CHALMERS

ENM061 - Power Electronic Converters 7.5 ECTS, 2017

Mebtu Beza
mebtu.beza@chalmers.se

Chalmers University of Technology
Department of Electrical Engineering
Division of Electric Power Engineering

CHALMERS

Lecture outline

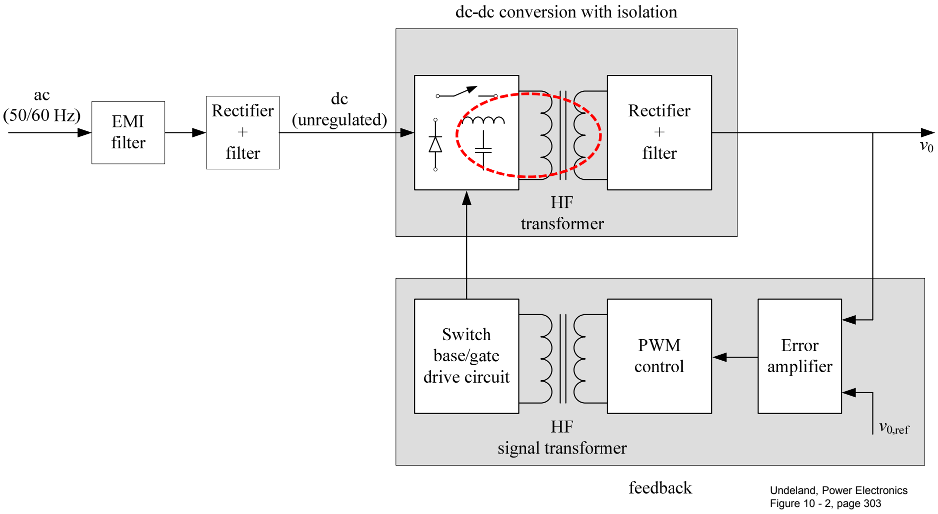
Passive components

- Resistors
- Capacitors
- Inductors
- Magnetic circuits and analogy to electrical circuits
- Transformers
- Brief description of the Tutorial and PSpice exercises
- Summary

Learning outcomes

- Fourier components and total harmonic distortion (THD) for basic waveforms.
- Operating principles of the most common active components (e.g. diode, thyristor, IGBT, and MOSFET) and passive components (e.g. capacitors, transformers and inductors).
- Operation of a pulse width modulation (PWM), the purpose of controlling the desired quantity and the need for a controller circuit within the power electronic converter.
- Analysis of ideal DC/DC converters (e.g. buck, boost, buck-boost, flyback, the forward, the push-pull, half-bridge and full-bridge converters) in CCM and DCM operation.
- Operating principles of single-phase and three-phase AC/DC inverters with different modulation strategies (e.g. PWM and square wave operation).
- Operation of multilevel converters (e.g. NPC, flying capacitor and MMC topologies) using current and voltage waveform analysis. Pros and Cons of the converter in terms of harmonics and losses.
- Operation of single- and three-phase diode rectifiers operating with voltage-stiff and current-stiff DC-side. Investigating the impact of line impedance within the converter circuit for current commutation.
- Operation of single- and three-phase thyristor rectifiers operating with a current-stiff DC-side and the impact of line impedance for current commutation. Investigating the use of 6/12-pulse configurations.
- Identify simple power electronic converter schematics. Recognizing the different parts in a physical circuit on which basic wave-shape and efficiency measurements is performed.
- Loss calculation in passive and active components. Evaluating the temperature rise in the active components and choosing an appropriate heat-sink. Gaining a basic understanding of component life time.
- Utilizing the software Cadence PSpice to simulate basic power electronic circuits and the practical labs to have a firsthand experience of how real DC/DC converters operate.

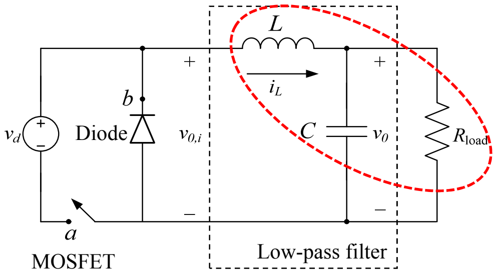
Switch-mode power supply

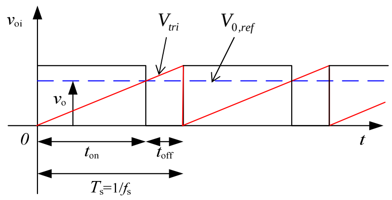


Undeland, Power Electronics
Figure 10 - 2, page 303

Switch-mode power supply

Equivalent circuit





Average load voltage

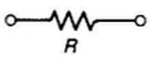
$$V_0 = \frac{1}{T_s}\int_0^{T_s} v_{0i}\,dt = \frac{t_{on}}{T_s}V_d = DV_d$$

Switching function

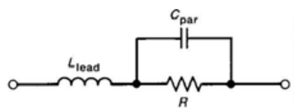
$$switch\ a = \begin{cases} on => Diode\ off, V_{0,ref} \geq V_{tri} \\ off\ => Diode\ on, V_{0,ref} < V_{tri} \end{cases}$$

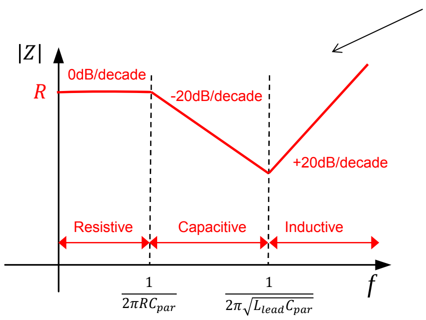
Resistors – Non Ideal Circuit Models

- Parasitic effects must be accounted for in high frequency applications
  - Ideal model $R = \frac{\rho l}{A}$



  - Non-ideal model



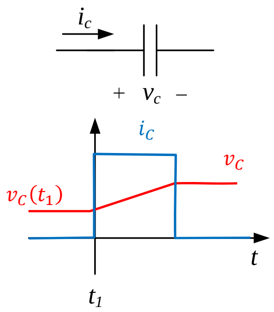


  - Various loads and losses are usually represented by an equivalent resistance

Capacitors – Ideal Behavior

$$i_C = C\frac{dv_C}{dt}$$

$$v_C = v_C(t_1) + \frac{1}{C}\int i_C dt$$



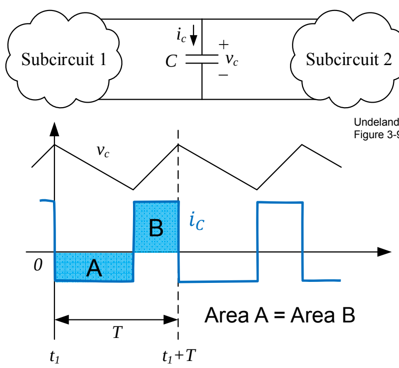
Average and RMS current and voltage?

Voltage stiff component

Capacitors – Ideal Behavior

The current-time areas (charge) are equal – no net storage of charges

$$v_C = v_C(t_1) + \frac{1}{C}\int i_C dt$$

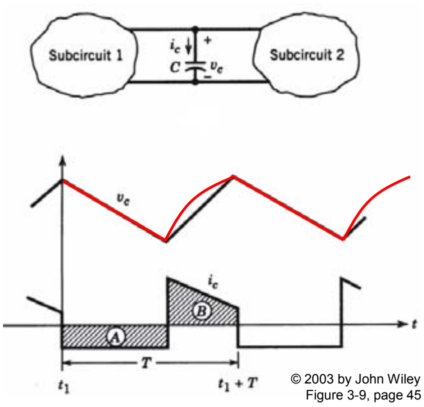


Undeland, Power Electronics
Figure 3-9, page 45

⇒ $I_{AVG,cap}$ = 0

⇒ $I_{RMS,cap}$ = ?

Capacitors – Ideal Behavior



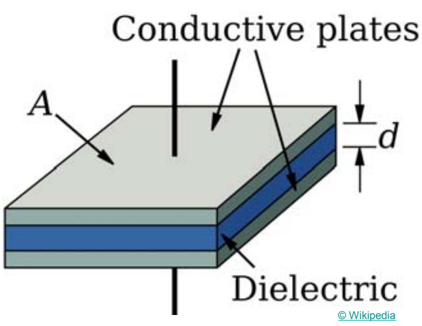
$$v_C = v_C(t_1) + \frac{1}{C}\int i_C dt$$

Figure 3-9, page 45

Ex.: what is wrong in this figure?

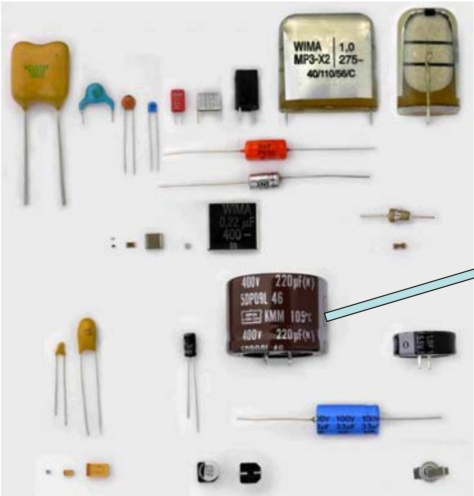
Capacitors – Physical Design

The capacitance is determined by $C = \frac{\varepsilon A}{d}$

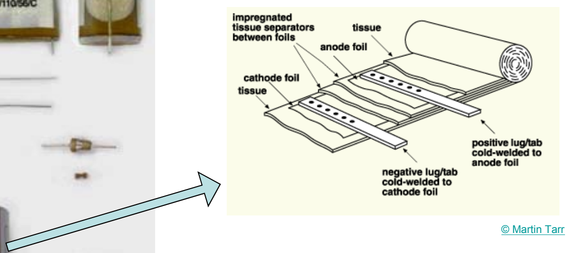


- The larger the plate area, the larger the capacitance value
- The smaller distance between the plates, the larger capacitance value
- The larger dielectric constant, the larger the capacitance

Capacitors – Physical Design



© Wikipedia



© Martin Tarr

Capacitors for Power Systems

Capacitor Banks – Applications		
Flexible AC Transmission Systems (FACTS)	Parallel Compensation	Static Var Compensator (SVC)
		Mechanically Switched Capacitor with Damping Network (MSCDN)
		Mechanically Switched Capacitors (MSC)
	Series Compensation	Thyristor Controlled Series Compensation (TCSC)
		Thyristor Protected Series Compensation (TPSC)
		Fixed Series Compensation (FSC)
AC Harmonic Filters		
AC PLC Filters		
Long Distance and Back-to-Back HVDC – AC & DC Filters		
AC & DC Surge Capacitors		

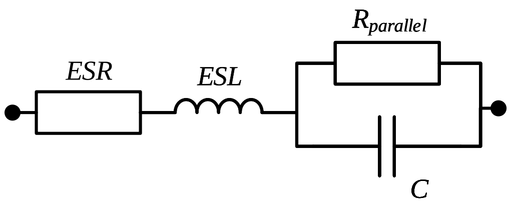
© Siemens

Technical data	
Type	impregnated all-film dielectric
Rated voltage	up to 8 kV
Rated frequency	50 Hz or 60 Hz
Rated power	up to 850 kvar
Average losses	< 0.15 W/kvar
Dielectric liquid	non-pcb
All-film dielectric	polypropylene
Temperature category	-50° C to + 55° C (D)
Standards	IEC 60871-1 ANSI/IEEE, CSA
Standard colour	Light grey (RAL 7035)

Capacitors – Non-Ideal Circuit Models

Simple capacitor model that accounts for:

- The insulation resistance (if necessary)
- The equivalent series inductance (if necessary)
- The equivalent series resistance (ESR)



Capacitors – Non-Ideal Behavior

Type ⊕ = polarized	Pic	Cap Range	ESR	Leakage	Voltage Rating	Temp Range	Gen Notes
Ceramic		pF - µF	low	med	high	-55° to +125°C	Multipurpose Cheap
Mica (silver mica)		pF - nF	low 0.01-0.1Ω	low	high	-55° to +125°C	For RF filters Expensive Very stable
Plastic Film (polyethylene polystyrene)		few µFs	med	med	high	varies	For low freq Cheap
Tantalum ⊕		µFs	high 0.5-5.0Ω	low	lowest	-55° to +125°C	Expensive Nonlinear (bad for audio)
OSCON ⊕		µFs	low 0.01-0.5Ω	low	low	-55° to +105°C	Best quality Highest price
Aluminum Electrolytic ⊕		high µFs	high 0.05-2.0Ω	med	low	-40° to +85°C	For low-med frequencies Cheap Hold charge for long time – not for production test

© PlanetAnalog

Capacitors – Non-Ideal Behavior

- **Leakage current and insulation resistance**

  A small DC-current will flow through the dielectric due to non-idealities. Temperature and material dependent.

- **Dielectric strength**

  Breakdown of the dielectric material due to high electric fields. Usually leads to a short circuit of the capacitor

- **Equivalent series resistance (ESR)**

  The sum of all ohmic losses and dielectric losses within the capacitor. It depends on material, temperature and frequency. It decides rated RMS-current due to internal heating.

- **Dissipation factor** (tan δ = ESR/$|X_c|$)

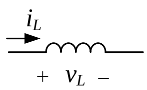
  The ratio of the resistive power loss in ESR to the reactive power oscillating in the capacitor. It is the inverse of Q-factor.

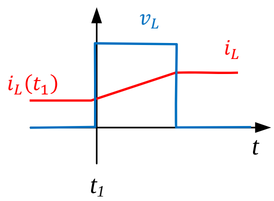
  i.e., Q_f = ω*maximum stored energy/dissipated power

Inductors

$$v_L = L\frac{di_L}{dt}$$

$$i_L = i_L(t_1) + \frac{1}{L}\int v_L dt$$





Average and RMS current and voltage?

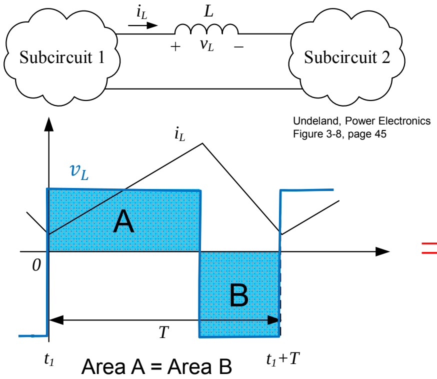
Current stiff component

Inductors

The volt-second areas are equal – no net storage of magnetic energy

$$i_L = i_L(t_1) + \frac{1}{L}\int v_L dt$$

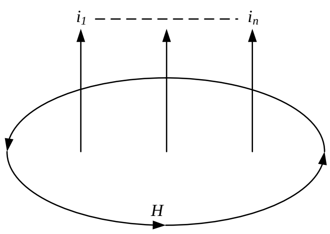
Ex.: Plot the waveform of v_L

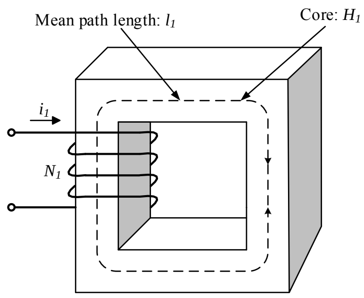


$\Rightarrow$ $V_{AVG,ind} = 0$

Inductors
Ampere's Law and the H-Field

Any current carrying unit produces a magnetic field of intensity *H* (A/m).





$$\oint H\, dl = \sum i$$

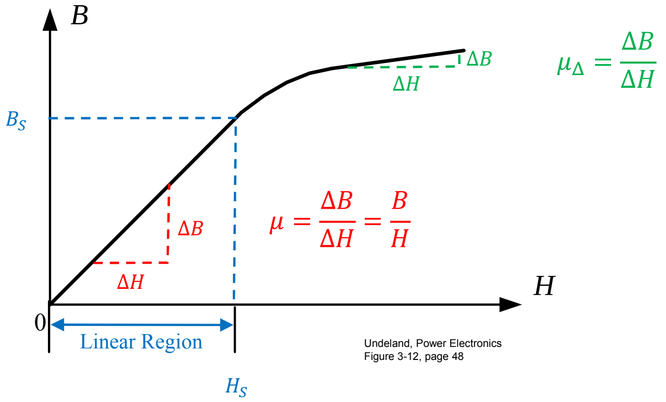
$$\sum_k H_k l_k = \sum_m N_m i_m$$

CHALMERS

Inductors

The Relationship Between B and H

$$B = \mu H = \mu_r \mu_0 H$$



Undeland, Power Electronics
Figure 3-12, page 48

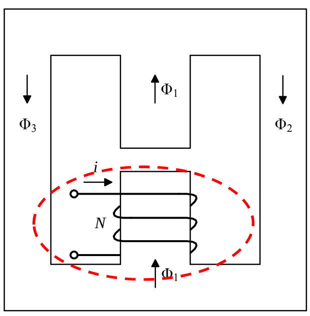
CHALMERS

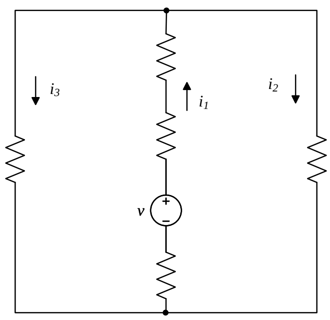
Inductors

Flux and Analogy to Electric Circuits

$$\Phi = \iint_A B \, dA$$

The B-field (flux density) over an area gives the total flux. Magnetic flux lines form closed loops (continuity of flux) and an analogy can be made to electric current and voltage





Undeland, Power Electronics
Figure 3-15, page 51

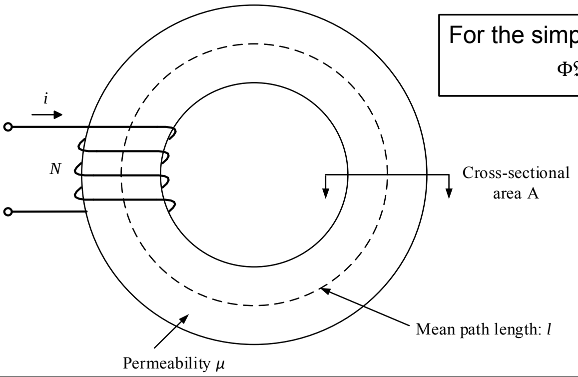
Inductors

Magnetic Resistance

$$\sum_k H_k l_k = \sum_m N_m i_m \rightarrow \Phi \sum_k \frac{l_k}{\mu_k A_k} = \sum_m N_m i_m \qquad \Re_k = \frac{l_k}{\mu_k A_k}$$

For the simple core we get:

$$\Phi\Re = Ni$$



Undeland, Power Electronics
Figure 3-14, page 49

Inductors

Inductance Definition

Faraday's Law:

$$e = N\frac{d\Phi}{dt}$$

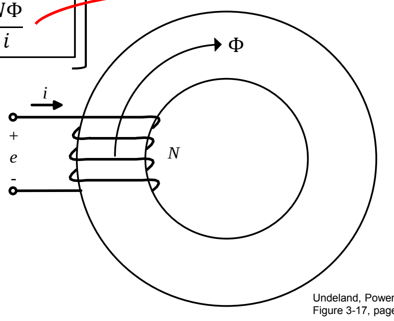
Definition of Inductance:

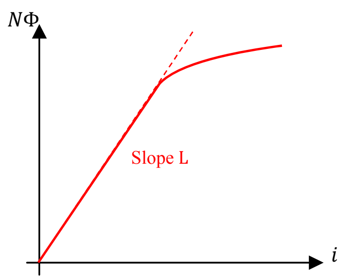
$$L = \frac{N\Phi}{i}$$

$$e = L\frac{di}{dt} + i\frac{dL}{dt} = L\frac{di}{dt}$$

From $\Phi\Re = Ni$ $\rightarrow$

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

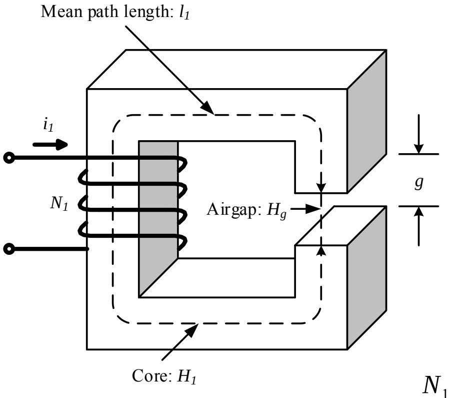




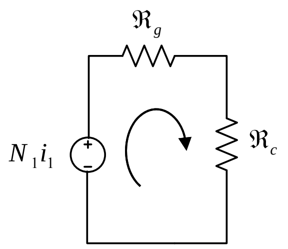
Undeland, Power Electronics
Figure 3-17, page 52

CHALMERS

Inductors
The Effect of an Airgap



Undeland, Power Electronics
Figure 3-10, page 46



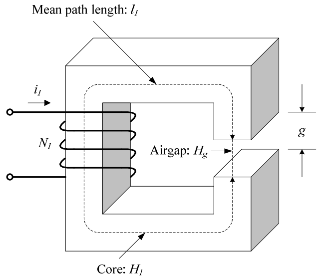
$$N_1 i_1 = \Phi\left(\Re_g + \Re_c\right)$$

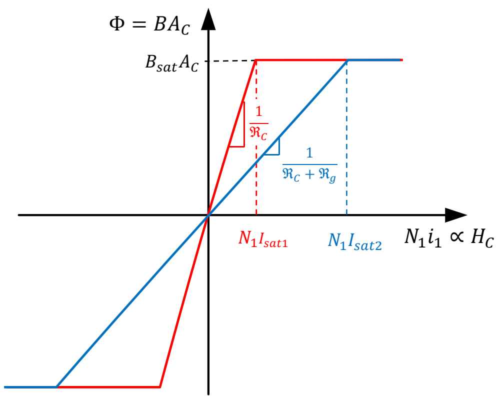
$$\Re_c = \frac{l_c}{\mu_r \mu_0 A_c}\left[H^{-1}\right]$$

$$\Re_g = \frac{l_g}{\mu_0 A_c}\left[H^{-1}\right]$$

CHALMERS

Inductors
The Effect of an Airgap





$$N_1 i_1 = \Phi\left(\Re_g + \Re_c\right)$$

$$L = \frac{N_1^2}{\Re_g + \Re_c}$$

$$\Phi_{sat} = B_{sat} A_c$$

$$I_{sat} = \frac{B_{sat} A_c}{N_1}\left(\Re_g + \Re_c\right)$$

Inductors

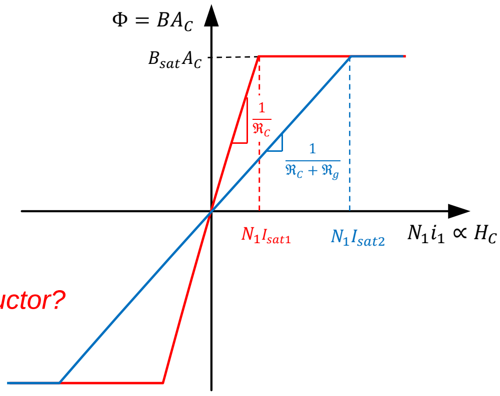
The Effect of an Airgap

- No airgap – the inductance is determined by the core

$$L_1 = \frac{N_1^2}{\Re_c}$$

- With airgap – the inductance is determined by the airgap

$$L_2 = \frac{N_1^2}{\Re_g + \Re_c}$$



Ex.: *do we need an air-gap in an inductor?*

$$\frac{1}{2} L_1 I_{sat1}^2 \quad < \quad \frac{1}{2} L_2 I_{sat2}^2$$

$$\Downarrow \qquad\qquad \Downarrow$$

$$\frac{1}{2} B_{sat} A_C N_1 I_{sat1} \qquad \frac{1}{2} B_{sat} A_C N_1 I_{sat2}$$

Inductors

Core Materials

Core type	B_{sat}	Relative core loss	Applications
Laminations iron, silicon steel	1.5 - 2.0 T	high	50-60 Hz transformers, inductors
Powdered cores powdered iron, molypermalloy	0.6 - 0.8 T	medium	1 kHz transformers, 100 kHz filter inductors
Ferrite Manganese-zinc, Nickel-zinc	0.25 - 0.5 T	low	20 kHz - 1 MHz transformers, ac inductors

CHALMERS

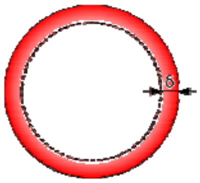
Inductors
Copper Losses

- DC resistance of wire

$$R = \rho \frac{\ell_b}{A_w}$$

where A_w is the wire bare cross-sectional area, and ℓ_b is the length of the wire. The resistivity ρ is equal to $1.724 \cdot 10^{-6}\ \Omega\ \text{cm}$ for soft-annealed copper at room temperature. This resistivity increases to $2.3 \cdot 10^{-6}\ \Omega\ \text{cm}$ at 100°C.

- Skin effect – the current crowds at the edges of a conductor due to eddy currents within the material



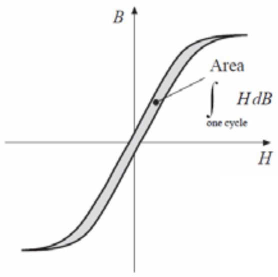
$$\delta = \sqrt{\frac{2\rho}{2\pi f \mu}}$$

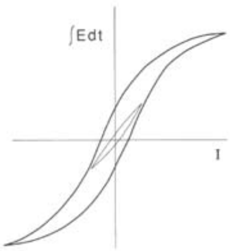
Undeland, Power Electronics
Chapter 30-1-3 and 30-2-3

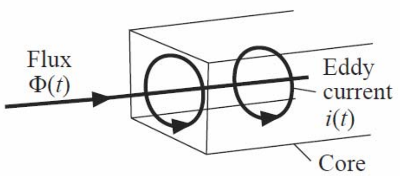
CHALMERS

Inductors
Core Losses

- Hysteresis losses
- Eddy current losses







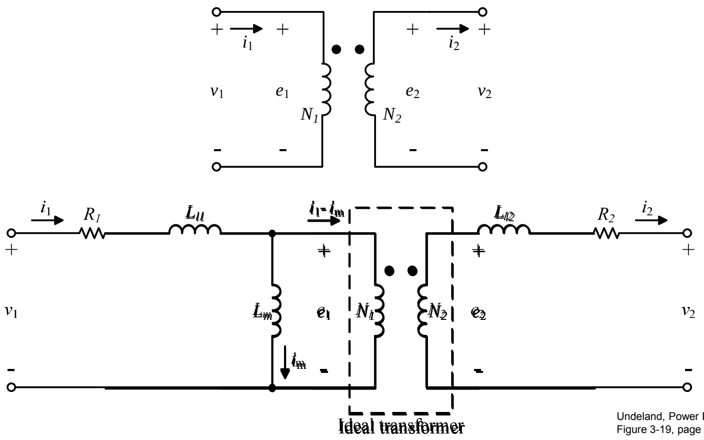
Undeland, Power Electronics
Chapter 30-1-2

Undeland, Power Electronics
Chapter 30-1-4

Inductors
Different Core Types

Transformers

- The equivalent circuit of the transformer including leakage inductances, winding resistances and magnetizing inductance.

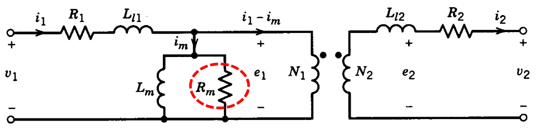


Undeland, Power Electronics
Figure 3-19, page 54

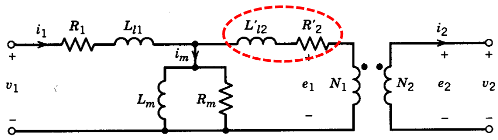
Transformers

- The equivalent circuit of the transformer including leakage inductances, winding resistances and magnetizing inductance.

Including core losses

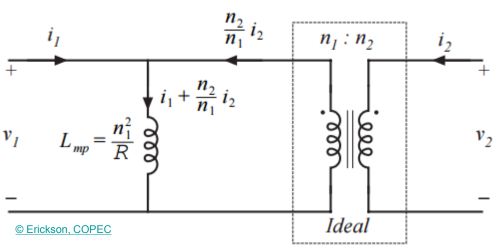


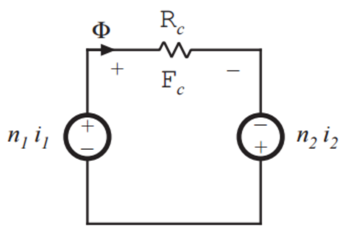
referring the components to the primary side



Undeland, Power Electronics
Figure 3-21, page 56

Transformers





For nonzero core reluctance, we obtain

$$\Phi R = n_1 i_1 + n_2 i_2 \quad \text{with} \quad v_1 = n_1 \frac{d\Phi}{dt}$$

Eliminate Φ:

$$v_1 = \frac{n_1^2}{R} \frac{d}{dt}\left[i_1 + \frac{n_2}{n_1} i_2 \right]$$

Ex.: Derive L_{mp}

This equation is of the form

$$v_1 = L_{mp} \frac{d\, i_{mp}}{dt}$$

with

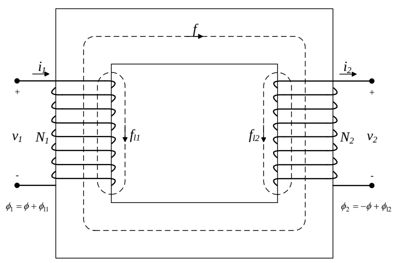
$$L_{mp} = \frac{n_1^2}{R}$$

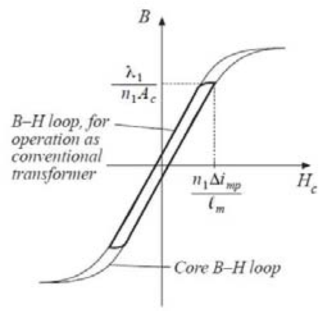
$$i_{mp} = i_1 + \frac{n_2}{n_1} i_2$$

CHALMERS

AC Transformer

- Core losses, copper losses and proximity losses are usually significant.
- No air gap in the core.
- The core is usually made of laminated steel.

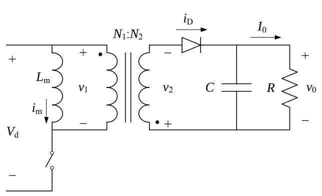


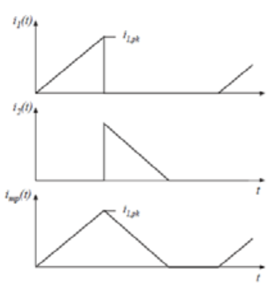


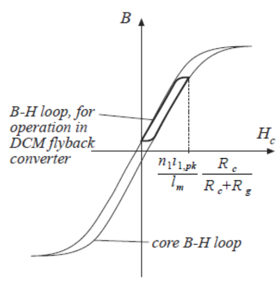
CHALMERS

Switched Converter Transformer

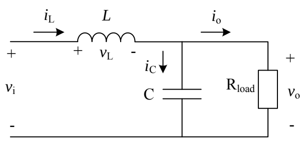
- Core losses, copper losses and proximity losses are usually significant.
- An air gap could be introduced to avoid saturation (eg. Flyback)
- The core is made of ferrite due to the high switching frequency.

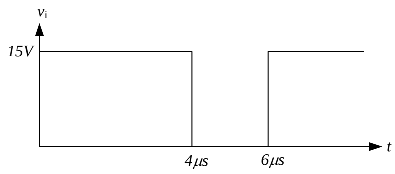






Tutorial 2



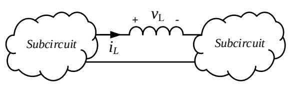


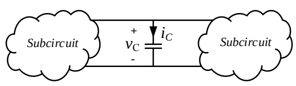
V_i repetitive and system in steady state. $L = 5uH$, $C = large$, $P_{load} = 250W$

- Average load voltage, average load current, capacitor RMS-current?
- What is the function of L and C?

PSpice 1

Power electronc circuits and Fourier analysis in Cadence PSpice





- Waveforms for different inputs
- Steady-state operation?

- Waveformes for different inputs
- Steady-state operation

CHALMERS

Summary

- Explain the voltage and current relationship for an inductor and a capacitor and explain what it means.
- What does ESR represent in a transformer.
- What do copper losses and core losses represent in an inductor and a transformer?
- What is the electrical analogy for a flux and reluctance in a magnetic circuit?
- Can you motivate why we use an air-gap in an inductor?
- Can you sketch the equivalent circuit representation of an ideal and non-ideal transformer?
- Learning outcome:
  - ❖ Operating principles of the most common passive components (e.g. capacitors, transformers and inductors).