronics

Laminated Silicon Steel- Used in low frequency AC applications where a "Soft Iron" core would suffer from high Eddy current losses. Has a high saturation flux density 1.5-1.8T.

Ferrite- Generally used in high frequency applications. The ceramic nature of the material means that it is highly resistant to electrical current and therefore has very low eddy current losses and does not need to be laminated. The saturation flux densities are in the 0.4-0.5T region.

Powdered Iron- Not generally used for transformers because powdered material has an inherent "Distributed air gap" which lowers the permeability of the core. They have a saturation flux density of around 1-1.5T.

Amorphous metal- These materials are non-crystalline or "glassy". They can be used to produce highly efficient transformers (with a high saturation flux density) but are generally more expensive than other materials. There are many types but for example "Metglas" cores have a saturation flux density of 1-1.5T.

Plus lots others….

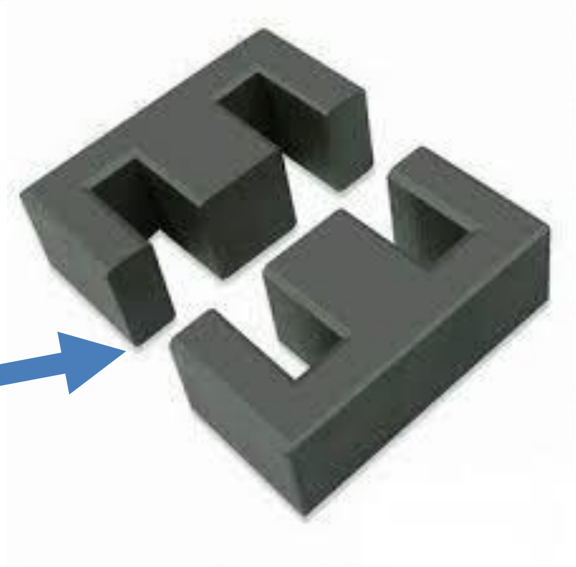
We are using Ferrite. Research these and make yourself comfortable with the justification of this material.

Core Shapes and Sizes

Various “I” and toroidal cores

ETD Cores

We will use this type in the main transformer and output inductor

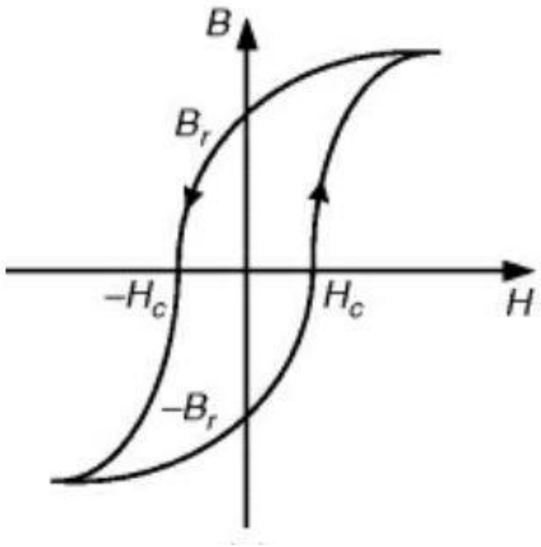


E Cores

Toroidal Core

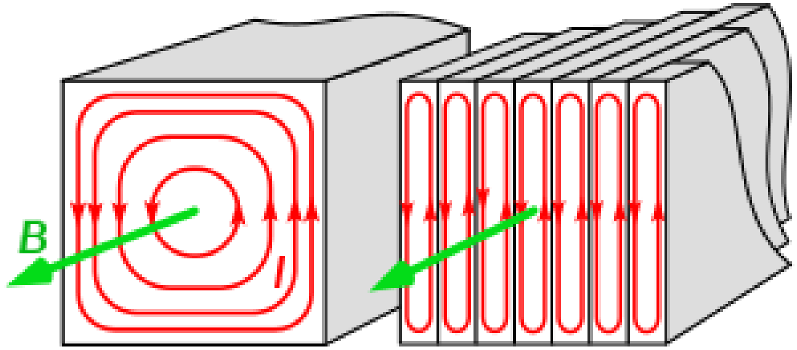
We will use this in the gate drive circuit

Core losses



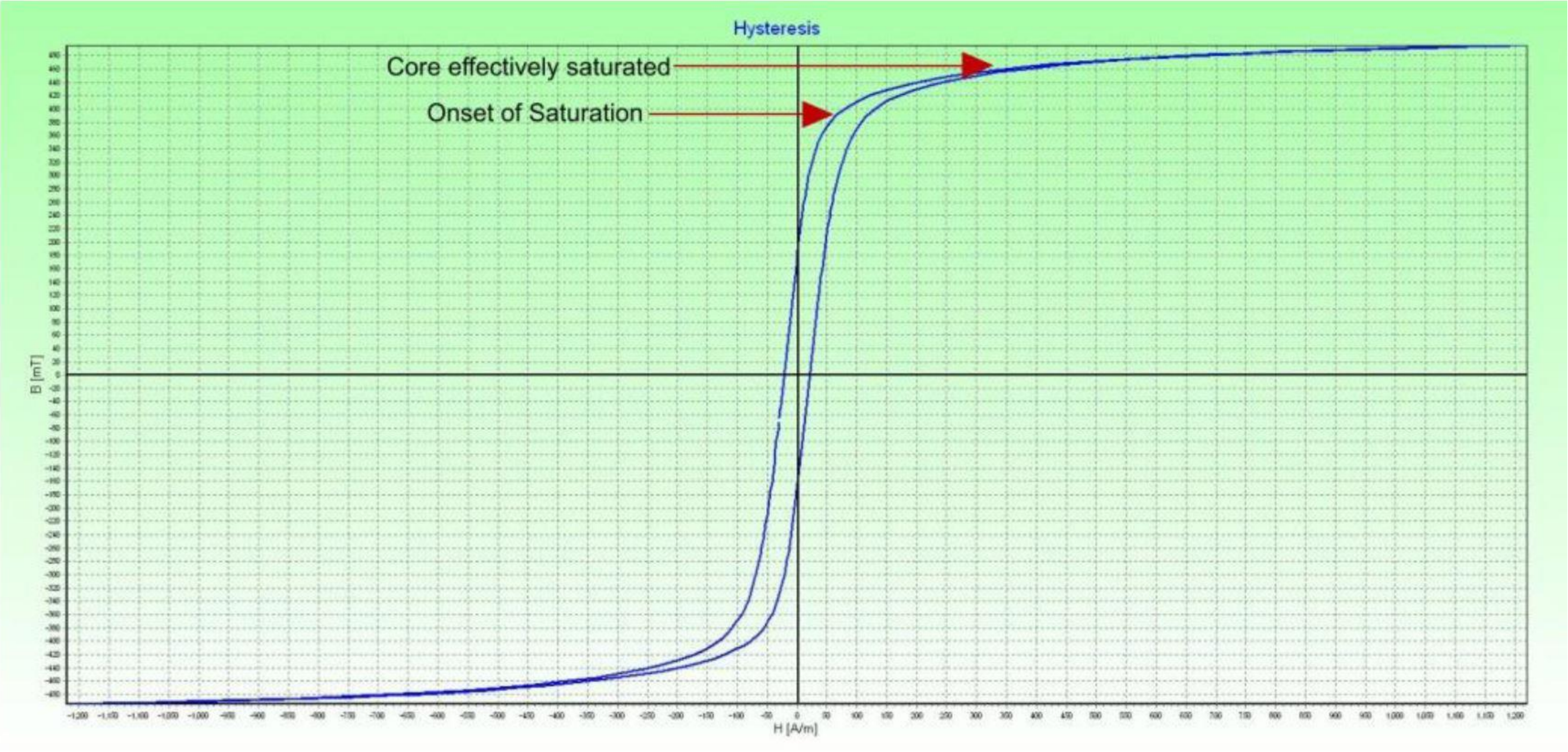
Hysteresis Loss- As the circuit drives flux around the BH-Loop, a certain amount of energy is lost in the core. As a result, the total Hysteresis loss is a function of how often the flux goes around this loop- i.e. the frequency as well as how far "into" the loop we travel (B_{max}).

As a result, at higher frequencies we tend to operate at a lower peak flux density (to achieve reasonable efficiency)



Eddy Current Loss- In magnetic circuits with a low electrical resistance, flux in the core sets up currents in the core material. This is why laminations are used (these get thinner at high frequencies)- it increases the resistance of the core. Materials, such as Ferrite have a very high resistivity and therefore exhibit very little eddy current loss

The BH-Loop for a magnetic material



- The path we take on our BH-loop, and how frequently we do this has an effect on the Hysteresis loss of the magnetic component that we are designing

Basic Transformer (XFMR) Design

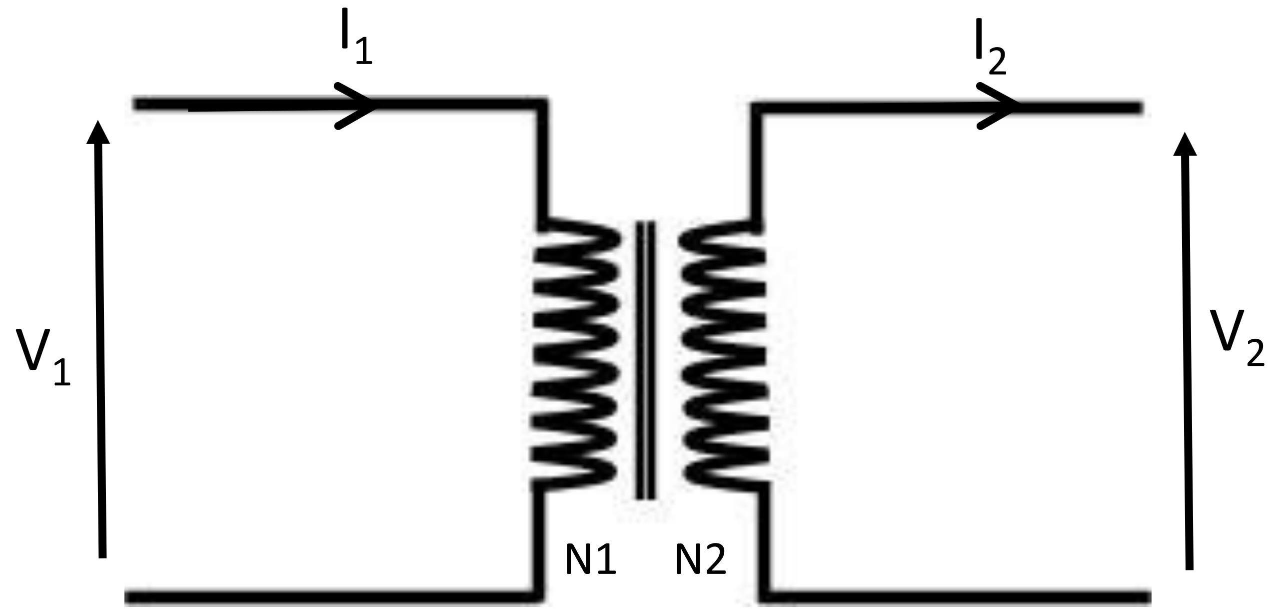
Introduction

- From the design work that we do in the lab we determine the turns ratio N2/N1 for our Forward Converter Transformer.

- We now need to calculate
  - The number of turns required on the primary
    - To achieve a reasonably high magnetising inductance (this helps overall converter efficiency)
    - Acceptable loss in the transformer (Efficiency)
    - We must avoid saturation of the core

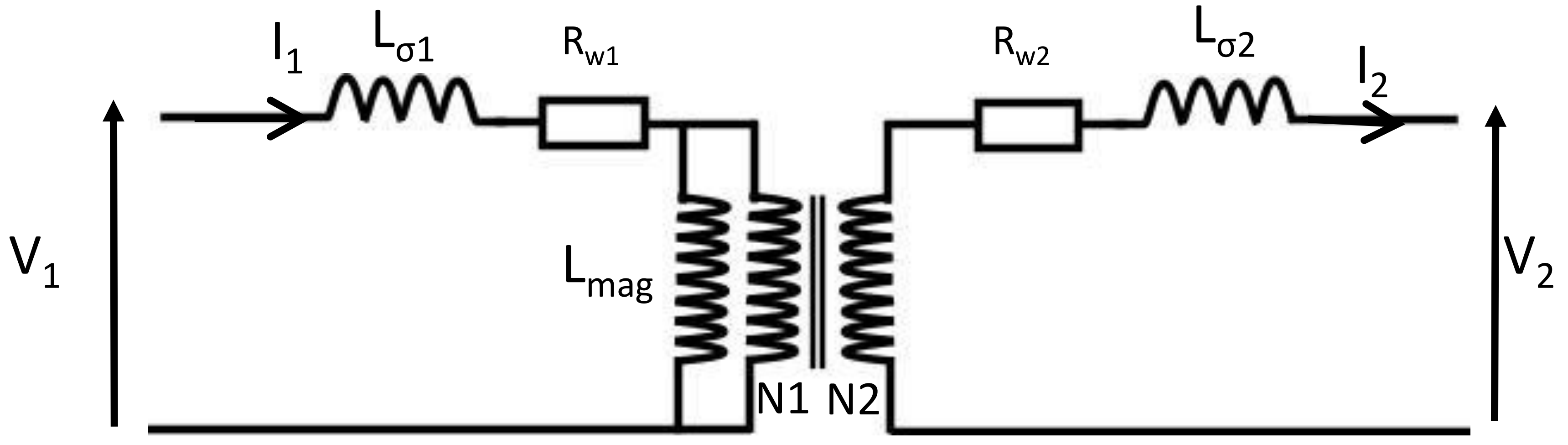
  - We also need to decide the size of wire we need
    - This has an impact on the resistance of the winding (i.e. winding loss- efficiency)_
    - We must be able to fit all windings (two for the main transformer), and any extra required insulation into the “Window Area” of the core

Transformer Basics: Ideal Transformer



$$\frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$$

Non-Ideal Transformer



L_{mag}- Magnetising Inductance- sets up the flux in the core

$L_{\sigma 1}$, $L_{\sigma 1}$- Leakage Inductance- a result of flux from primary winding which does not link with the secondary winding

R_{w1}, R_{w2} – Winding resistance of the primary and secondary windings

Transformer Design Equation

Starting from Faraday's law:

$$V = N\frac{d\varphi}{dt} \qquad [1]$$

Where V is the voltage applied to the winding, N is the number of turns and φ is the flux created in the core. Rearranging this into the integral form gives:

$$\frac{1}{N}\int V\,dt = \varphi_1 - \varphi_0 \qquad [2]$$

Which can be converted to flux density (B) by considering

$$\frac{VTA}{NA_{core}} = B_1 - B_0 = \Delta B \qquad [3]$$

Where VTA is the "Voltage Time Area" (See Power Electronics analysis in EEEE2045) and A_{core} is the cross sectional area of the core. Finally ΔB is the change in flux density.

This can clearly be re-arranged and re-labelled to calculate the number of windings required:

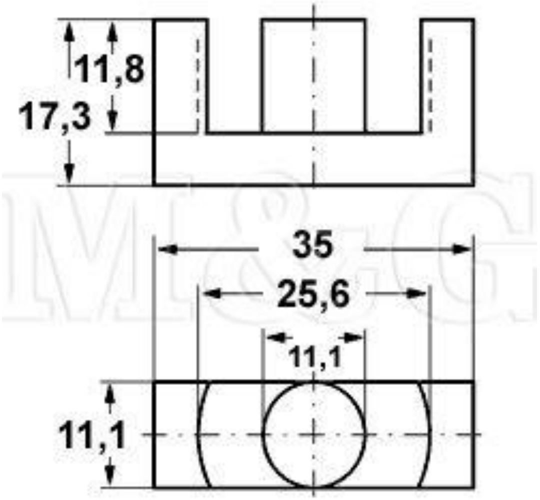
$$\frac{VTA}{\Delta BA_{core}} = N \qquad [4]$$

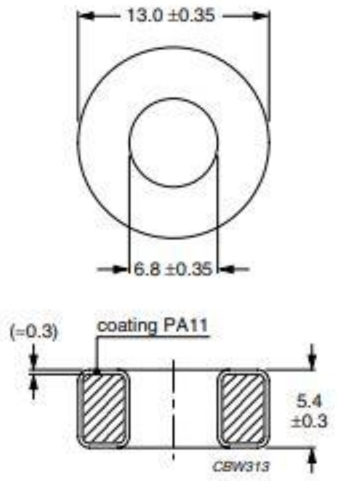
You need to decide what the "Worst case" VTA that will be applied to the core- this will give the largest shift in flux density. $\Delta B = B_{max}$ i.e. the highest VTA must keep the flux density below the B_{max} chosen in the previous section. Clearly the calculated N must be a whole number.

Core Dimensions Selection

- How do we know what size core to use?
  - This used to be done by getting a large book from the manufacturer and using tables to get an initial guess for the required
  - This would sometimes require an iterative procedure
  - Nowadays, since software is available this process is a lot easier
  - The “Area Product” Rule is used to work out the dimensions of the core- this usually considers several things
    - Maximum Flux Density
    - Current Density of wires (and therefore wire dimensions)
    - Core Losses
    - Etc.

- For the project- we have selected the cores for you
  - This is because it can be difficult to get ferrite cores in large quantities on short lead times- so we purchased lots over the summer
  - They are a little big for the application but this gives plenty of headroom for different designs



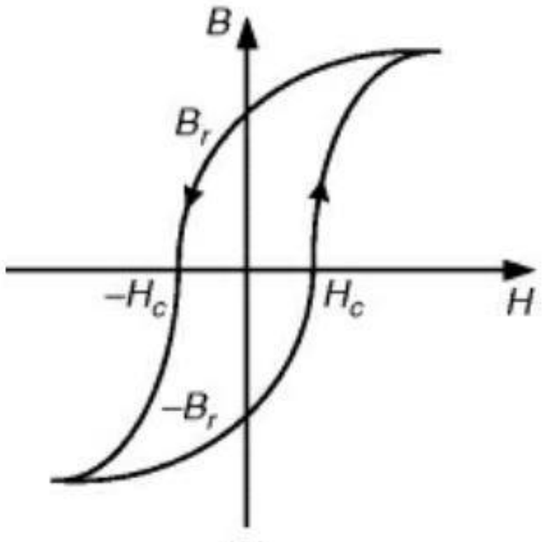


How high for B_{max}?

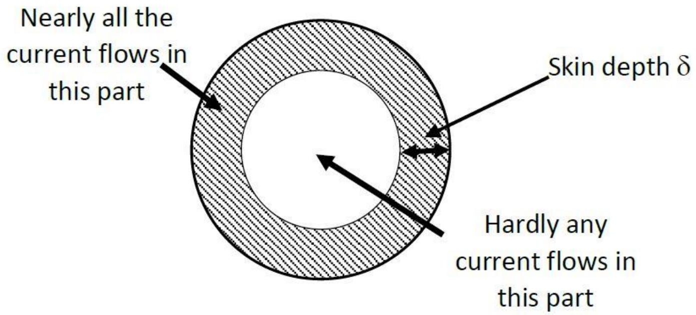
- We want to avoid saturating the magnetic core because this will result in the magnetising inductance reducing
  - This, in turn, will result in a high primary side current which may damage our MOSFETs

- In low frequency cores (50/60Hz) if you look at the magnetising current (no load current) it is sometimes quite non-linear
  - This is because designers often run into the high end of the flux density curve
  - This means the smallest possible core is used
  - Core losses are less of an issue at these frequencies

- At high frequencies the core loss can become significant if a high flux density is used
  - Data sheets/software for the material will give some ideas of the W/m^3 of material at different flux densities
  - It is not uncommon to run at a relatively low flux density as a result in order to maximise efficiency



What size wire?



Skin effect in circular wire

- In order to specify the required wire size we consider the current density in the wire
    - Usually anywhere between 2-8Amm^{-2} is considered
    - Obviously, the higher the value, the smaller the wire, the higher the loss
    - Clearly, all windings must be able to fit onto the bobbin too (it is impossible to fit this area 100%, search for *fill factor*)

- Unfortunately, at high frequencies, physics presents us with a new set of problems:
    - "Skin" and "Proximity" effects result in the current being bound onto the outside area of the wire
    - This means, at high frequency, the AC resistance of the wire becomes higher than at DC
    - This must be considered in the project for the main Forward Converter Transformer

- Issues with the aforementioned effects at high frequencies can be reduced by using *Litz* wire which is specially braided
    - This is expensive- we will not use it!
    - It's effect can be approximated by using several smaller wires, twisted together rather than a single wire for the winding

Winding layout: Gate Drive Transformer Example

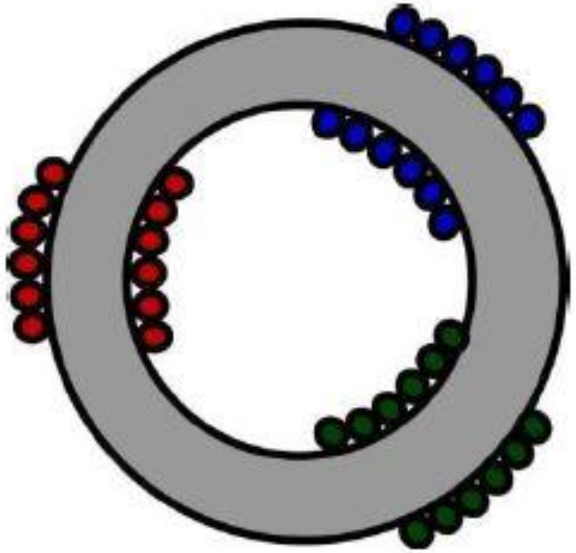


Figure 4a: Option 1: Put each winding separately spaced around the core

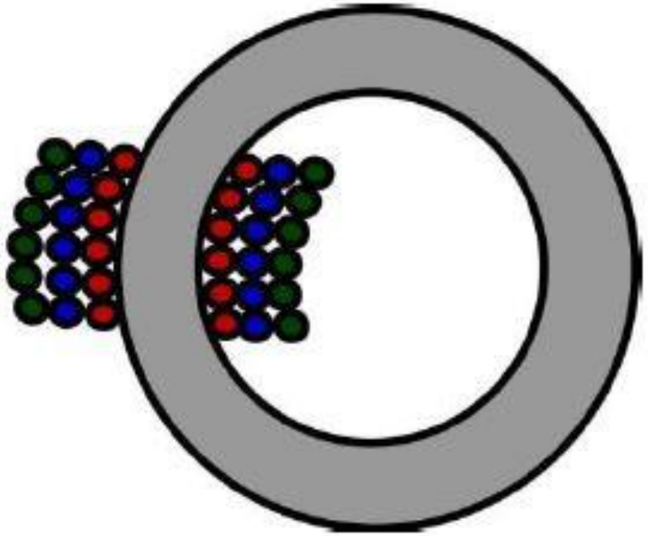


Figure 4b: Option 2: Put each winding on top of each other (note: turns could be distributed further around the transformer)

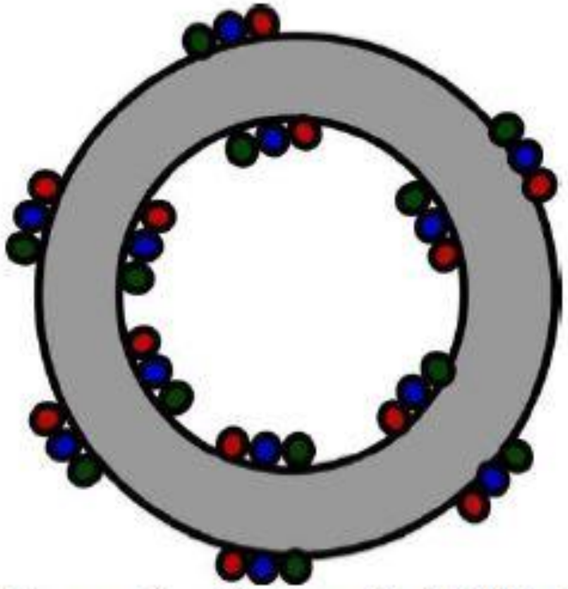


Figure 4c: Option 3: "Trifilar" wind the three windings together, next to each other at the same time

- Note: The arrangement of the winding has an impact on many things- the most important for our design is the leakage inductance. The gate drive circuit design (see earlier slide) assumes that there is none- **which configuration (above) do you think will have the lowest?**

Basic Inductor Design

Introduction

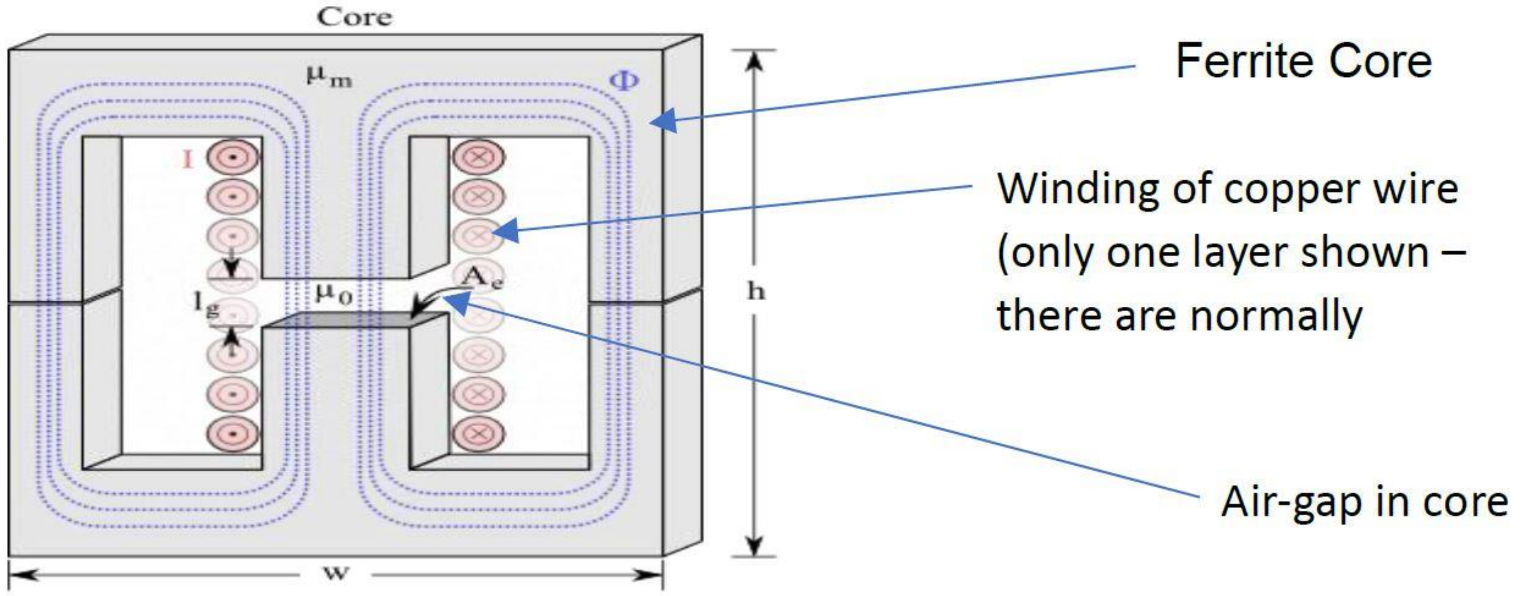
- From the design work that we do in the lab we determine the inductance value that we need in the output filter of our converter

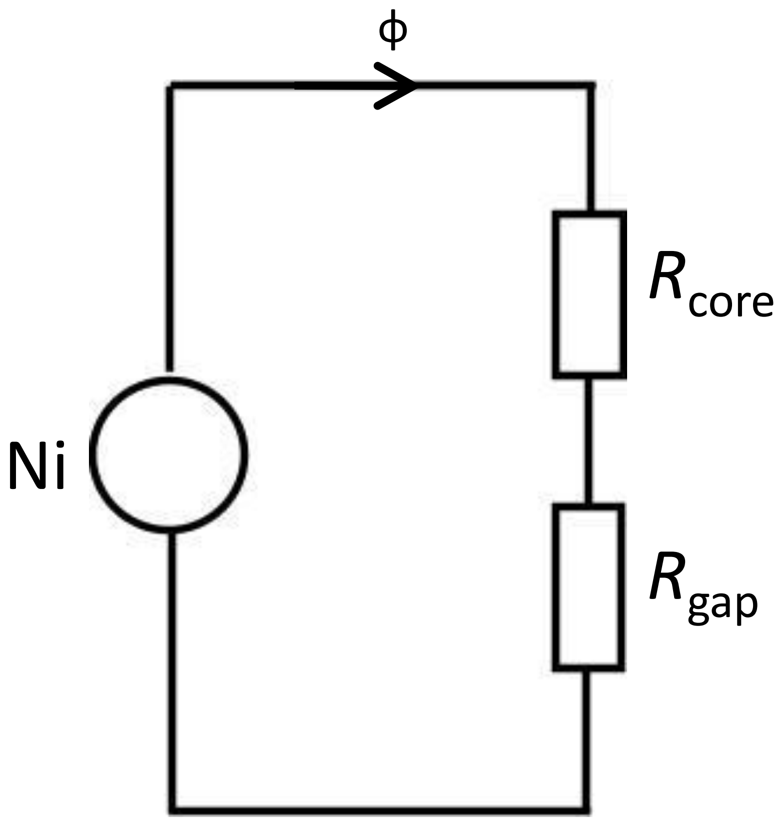
- Different to the transformer- the inductor has an air gap in the core… this is where the energy is stored

- We now need to calculate
  - The air gap length that we will use
  - The number of turns required to achieve the required inductance
    - Again, we want acceptable loss in the core (Efficiency)
    - We must avoid saturation of the core

- We also need to decide the size of wire we need
  - This has an impact on the resistance of the winding (i.e. winding loss- efficiency)
  - Clearly, as for the transformer, the wire must fit onto the core bobbin

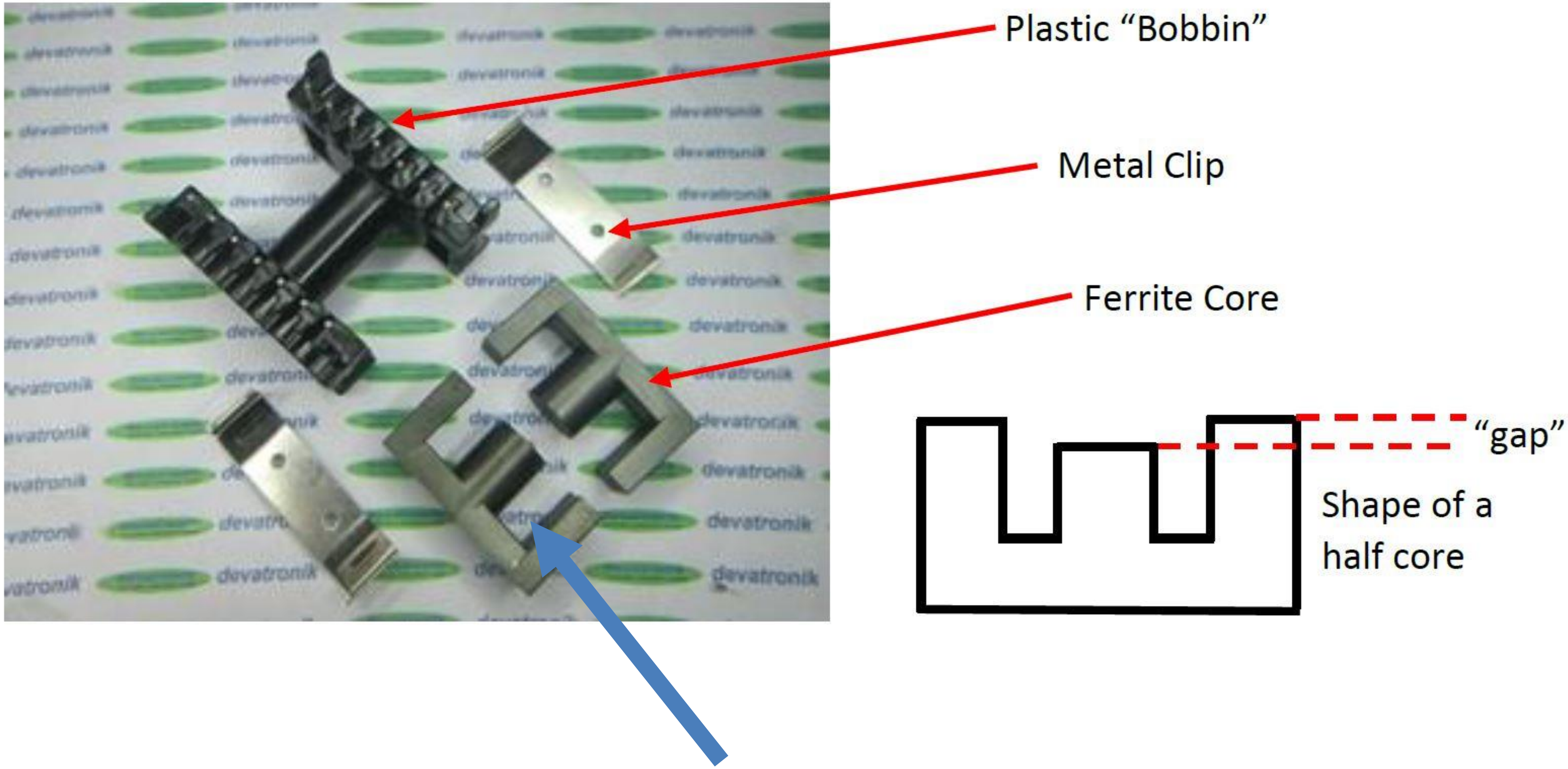
Inductor Basics





- Note the air gap in the EE core inductor above- different sizes of air gap can be obtained from the manufacturer
  - It is VERY difficult to cut an air gap yourself. Ferrite is a type of ceramic and can easily crack or shatter
  - Manufactured air gaps come in (for example) 0.5mm, 1mm, 1.5mm and 2mm
  - Note that reluctance R_{gap}>>R_{core} – sometimes this fact can be used to get a fast "paper design"

Example of an inductor core



Note: ETD Core- this is the type which we will use for inductor

- The centre limb is round, making it easier to wind onto

Simple Design Process for Inductor

$$L = \frac{N^2}{\Re}$$

This, you will find in your first year notes

For a magnetic path which is partly in the core and partly in the air-gap the reluctance $\Re$ is given by:

$$\Re = \frac{1}{A}\left[\frac{l_{core}}{\mu_r \mu_0} + \frac{g}{\mu_0}\right]$$

Derivation is simple, just add the gap and air Reluctance

Now looking at equation [4] in a bit more detail. μ_r is at least 1000 and even though l_{core} is greater than g, the term on the right-hand side dominates and we can assume that the gap accounts for nearly all of the reluctance (this is in fact that same as saying that most of the energy is stored in the gap). Ignoring the reluctance of the core we get a simple expression for the inductance (noting that μ_0 is $4\pi * 10^{-7}$).

$$L = \frac{N^2 \mu_0 A}{g} \rightarrow N = \sqrt{\frac{gL}{\mu_0 A}}$$

- Alternatively, the data sheet for the core may include an inductance factor, A_L
  - This can be used to calculate the number of turns required for a required inductance directly

Simple Design Process for Inductor II

Now we can start to see if the design is any good. The first thing to check is the peak flux density given by:

$$\hat{B}_{max} = \frac{\hat{\Phi}}{A} = \frac{L\hat{\imath}}{NA} = \frac{N\mu_0\hat{\imath}}{g} = \sqrt{\frac{\mu_0 L}{gA}}\,\hat{\imath}$$

For an inductor we really want to stay on the most linear part of the BH-Loop

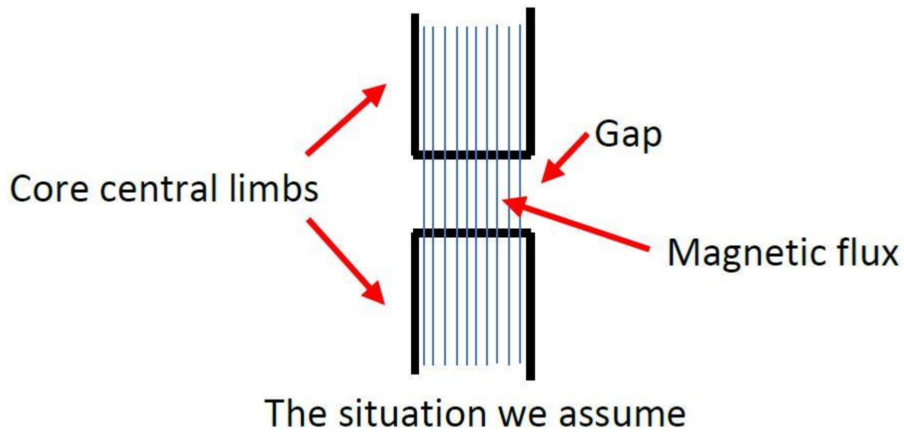
- This means that the inductance won't vary significantly as a function of current (i.e. μ will be constant)
- This variable L would have an impact on output ripple and the control system for the circuit (later)

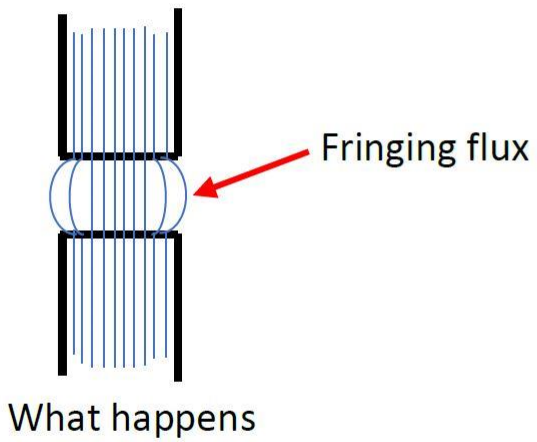
- If we find that B_{max} is too high for our peak current- we can increase the gap size and try again.

- If we can't get a core with our required gap- we need to use a bigger core
  - This may also become an iterative process

- Finally, if all is good, we need to select our wire (from current density) and it must fit on the bobbin- remember we cannot fill the area on the bobbin 100% (*fill factor*)

Fringing





- Fringing describes how the flux bulges out when flowing through the air gap
  - This flux can couple into the winding of the inductor, increasing losses
  - Fringing has the effect of making the air gap seem smaller (i.e. reduces reluctance)

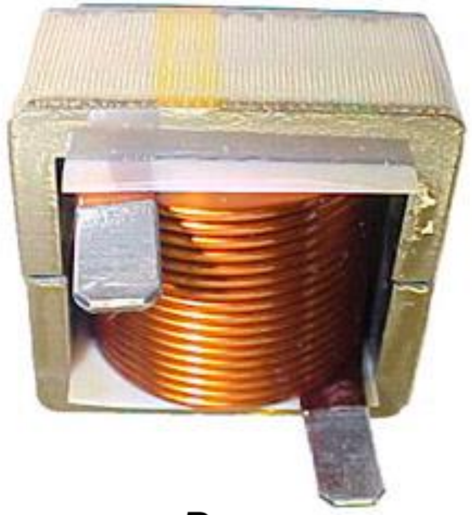
- The fringing flux will be small if we don't have a gap that is too large- this is partly why the available core gap sizes tend to be less than a few mm

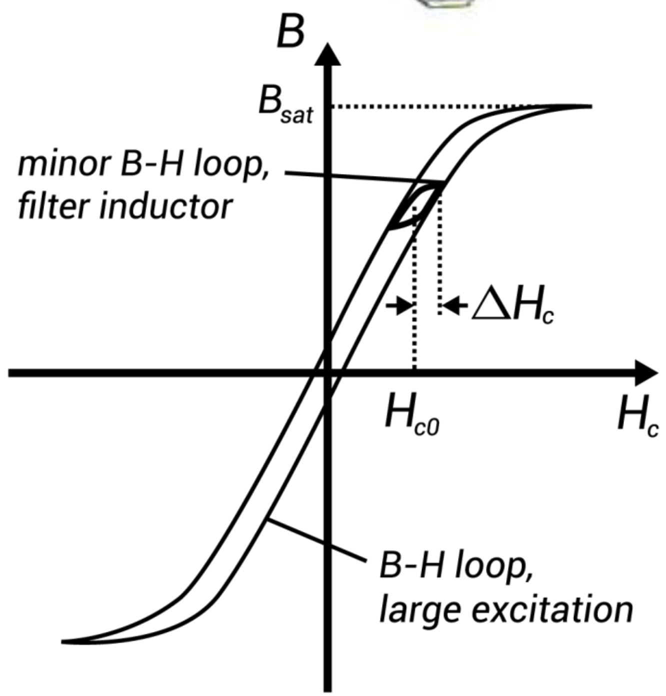
- If a large gap is required- magnetic cores can be built in pieces and the air gap is distributed across the whole core (keeping each gap small whilst achieving the required overall gap size)

Other considerations

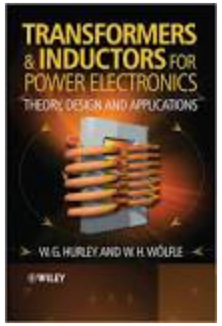
- As for the transformer we must still consider:
  - Core losses- is this exactly the same as the transformer case? Have a think about it (see figure on right…).
  - Skin Effect
  - Wire losses- is this exactly the same as the transformer case? Have a think about it.
  - The winding must fit on the bobbin
  - Etc.

- **The handouts on Moodle will help with this!**



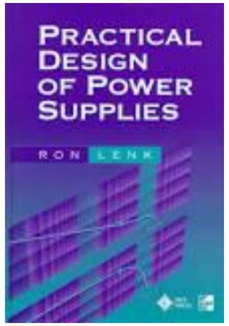


References

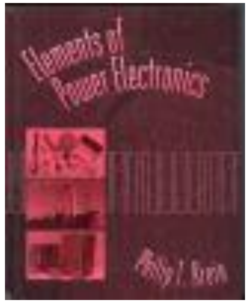


[1] Hurley and Wolfle “Transformers and Inductors for Power Electronics”, 2013
-Available in library- this is an excellent book

[2] Kazmierczuk, “High Frequency Magnetic Components”, 2014
-Good book for theory- lots of equations and calculus ☹



[3] Lenk, “Practical Design of Power Supplies”, 2005
-Very accessible, design focussed



[4] Krein, “Elements of Power Electronics”, 1998
-Excellent book on power electronics, has a good magnetics chapter

There are lots of other good books/resources in the library as well as online

EEEE2046: Energy Project 22/23
Magnetic Components

Questions???