Power Electronics

Day 9 -- Magnetics

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Introduction to Magnetics

- First, notation:

$$\oint_s \varepsilon \mathbf{E} \cdot d\mathbf{s} = \int_v \rho_v \, dv$$ Gauss' Law

$$\oint_s \mathbf{B} \cdot d\mathbf{s} = 0$$ Gauss' Law (magnetic fields)

$$\oint_\ell \mathbf{E} \cdot d\ell = \frac{-d}{dt} \int_s \mathbf{B} \cdot d\mathbf{s}$$ Faraday's Law

$$\oint_\ell \mathbf{H} \cdot d\ell = \int_s \mathbf{J} \cdot d\mathbf{s} + \frac{\partial}{\partial t} \int_s \varepsilon \mathbf{E} \cdot d\mathbf{s}$$ Ampere's Law

$$\oint_s \mathbf{J} \cdot d\mathbf{s} = \frac{-d}{dt} \int_v \rho_v \, dv$$ Conservation of charge

Magnetic Field System

- In almost any converter, the electric fields are not large.
- The currents are likely to be considerable.
- This supports simplification.
- The displacement current term in Ampere's Law can be ignored.

Magnetic Field System

- We also define flux ϕ.

$$\int_s \mathbf{B}\cdot d\mathbf{s} = \varphi$$ Definition of flux

$$\oint_s \mathbf{B} \cdot d\mathbf{s} = 0$$ Gauss' Law (magnetic fields)

$$\oint_\ell \mathbf{E}\cdot d\ell = \frac{-d}{dt}\int_s \mathbf{B}\cdot d\mathbf{s}$$ Faraday's Law

$$\oint_\ell \mathbf{H} \cdot d\ell = \int_s \mathbf{J} \cdot d\mathbf{s}$$ Ampere's Law

Materials

- Permeability μ.
- Vacuum has $\mu_0 = 4\pi \times 10^{-7}$ H/m.
- Materials:
  - Diamagnetic → $\mu < \mu_0$
  - Paramagnetic → $\mu > \mu_0$
  - Ferromagnetic → $\mu >> \mu_0$
  - Superconductors → $\mu \sim 0$
- Diamagnetic and paramagnetic materials are still close to μ_0.

Materials

- We are interested in ferromagnetic materials for applications in devices, since they are much different from air or conductors.
- Superconductors are also of interest (future converters).

Materials

- Ferromagnetic elements
  - Iron, nickel, cobalt
  - Some rare earths: gadolinium, dysprosium (but low Curie temperature)
- Compounds
  - Chromium oxide
  - Oxides of iron, nickel, …
- Alloys
  - Manganese, aluminum, zinc, rare earths, …

Materials

- Most common for us:
  - Magnetic steels (good for low frequency)
  - Ferrites (magnetic oxides mixed and assembled in ceramic form)
  - Pure powdered iron in a ceramic matrix.
  - Other powdered alloys.
- Others of interest:
  - Permanent magnets: samarium cobalt, neodymium-iron-boron, ferrites
  - High-temperature superconductors

Magnetic Circuits

- Faraday's Law is KVL if we *define* a changing flux $d\phi/dt$ as voltage (EMF).
- Ampere's Law looks similar, if the term on the right side is defined as MMF.

$$\oint_{\ell} \mathbf{H} \cdot d\mathbf{l} = \int_{s} \mathbf{J} \cdot d\mathbf{s} .$$

Magnetic Circuits

- KVL: $$\sum_{loop} EMF = 0$$

- Ampere: $$\sum_{loop} MMF = 0$$

Magnetic Circuits

- Ampere’s Law becomes like a “KVL for MMF.”
- Gauss’ Law (magnetic fields) becomes like “KCL for flux.”
- We take MMF as a forcing variable and flux as a flow variable.

Magnetic Circuits

- Gauss' Law

$$\oint_s B \cdot ds = 0$$

- Define a "flux node."

$$\sum_{closed\ region} \phi = 0$$

- We have:

$$\sum_{node} \phi = 0$$

- This is like "KCL for flux."

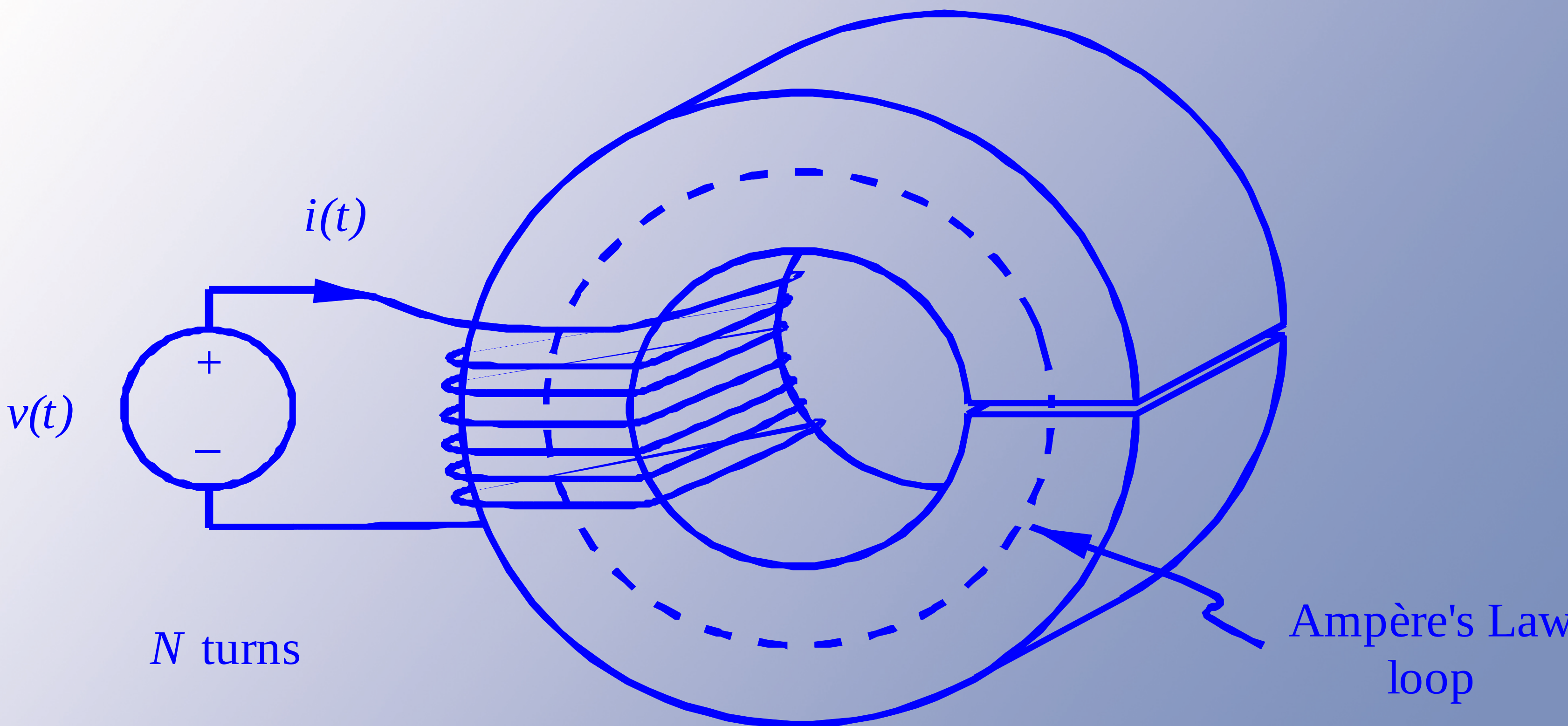
Magnetic Circuits

- Ampere's Law acts like "KVL for MMF."
- Gauss' Law (magnetic fields) acts like "KCL for flux."
- This supports a "magnetic circuit" simplification of the equations.
- First, the equations directly.

Inductance

- A coil of wire around a ferromagnetic core.
- Faraday's Law: Voltage applied to the coil should produce a rate of change of flux.
- Ampere's Law: Current produces MMF.

Coil on a Core



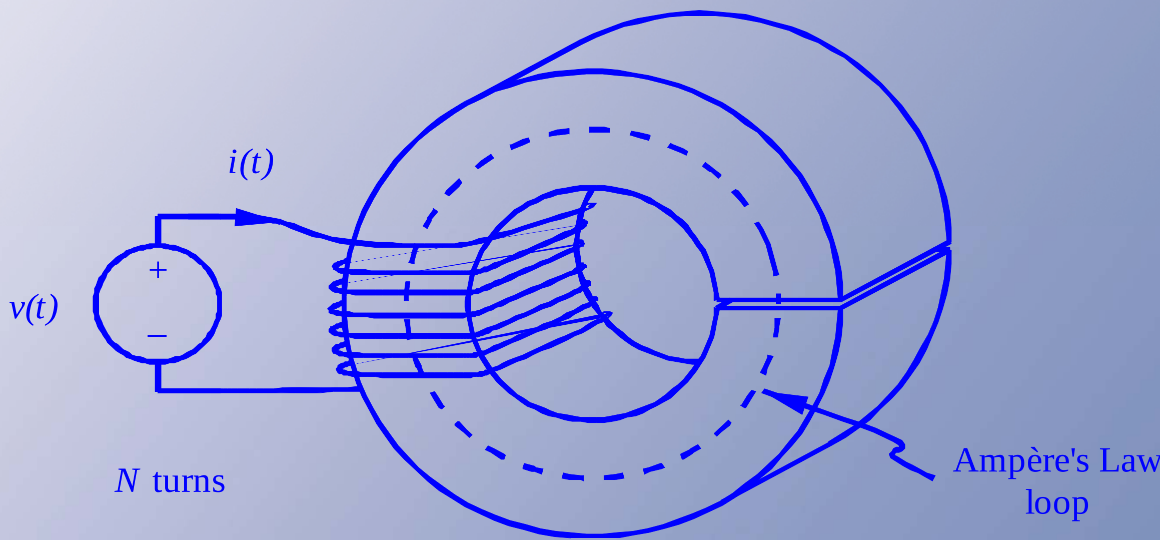
- Faraday’s Law: loop is the wire.
- Ampere’s Law: loop is in the core.

Inductance

- Write Faraday's Law and Ampere's Law for this arrangement.
- We define flux linkage, λ, as $N\phi$.
- Faraday's Law can be written in a tighter notation: $v_{in} = d\lambda/dt$.

Ampere’s Law

- For Ampere’s Law, we can draw a loop through the center of the core.
- Assuming (arbitrarily for now) that H is the same throughout the core, the integrals become $H_{core}\ell_{core} + H_{air}\ell_{air} = Ni$, and $\mu H = B$.



Ampere's Law

- Re-write in terms of ϕ (we're ultimately trying to link Ampere's Law and Faraday's Law). $B_{core}\ell_{core}/\mu_{core} + B_{air}\ell_{air}/\mu_{air} = Ni$.
- But $\phi = B\,A$, with A as the cross-section area.
- $\phi_{core}\ell_{core}/(\mu_{core}A_{core}) + \phi_{air}\ell_{air}/(\mu_{air}A_{air}) = Ni$.

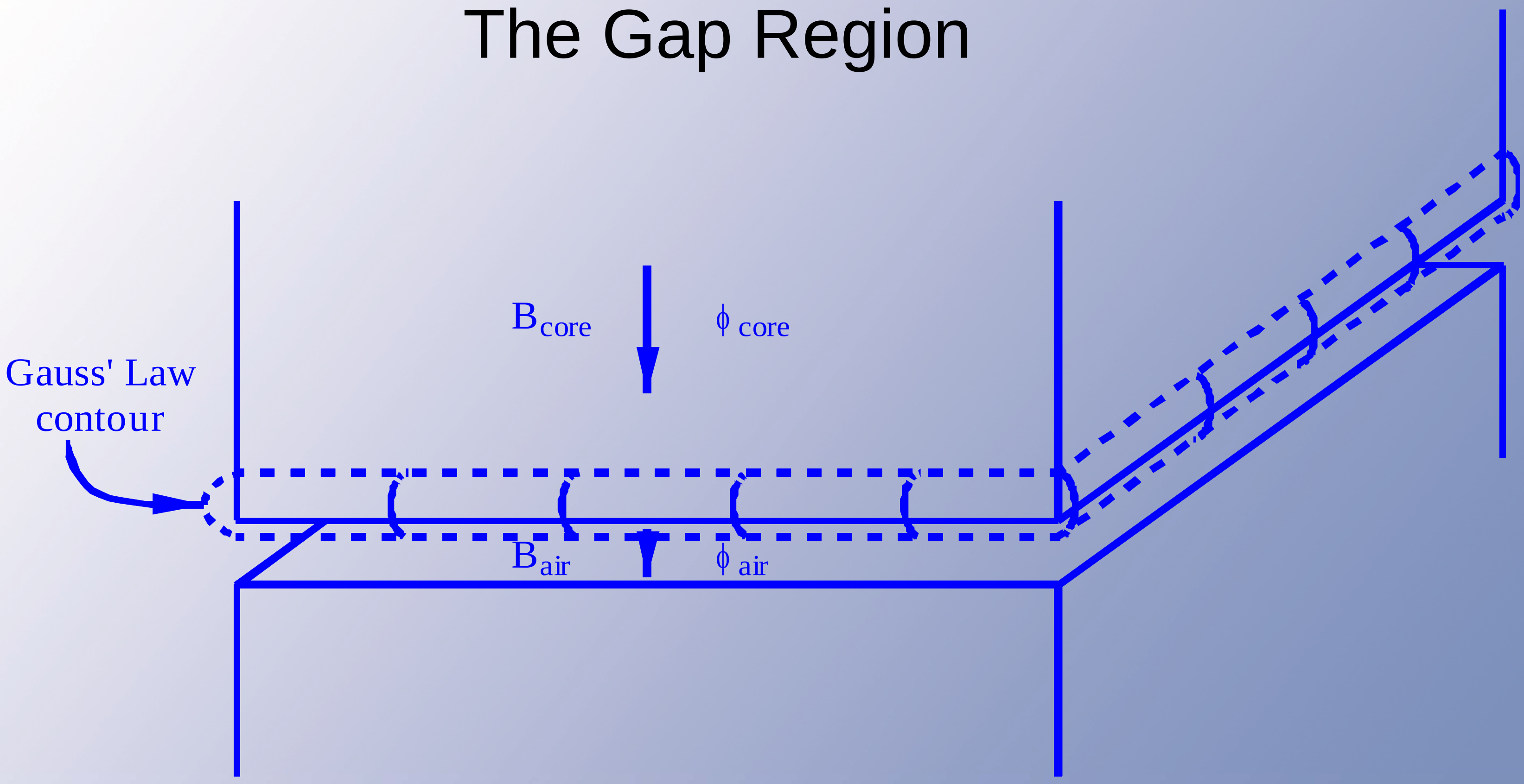
Reluctance

- We define reluctance, $\mathcal{R}$, as $\ell/(\mu A)$ for a material.
- This means $\phi_{core}\mathcal{R}_{core} + \phi_{air}\mathcal{R}_{air} = Ni$.
- Now, the magnetic circuit idea: Since ϕ is flow and MMF = Ni is forcing, the $\phi\mathcal{R}$ terms are an "MMF drop," and Ni is an "MMF source."

Flux Relations

- But two fluxes appear. Can we relate them?
- Define a “node:” the end of the core as it interfaces with the air gap.
- This region meets Gauss’ Law.

The Gap Region



- Gauss' Law applies to the dotted volume.

Flux Relations

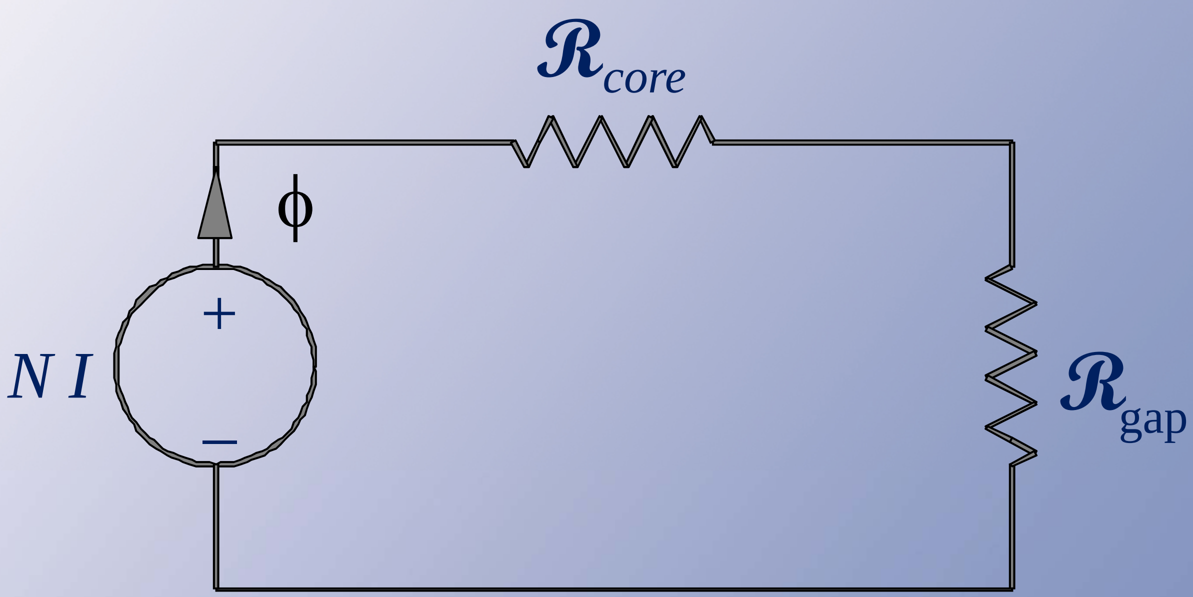
- If a very thin region is used, the total flux entering its surface is $B_{core}A_{core} - B_{air}A_{air} = 0$.
- These are the fluxes $\phi_{core} - \phi_{air} = 0$.
- Thus Gauss' Law means there is only one flux, ϕ.
- Now $\phi(\mathcal{R}_{core} + \mathcal{R}_{air}) = Ni$, or $\phi\mathcal{R}_{tot} = Ni$.

Back to Faraday's Law

- Take time derivatives. Reluctance is constant. $\mathcal{R}_{tot} d\phi/dt = N\, di/dt$, and $\lambda = N\phi$.
- Rewrite: $d\lambda/dt = N^2/\mathcal{R}_{tot}\, di/dt$.
- The coil voltage is related to current as $v_{in} = N^2/\mathcal{R}\ di/dt$.
- $N^2/\mathcal{R}$ defines an inductance, L.
- Manufacturers provide a per-unit inductance, A_L equal to $1/\mathcal{R}$. Typical values: nanohenries per turn^2.

Magnetic Circuit

- The equations we built can be represented with a circuit:



Magnetic Circuits

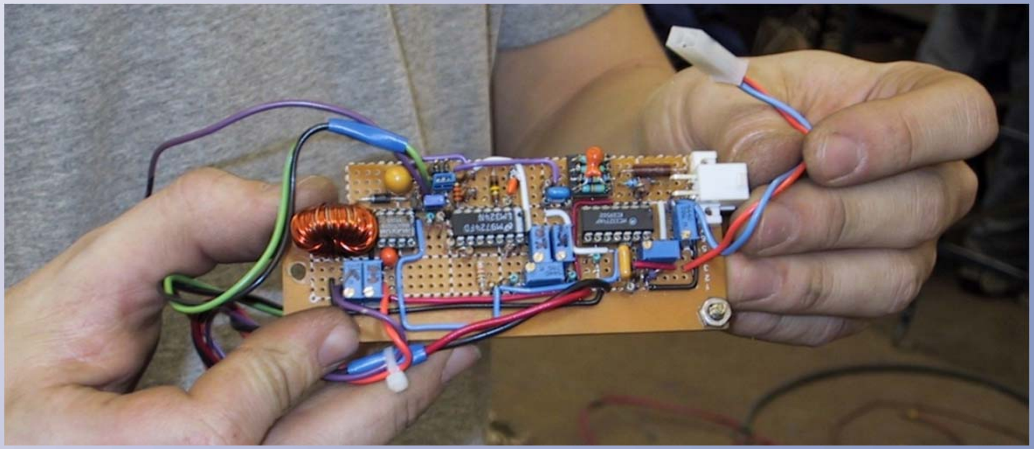
- Magnetic structures can be constructed as reluctance circuits of this type.
- This supports identification of inductance and analysis of devices.
- It does not model any losses.

Reluctance

- The magnetic circuit analogue relations are given in Table 12.2.
- A “magnetic conductor” has high permeability and low reluctance.
- A “magnetic insulator” has high reluctance.

Limitations

- In electric circuits, the conductors are very good, and the insulators are nearly perfect.
- The ratio of resistance in a circuit to resistance of the insulation can be lower than 10^{-20}.



- This is not true in magnetics.

Limitations

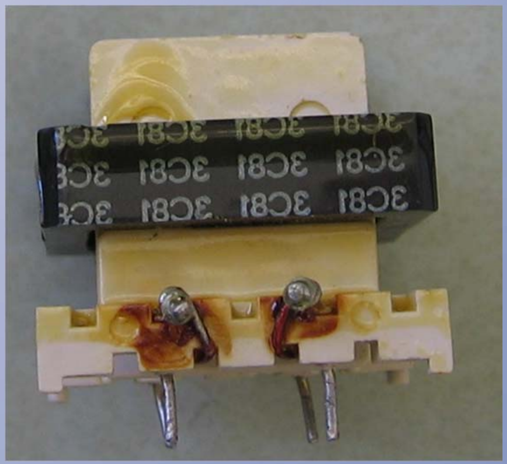
- The reluctance ratio between a core and the surroundings can be more than 10^{-3}, and is rarely smaller than 10^{-5}.
- This is like taking the insulation off a circuit and operating it in a pail of salt water.

Leakage

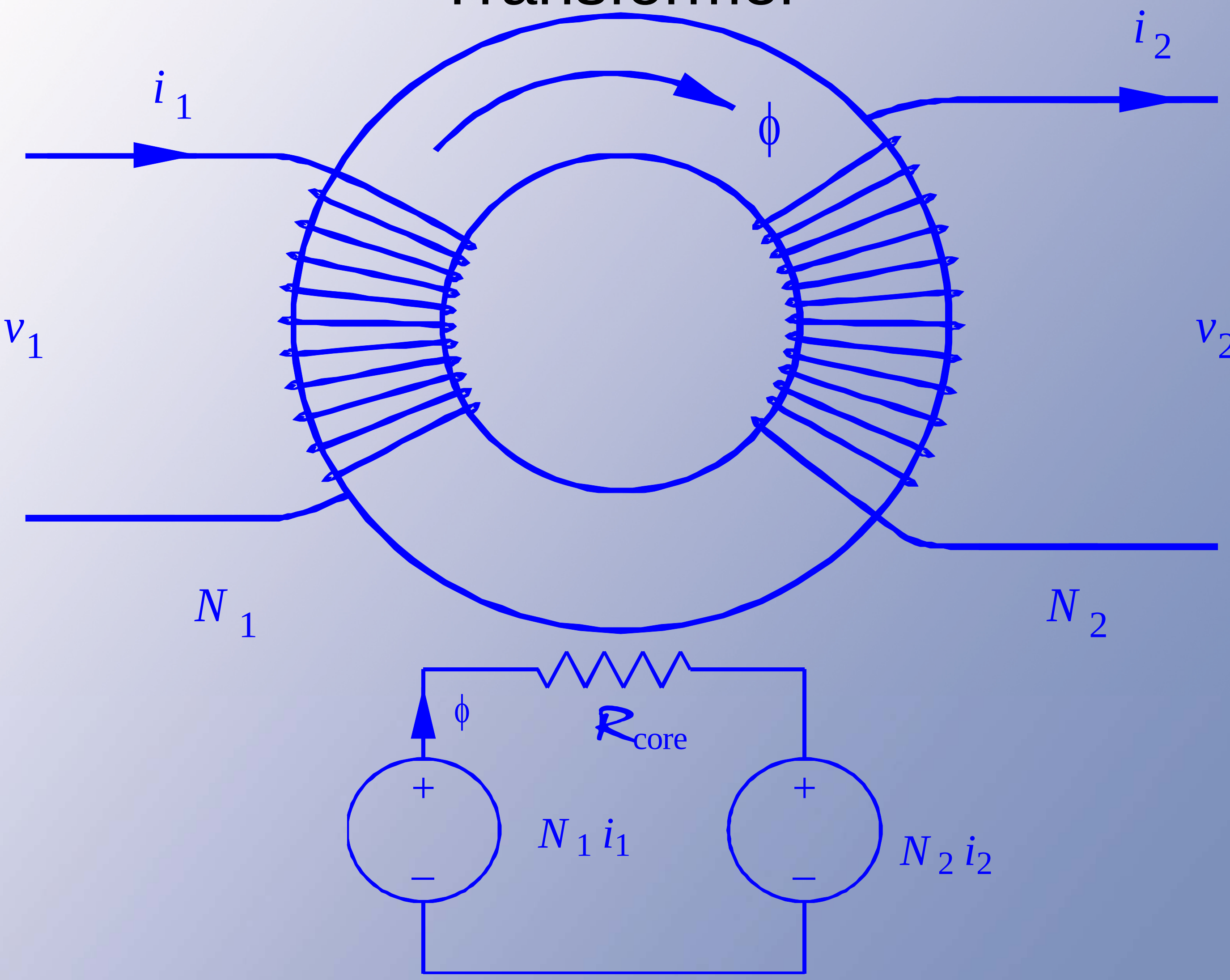
- This analogy suggests that much of the flux leaks out into the surroundings.
- Leakage is an important issue.
- Also, the value μ_{core} comes from a nonlinear relation, and is not constant.

Transformers

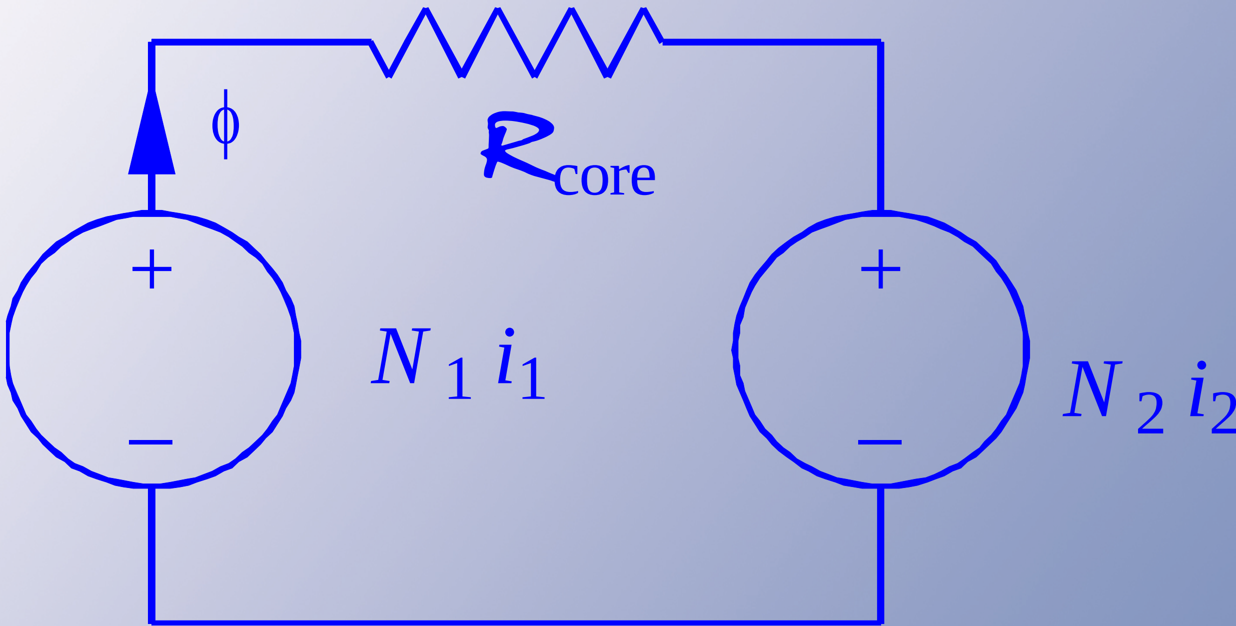
- A transformer has two windings, and the net MMF balances the reluctance MMF drop.
- If core reluctance is very low, there is an MMF balance, $N_1 i_1 = N_2 i_2$. With flux ϕ, the voltages are $v_1 = N_1\, d\phi/dt$, $v_2 = N_2\, d\phi/dt$.



Transformer



Transformer

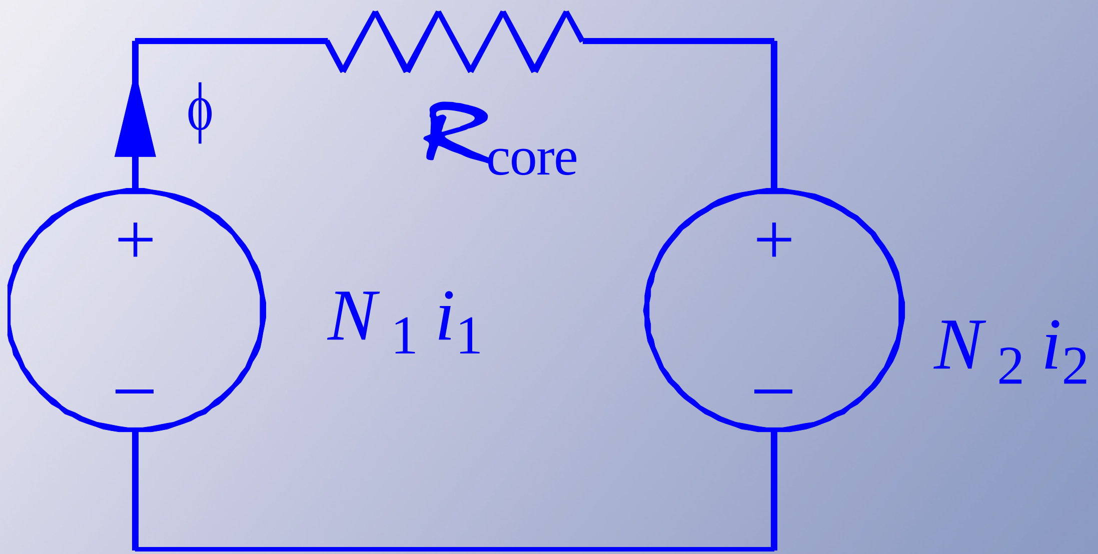


- Ideal case requires $N_1 i_1 = N_2 i_2$.
- $v_1 = d\lambda_1/dt = N_1\ d\phi/dt$
- $v_2 = d\lambda_2/dt = N_2\ d\phi/dt$

Ideal Case

- If the derivative $d\phi/dt$ is nonzero, the voltage ratio $v_1/v_2 = N_1/N_2$.
- A very low reluctance core yields an ideal (but ac) transformer.
- The reality is that reluctance is nonzero, and flux flows even if i_2 is set to zero.

Transformer



- Real case: $N_1 i_1 \neq N_2 i_2$.
- There is an "MMF drop," associated with the magnetizing inductance.

Ideal Coupled L

- The nonzero reluctance yields inductance $L_1 = N_1^2/\mathcal{R}$, seen from the #1 side, and $L_2 = N_2^2/\mathcal{R}$, seen from the #2 side.
- This supports the coupled inductor application for flyback converters.

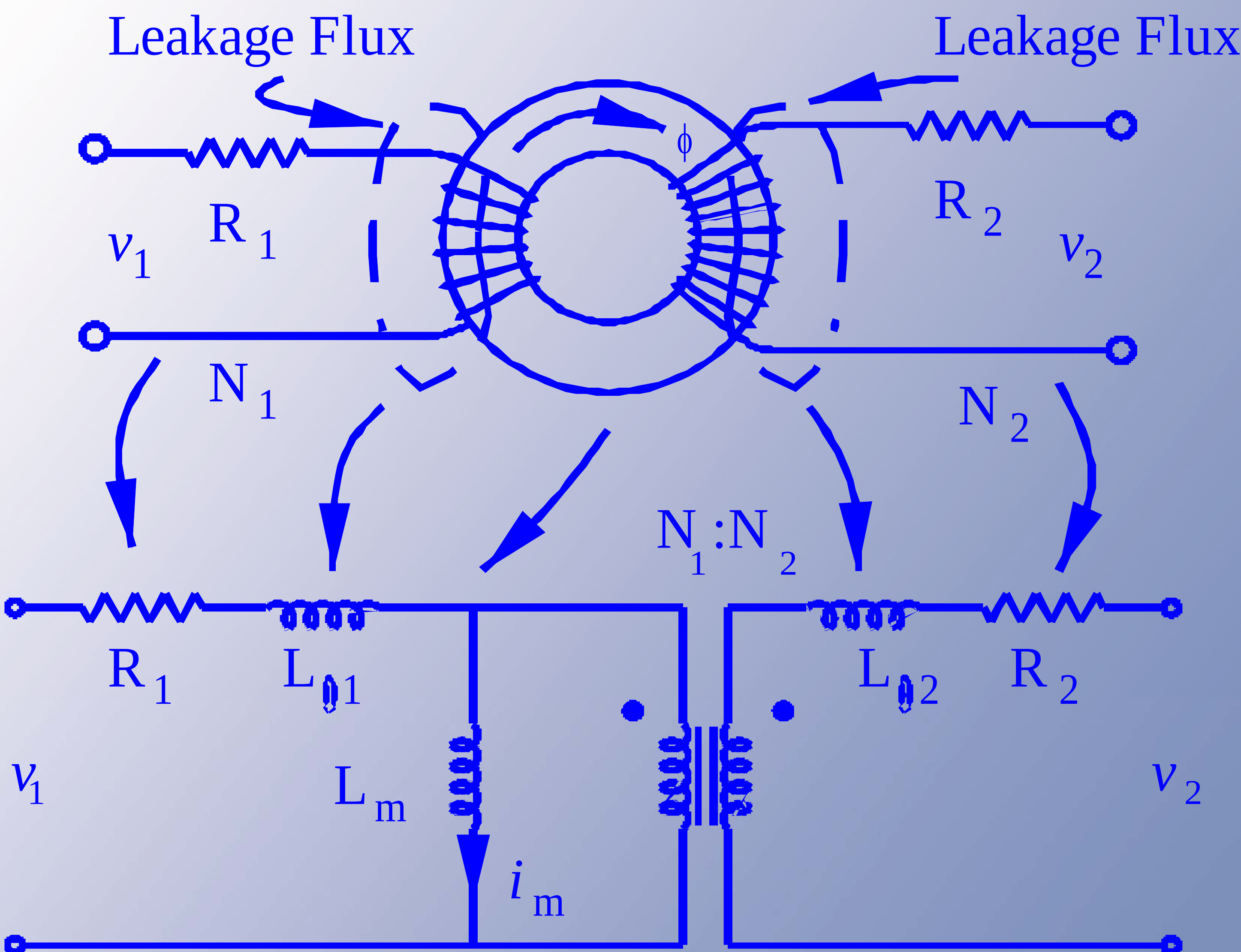
Ideal Cases

- An ideal transformer has low reluctance. No stored energy.
- An ideal coupled inductor has significant reluctance, but no other effects. This is the *magnetizing inductance*, and it can store energy.

Real Cases

- The cores must be wound with wire -- series resistance is introduced.
- There is leakage flux, and such flux flows through its own reluctance path, forming an inductance.

Device Circuit Model



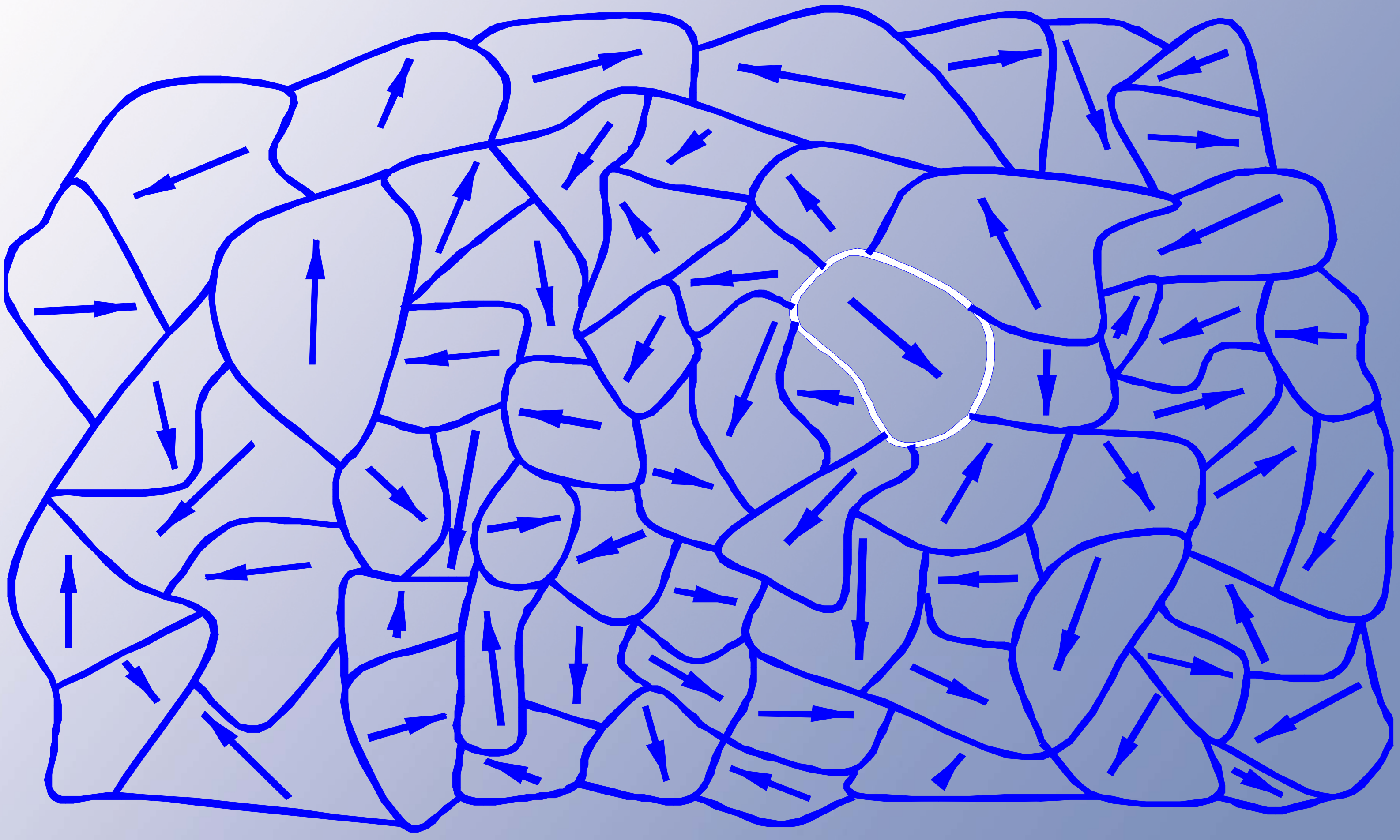
Some Points

- The resistances are rarely negligible, since limited space means limited copper.
- The leakage can be low, but it still introduces “stray” stored energy.
- This does not model losses in the core itself.

Hysteresis

- For ferromagnetic materials, the basis of high permeability is inherently nonlinear.
- The process is not entirely reversible.
- This hysteresis effect gives rise to losses.

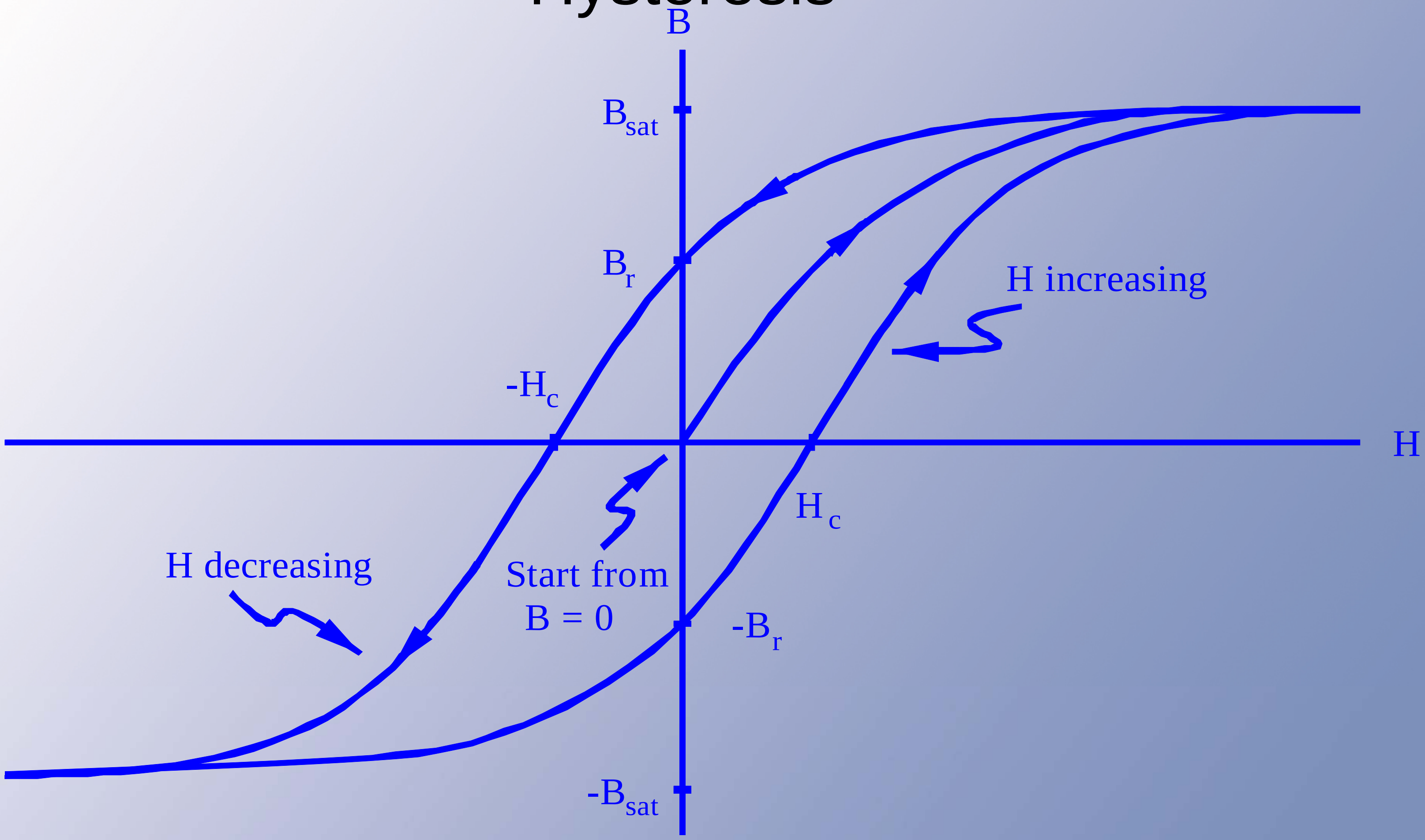
Domain Alignment



Hysteresis

- Since domains are a large group of atoms that align together, small MMF changes yield large flux changes.
- This implies high μ values.
- But it is nonlinear: once domains are aligned, they cannot add much more flux.

Hysteresis


B
B_{sat}
B_r
$-H_c$
H
H_c
H increasing
H decreasing
Start from
B = 0
$-B_r$
$-B_{sat}$

Hysteresis

- The units within the loop (B x H) are energy per unit volume.
- A certain energy (per unit volume) is lost each time the loop is traversed.
- At a frequency f, there is a power loss of f times the loss represented by the loop.

Hysteresis

- With hysteresis, we see that a real magnetic device has loss within the core.
- In addition, the core is a little bit conductive, which leads to internal i_2R loss.

Basis of Losses

- There are losses in windings ("copper losses") and losses in the magnetic core.
- Domain alignment irreversibility: gives hysteresis loss each time around the loop. This is approximately proportional to frequency.
- Eddy current losses: The field induces current within the core.

Basis of Losses

- Steel cores are built with thin, insulated, layers to reduce conductive path lengths.
- These lamination methods work adequately up to a few kHz.
- For higher frequencies, poorly conducting ceramics (ferrites) are a better solution.
- Ferrites can function to several MHz.

Basis of Losses

- Eddy current loss depends both on field strength and on frequency.
- Since v = NA dB/dt, and loss depends on v^2, we expect losses proportional to B^2 and to f^2.

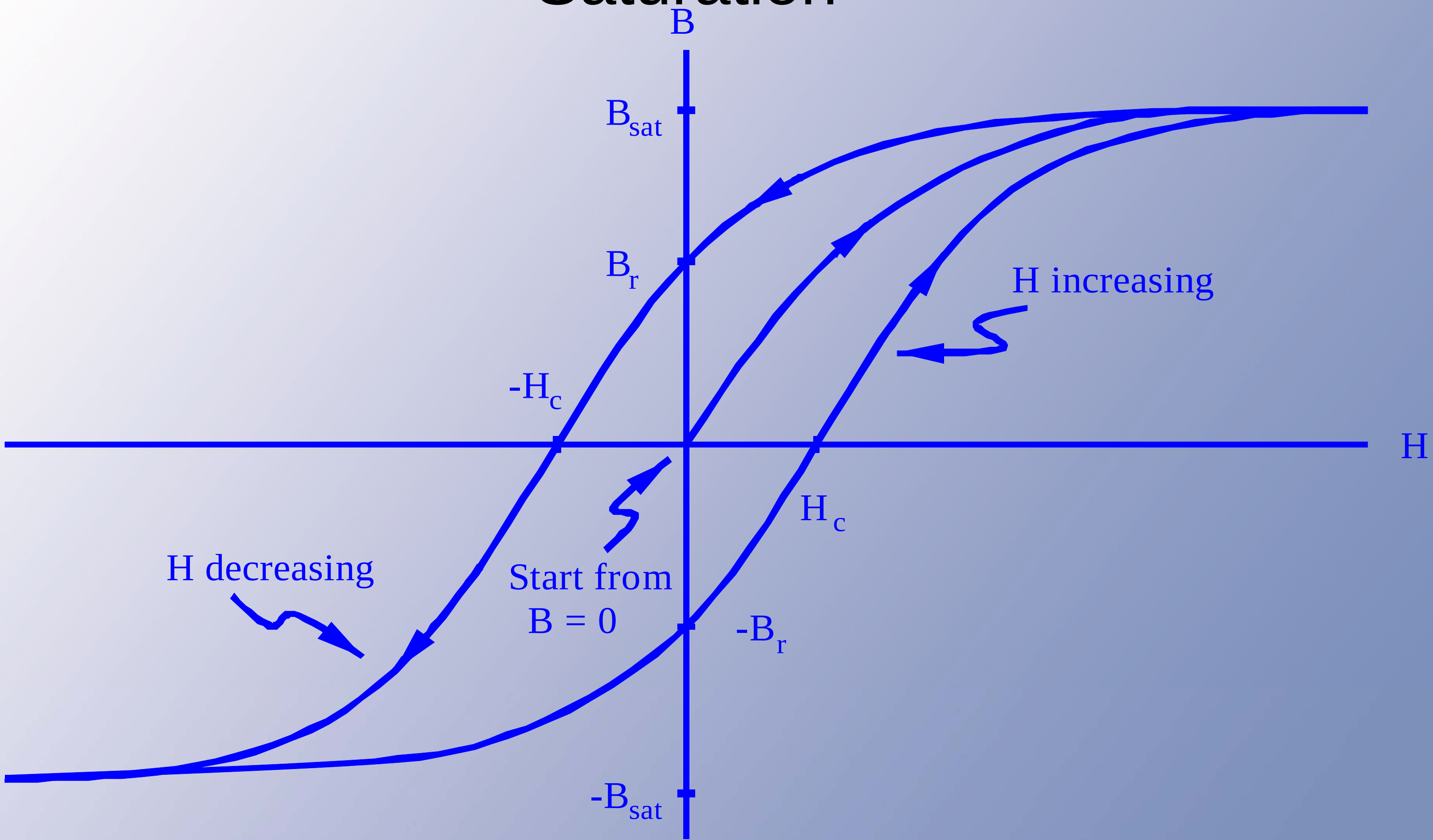
Core Loss Summary

- Loss in the core is given by $P_{loss} = P_0 f^{\alpha} B^{\beta}$, where α and β are material constants (from measurements).
- Ideally α should be between 1 and 2 and $\beta = 2$, but the reality is a bit worse.
- Example: 3F3 ferrite material has $\alpha = 1.4$, $\beta = 2.4$.

Saturation

- What happens in saturation? At high B levels, the permeability drops toward μ_0.
- The core becomes “transparent” and acts like the surrounding air.
- Little additional energy is stored.

Saturation


B
B$_{sat}$
B$_r$
-H$_c$
H increasing
H
H$_c$
H decreasing
Start from
B = 0
-B$_r$
-B$_{sat}$

Saturation

We avoid saturation for at least three reasons:

1. If the core is invisible, why use it?
2. With little extra stored energy, saturation is not helpful.
3. The inductance drops a lot, and usually currents rise excessively.

Saturation and Flux

- For steel and iron, the saturation level exceeds 1.5 T (1.5 Wb/m^2).
- For ferrites, the saturation level is about 0.35 T.
- In design, we often use 1 T and 0.3 T, respectively.
- Therefore, we have a definite value B_{sat} that must be considered in design.

Finding Flux Density

- For design, we want $B < B_{sat}$.
- The flux is MMF/reluctance.
- In a single-winding core, $\phi = Ni/\mathcal{R}$.
- Flux density $B = \phi/A$, $B = Ni/(\mathcal{R}A)$.
- We want $B < B_{sat}$, so $Ni/(\mathcal{R}A) < B_{sat}$.
- There is an MMF limit:

$$Ni < B_{sat}\mathcal{R}A.$$

Amp-Turn Limit

- So we have an amp-turn limit, $Ni < B_{sat}\mathcal{R}A$.
- With $\mathcal{R} = \ell/(\mu A)$, this gives $Ni < B_{sat}\,\ell/\mu$.

- What are the implications for energy storage? $\frac{1}{2} L i^2$ now is limited since current has a limit.

Energy Limit

- Since $L = N^2/\mathcal{R}$, the stored energy $\frac{1}{2} Li^2$ is given by $\frac{1}{2} N^2 i^2/\mathcal{R}$.
- At maximum Ni, we have $W_{max} = \frac{1}{2} (Ni)_{max}^2/\mathcal{R}$, with $Ni_{max} = B_{sat}\mathcal{R}A$.
- Therefore $W_{max} = \frac{1}{2} B_{sat}^2 \mathcal{R}A^2$.
- Simplify: $W_{max} = \frac{1}{2} B_{sat}^2 \ell A/\mu$.

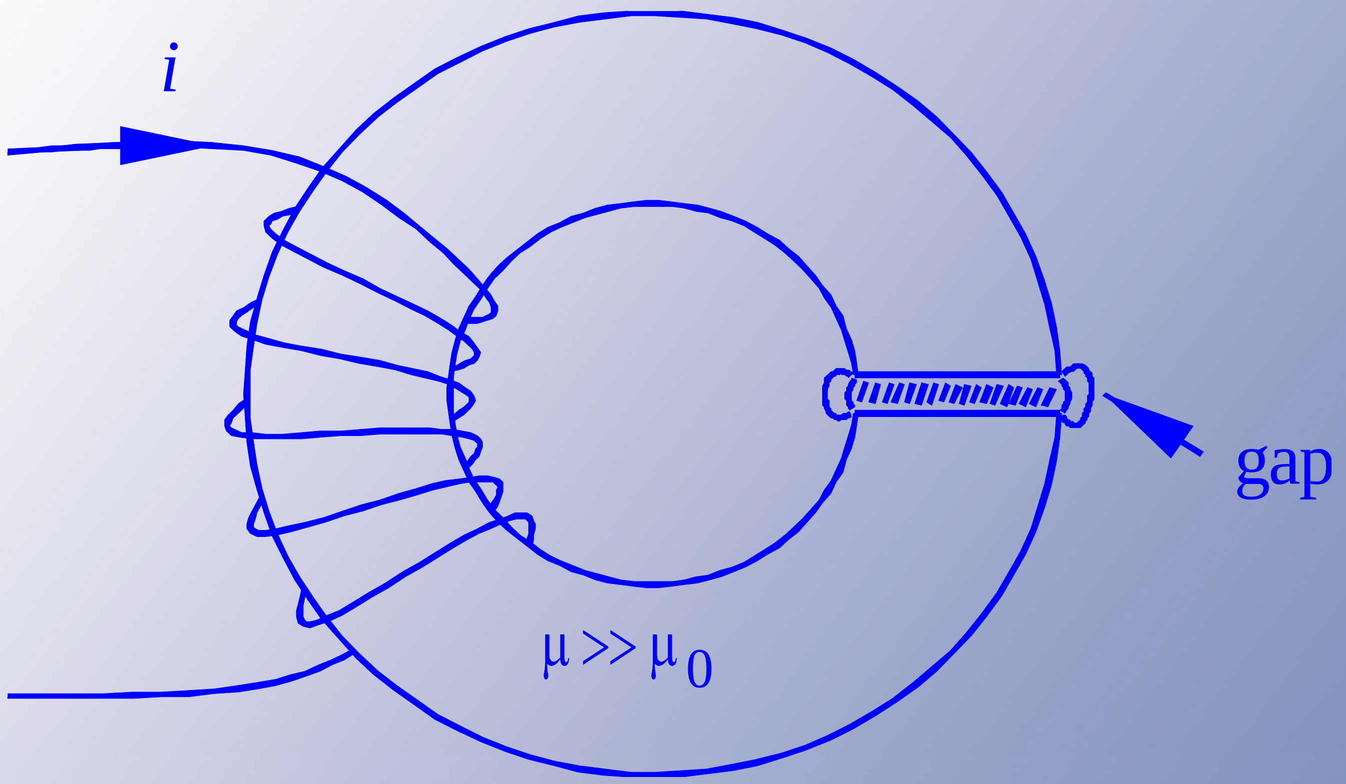
Energy Limit

- Interesting: Higher reluctance (lower permeability) leads to higher energy.
- Since ℓA is the core volume, storage is proportional to volume.

Storage

- Inductors nearly always have air gaps, which act as the energy storage region.
- The maximum energy relation can be used to determine air gap volume, and to estimate total core volume.

Storage



- Since $\mu >> \mu_0$, almost all energy storage is inside the gap volume.

Storage

- Stored energy in an air gap: $W_{max} = ½\ B_{sat}^2\ Vol_{gap}/\mu_0$.
- Consider 1 mH, 20 A inductor with a ferrite core. Then B < 0.3 T.
- The target stored energy is 0.2 J.
- The gap volume should be $(0.2\ J)(4\pi \times 10^{-7}\ H/m)(2)/(0.3\ T)^2 = 5.59 \times 10^{-6}\ m^3$.
- The gap volume should be about 6 cm^3.

Storage

- Since the gap volume is a small fraction of the core volume, this translates to a core that is many cm^3 in size.
- We could just use an air core, but this makes all the flux leakage flux, and couples it into the outside world.
- It is hard to make substantial L values with an air core.

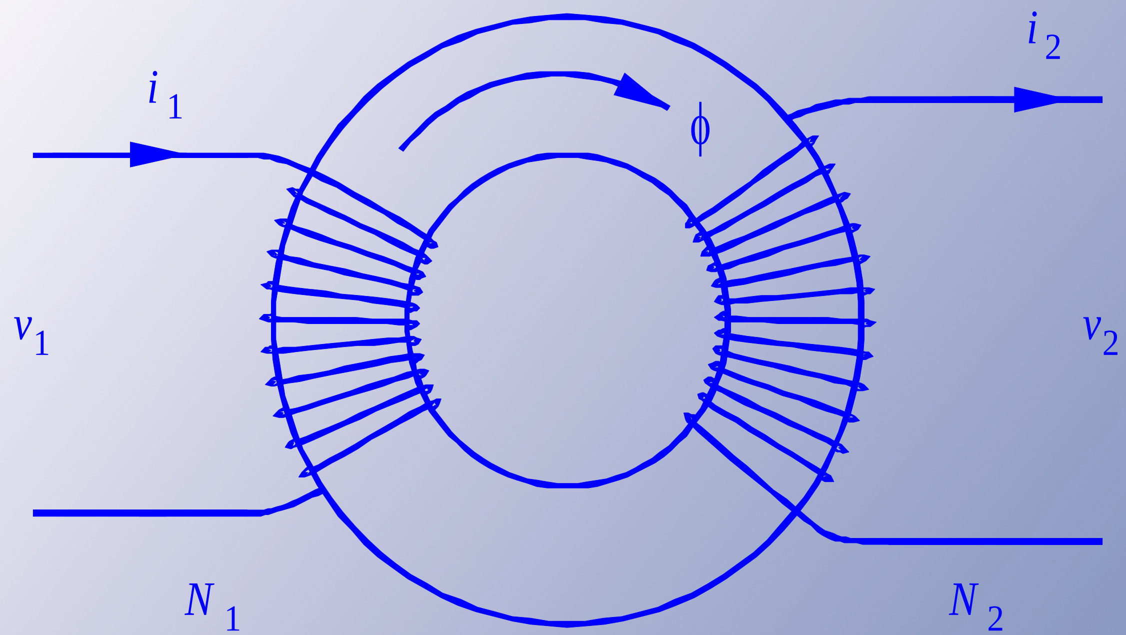
Design Issues

- Two design issues so far:
  - An amp-turn limit.
  - A gap volume for energy storage (which also implies a core volume.

Other Limits

- In transformers, the amp-turn limit is not really useful, since there are multiple windings acting together.
- In any case, $v = d\lambda/dt$, so $\lambda = \int v\, dt$.
- This is related: $\lambda = N\phi = NBA$.

Transformer Limits



- Given ϕ, $v_1 = d\lambda_1/dt = N_1 d\phi/dt = N_1 A\ dB/dt$.
- So $\int v_1\ dt = N_1 AB$, $B < B_{sat}$.

Volt-Second Limit

- The integral $\int (v\,dt)/(NA) < B_{sat}$ represents a *volt-second limit*.
- For square waves, with piecewise-constant voltage, this is clear:
  $(V\,\Delta t)/(NA) < B_{sat}$, or $V\,\Delta t < B_{sat}NA$.
- For sinusoidal voltages, $v = V_0\cos(\omega t)$; the integral becomes $V_0/(\omega NA) < B_{sat}$.
- The limit $V_0/N < \omega B_{sat}A$ is called a *volts per turn limit*.

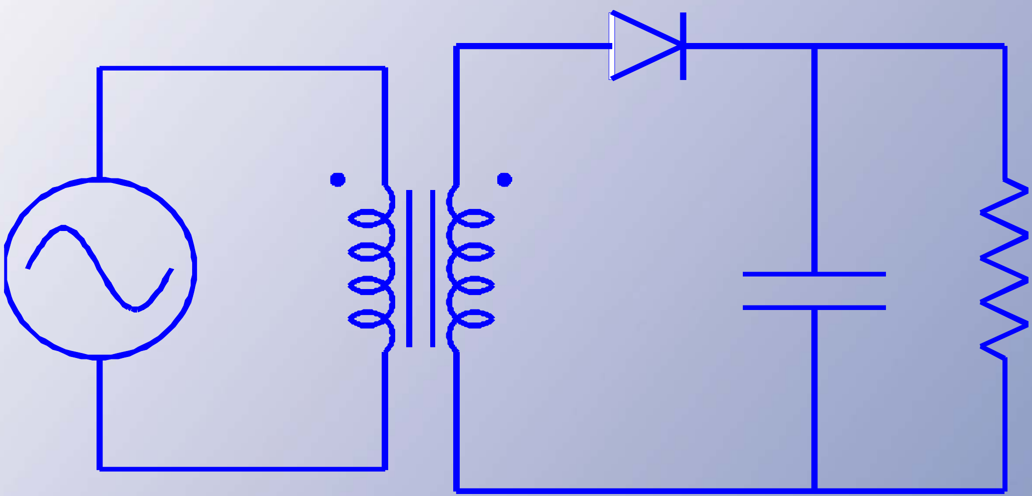
Limits So Far

- All these limits reflect a single issue: maintain $B < B_{sat}$.
- The implications include:
  - A current limit, $Ni < B_{sat}\mathcal{R}A$.
  - A volt-second limit, $\int (v\,dt) < B_{sat}NA$.
  - An energy limit, $W < \frac{1}{2} B_{sat}Vol/\mu$.

Current and Volt Limits

- A transformer that sustains dc current must satisfy both the amp-turn and volt-second limits.
- This is because dc current only acts in one winding.
- $\int (v\,dt)/(NA) + Ni_{dc}/(\mathcal{R}A) < B_{sat}$.

Dc Current Limits



- Circuits like this half-wave rectifier impose dc current on a transformer winding.
- The current produces a “flux offset.”
- Less flux is available to handle the voltage.

Example

- A laminated steel core, with 1 cm^2 cross-section, is to be used for a 120 V to 12 V, 60 Hz transformer. The Ampere's Law path length is 12 cm, and $\mu = 10^4\mu_0$.
- How many turns?
- How much dc current can flow?

Example

The volt-second limit for $170\cos(120\pi t)$ V tells us $170/(\omega NA) < B_{sat}$.

For steel, let us keep B < 1 T. Then N > 4510 turns.

The limit is 37.7 mV/turn.

How Much Dc?

- Let us use 4510 to 451 turns for 120 V to 12 V. How much dc current is allowed on the low side?
- $Ni < B_{sat}\mathcal{R}A$, $\mathcal{R} = \ell/(\mu A) = 9549\ H^{-1}$.
- Ignoring the voltage, $Ni < 0.95$ A-turn, and $i < 2.1$ mA, but we cannot allow this much because of v!

Limits

- In general, it is hard for a transformer to tolerate dc current.
- 50 Hz and 60 Hz transformers are large and have many turns.
- A 6000 Hz transformer of the same size would need only 46 turns on the high-voltage side.
- Here perhaps 50:5 to get the desired 10:1 ratio.

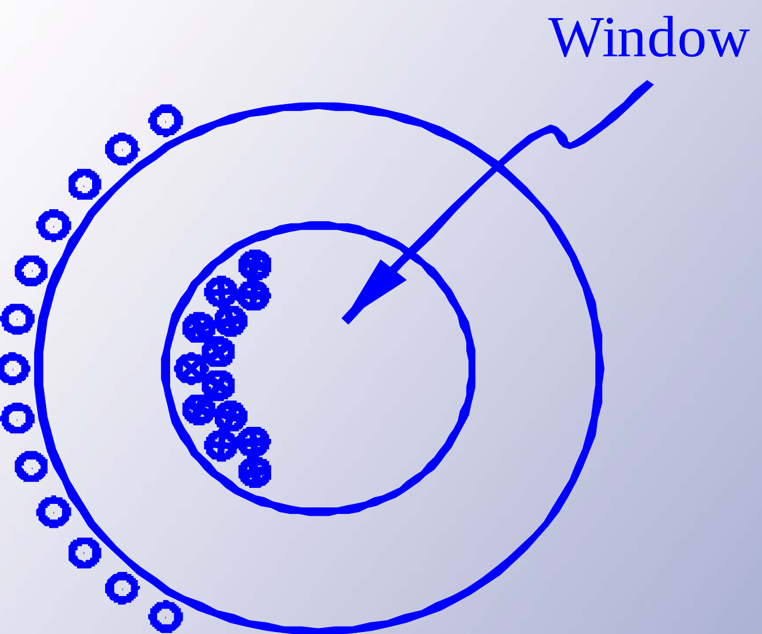
Limits

- The volts per turn limit suggests more turns.
- The amp-turn limit suggests fewer turns.
- We recall that wire size issues also lead to current limits.

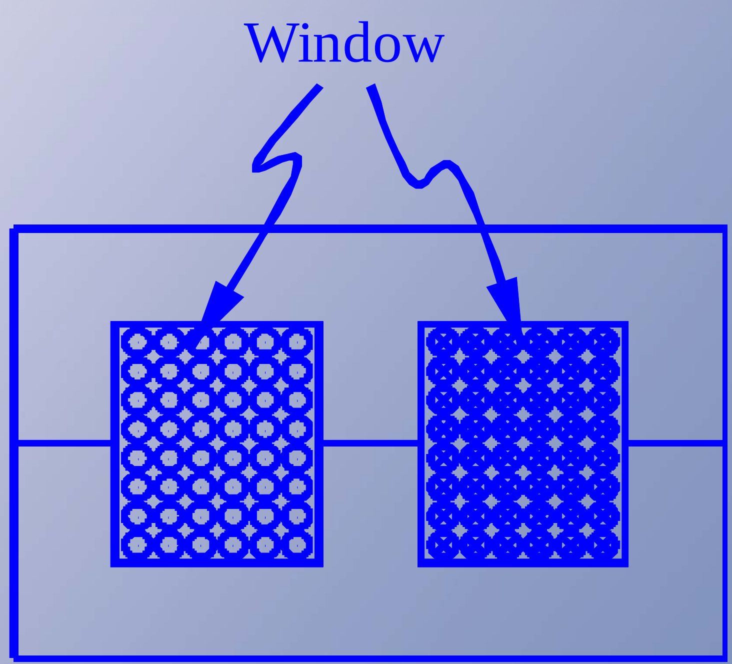
Copper Limit

- There is a geometric limit on copper: The amount of space for windings in any core.
- The windings pass through the core *window*.
- Not all the window can be filled with copper (insulation, air).
- The window has a *fill factor* less than 1.

Copper Limit



Toroid, fill factor ~ 10%



E - E core, fill factor ~ 50%

It is hard to have a window for which more than 50% is actual copper.

Copper Limit

- If we could fill 50% of the window, then the fill factor is ½ and the copper area is $A_{win}/2$.
- This area carries Ni. It must meet the copper current density limit.
- $2Ni/A_{win} < J_{limit}$, which might be 100 A/cm^2 or so.
- This is another limit on amp-turns.

Design for Losses

The total losses are minimized if:

- Losses in windings match losses in the core.
- Losses match in each winding if there are several.

To match winding losses: Use the same current density J in every winding.

Winding Issues

- Toroids are nice because they are easy to fabricate and good at confining flux.
- However, they are hard to wind (usually wound by hand).
- Other “split” cores are used for ease of winding.

Inductor Example

- Design a 500 uH inductor that can handle 10 A (peak) in a 50 kHz PWM application.
- Since there is one winding and the peak current is known, we can find flux from Ni/$\mathcal{R}$.

Material, Size?

- Choices: ferrite or powdered iron. Steel is probably not an option at 50 kHz.
- Powdered iron has higher saturation flux – and it is cheap.
- Let us select powdered iron (this is a possible frequency for it, although a touch high, but other powdered materials can achieve it).

Material, Size?

- This material has a “distributed air gap,” so total core volume is at issue.
- There are many kinds. Typical power parts have $\mu \approx 75\mu_0$.
- Our inductor must store up to $\frac{1}{2} Li^2 = \frac{1}{2}(500\ uH)(10\ A)^2 = 25\ mJ$.

Size

With saturation at 1 T, our energy limit requires 25 mJ < ½ $(1T)^2 Vol/(75\mu_0)$.

The volume should be at least $4.7 \text{ x } 10^6 \text{ m}^3$, or 4.7 cm^3.

Size

- In a catalog, I found a toroid with these properties, and volume of 6.44 cm^3. The OD is 3.6 cm, the ID is 2.2 cm, and the core is 1.05 cm thick.
- Reluctance? Length = 9.16 cm (from the catalog), A = 0.711 cm^2.
- Winding window? The window diameter was 2.2 cm, for an area of 3.94 cm^2.

Reluctance

The reluctance is 1.37×10^7 H^{-1}, from these numbers.

The manufacturer reports A_L = 73 nH, which is consistent.

We want $N^2 \times A_L$ = 500 uH, so N^2 = (500 uH)/(73 nH) = 6849.

This gives N = 83.

Coil

- Will the wire fit? We want 10 A. For powdered iron, the density should be in the 500 A/cm^2 range (or less) for loss matching.
- This is equivalent to #14 AWG, although we will probably strand it, since #14 is hard to wind.

Coil

- #14 wire has an area of 2.08 mm^2.
- For 83 turns, this is 173 mm^2.
- The window diameter was 2.2 cm, for an area of 3.94 cm^2, or 394 mm^2.
- This requires 44% fill. The window might be just big enough, but this is very tight.
- A larger core would be better: this one pushes thermal limits.

Larger Core

- A larger core: T200-26 toroid. This has an outside diameter of 2.0 in (50.8 mm) and inside diameter of 31.8 mm.
- Catalog information: volume 16.4 cm^3, magnetic path length ℓ = 13.0 cm, core cross section area A_e = 1.27 cm^2.
- The catalog lists A_L = 92 nH.

Larger Core

- To get 500 uH, we need $N^2/\mathcal{R} = N^2 A_L = 500$ uH.
- This requires $N^2 = 5435$, $N = 74$ turns.
- The window is much larger, at 794 mm^2.
- This is a 22% fill. Now the wire fits better.
- We can move to #12 wire, which gives reasonable current density.

Flux

- We apply 740 A-turns to the core.
- The flux is $Ni/\mathcal{R}$, or $740/1.09 \times 10^7$. This is 6.8×10^{-5} Wb.
- From the area of 1.27 cm^2, the flux density is $B = 0.53$ T.
- Not close to saturation, and this should help keep losses low.
- The toroid design is a powdered iron core with 74 turns of #12 AWG wire.

Transformer Example

- How much power can a ferrite toroid with 0.87 in OD, 0.54 in ID, and 0.25 in thickness handle in a forward converter application? The switching frequency is 200 kHz, and the peak voltage is 200 V. The turns ratio is 10:1.
- Notice that a ferrite has been selected because of the high frequency.

Transformer

- We want a core with low reluctance because this is a transformer.
- The core must handle 200 V for 2.5 us, so the volt-second rating must be at least 500 uV-s.
- From our integration, the volt-second product gives V-s/(NA) < B_{sat}.
- For this core, A = 0.259 cm^2. We need N > 64 turns on the high-voltage side.
- Use 70:7 to give 10:1 ratio.

Windings

- There are two windings, and also 50% fill at best.
- Each winding should have the same current density to be sure neither is overdesigned.
- Therefore, each winding takes up the same total area.
- Thus let the primary copper take up no more than 25% of the window.

Windings

- The window area is 1.4 cm^2, so the winding copper can use up to 0.35 cm^2. With 70 turns, this is 0.50 mm^2 per turn.
- If we choose a wire size of #21 AWG, it has an area of 0.41 mm^2. This should fit.
- At 250 A/cm^2, it can carry 1 A.

End Result

- We have designed as follows:
  - Primary: 70 turns of #21 AWG, rated for up to 1 A.
  - Secondary: 7 turns of #11 AWG, rated for up to 10 A.
  - The primary can handle a 200 V square wave.
  - The secondary can handle a 20 V square wave.

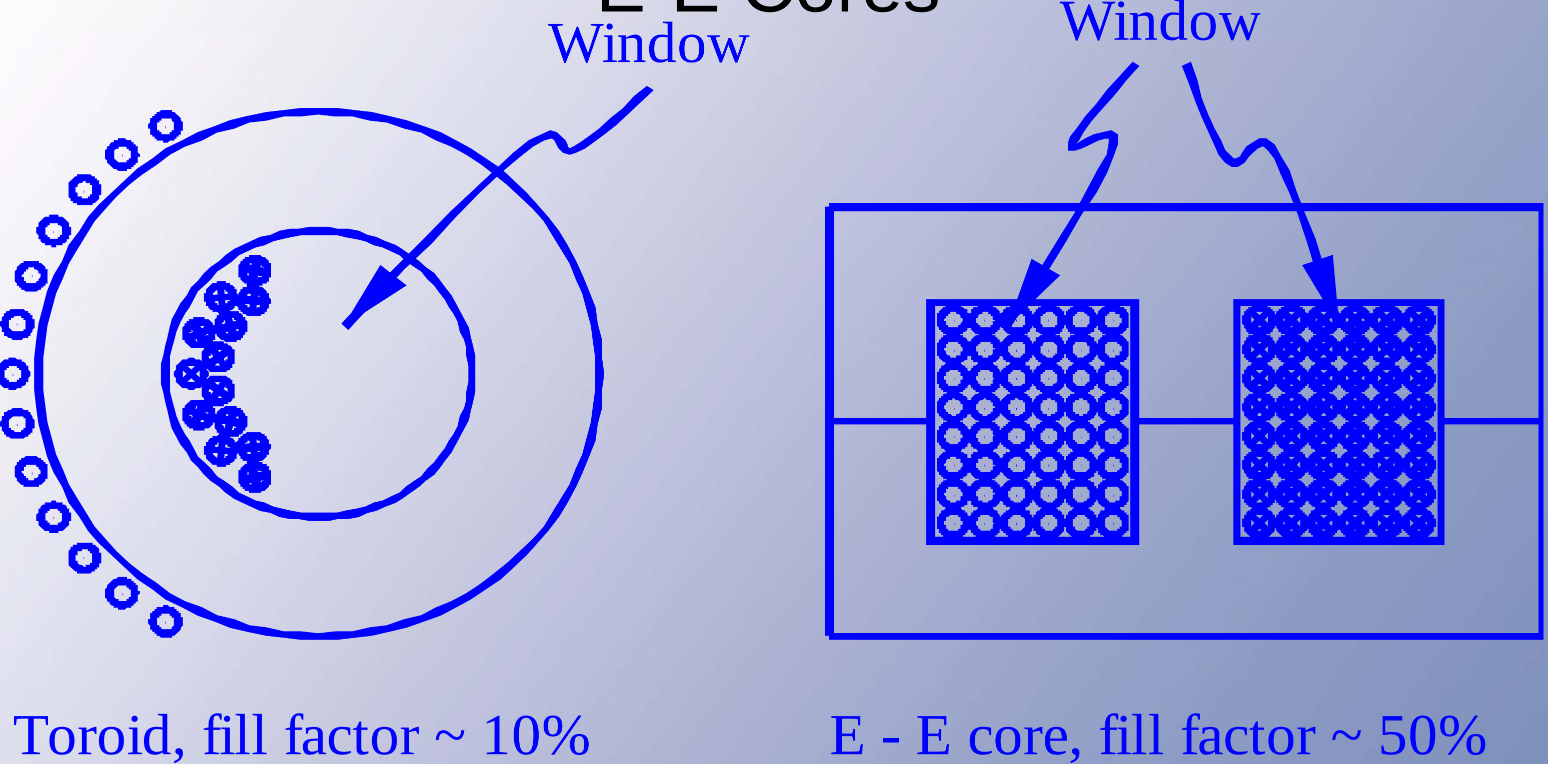
Result

- This small core can handle 200 V peak and 1 A of flow, with a square wave input. This gives 200 W.
- A small core less than 1 inch across provides a 200 W transformer!
- The same core at 60 Hz would need 217000 turns and would handle 60 mW – if we could find small enough wire.

Core Types

- Toroids are common for cases with just a few turns.
- They confine fields well, and require little extra shielding.
- The shape tends to give a low cost.
- But, it is hard to wind them.
- Also, a change in permeability requires a change in materials.

E-E Cores



- E-E cores are one of the simplest “split core” types.

E-E cores

- With a split core, the winding can be set up on a separate bobbin or paper tube, then the core is assembled around it.
- This leads to very simple machine-wound coils.
- With a split core, an air gap can be produced by grinding down the center post or adding a filler sheet.

E-E cores

- E-E cores are in common use for transformers and often for inductors.
- High permeability materials are used most often, and any change involves the air gap rather than the material.
- Most E-E cores are either steel laminations or cast ferrites.

Pot Cores

- A pot core looks like an E-E core that has been rotated.
- This geometry gives extremely good magnetic shielding.
- As in the E-E core, the winding is set up on a separate bobbin.
- The center post can be ground to make an air gap.

Pot Cores

- Pot cores work well in the highest frequency applications.
- They are more expensive because of the complicated shape. Ferrites are used.
- Often, the current density must be lower for pot cores, since the winding is enclosed.