Electrical Machines and Drives ET4117

Henk Polinder

Personal

At EE TUDelft:

- 86-92 MSc
- 92-98 PhD
- 96-?? U(H)D
- 08 ABB – fault tolerant generator systems
- 02/04/06 Visiting professor in Newcastle, Quebec, Edinburgh
- 98-99 Lagerweij – design of a 750 kW direct drive generator

Electrical machines and drives ET4117

- Introduction
  - Organisation
  - Objectives
  - Motivation
  - Structure
  - How to deal with drives
    - Characterization of mechanical loads
    - Control
    - Power electronics
- Maxwell's equations / Magnetic circuits (chapter 1)

Organisation 1

- Course: Electrical Machines and Drives ET4117
- Number of ECTS credits: 4
- Book: P.C. Sen, 'Principles of electric machines and power electronics', New York: John Wiley and Sons, 1997 (second edition) ISBN 0-471-02295-0
- Book: A.E. Fitzgerald, C. Kingsley, S.D. Umans, 'Electric Machinery', New York: McGraw-Hill, 2003 (sixth edition) ISBN 0-07-112193-5
- Prerequisites: Electrical conversions, mainly chapters 3 (magnetic circuits) and 7 (synchronous machine)
- Assessment:
  - November: written examination - closed book
  - January: resit
- Study goals: see blackboard

Organisation 2

- Information: blackboard
  - please enroll !!!
  - course objectives
  - slides
  - old exams
- Lecturer: dr.ir. H. Polinder
  - room number LB03.610
  - e-mail: h.polinder@tudelft.nl

Organisation 3

- Laboratory work:
- 3 half days between 17 September and 3 November
- DC machines, IM and SM
- In groups of up to 8 students
- Register via blackboard
  - 17 (morning), 17 (afternoon), 20 (afternoon) Sept for DCM
  - 24 (morning), 24 (afternoon), 27 (afternoon) Sept for DCM
  - 1 (morning), 1 (afternoon), 4 (afternoon) Oct for IM
  - 8 (morning), 8 (afternoon), 11 (afternoon) Oct for IM
  - 15 (morning), 15 (afternoon), 18 (afternoon) Oct for SM
  - 22 (morning), 22 (afternoon), 25 (afternoon) Oct for SM

Facts about studying

- Studying is an activity of students, not of lecturers. So, you have to do it yourself.
- The objective of a lecture is not that the lecturer can tell his story without interruption.
- Most lecturers like questions (I do).
- Stupid questions are rarely asked.
- Asking a stupid question does not mean that you are stupid.
- Following lectures in an inactive way is not a good way of studying
- Preparing lectures is an effective way of studying.

Lectures

Therefore, I will try to help your study process by

- discussing important and difficult points (not everything)
- giving background information
- discussing applications
- showing slides
- showing computer simulations
- doing important exercises in the lectures (colstruction)
- giving demonstrations
- answering your questions
- activating you by asking questions
- giving you the opportunity to prepare the lectures
- laboratory work

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Objectives: overview over electric drives

- Students must be able to
  - recognize
  - sketch cross sections of
  - explain the principle of operation of
  - derive steady-state equations for voltage and torque of
  - mention suitable PE converter types used to drive
- the following types of electric machines
  - DC machines
  - induction (asynchronous) machines
  - synchronous machines
  - PMAC machines
  - switched reluctance, single-phase machines (qualitative)

Objectives

- The course is intended to give an overview over different types of electrical machines and drives.
- Different mechanical loads for electrical machines.
- Focus on understanding of steady state, no dynamics.
- Understanding electrical machines starts with Maxwell's equations applied to magnetic circuits including permanent magnets.
- Blackboard: more detailed list of course objectives.

Objectives: scientific course

- What is scientific about this course?

Objectives: scientific methods

- Laws of nature:
  - Formulation of hypothesis
  - Validation by means of observations

- Development of theory / hypotheses
  - Starting points: laws of nature
  - Explicit assumptions
  - Sound derivations
  - Resulting equations, models
- Experimental validation

- Reduction of reality!!

Motivation - applications

- Why do we talk about machines and not motors or generators?

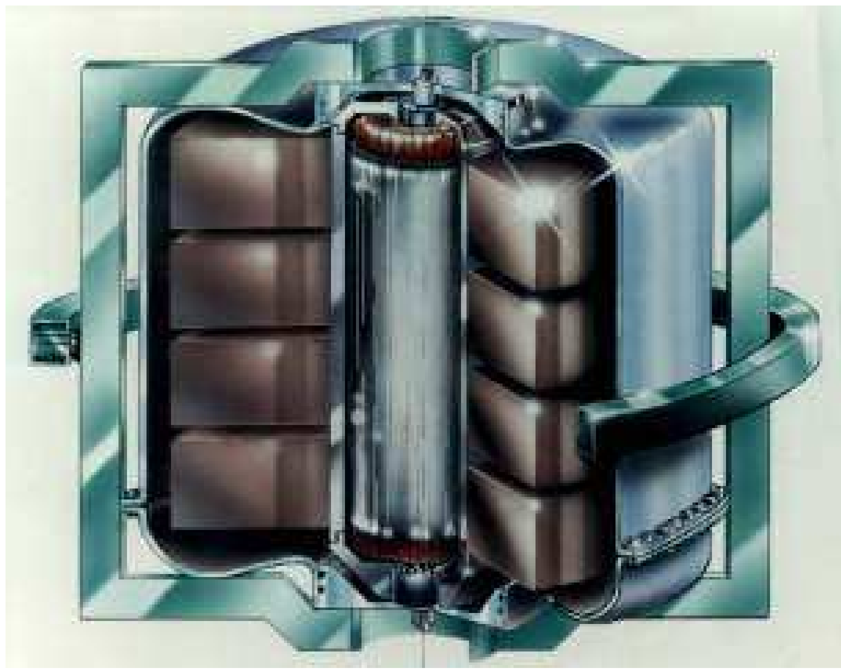
- Why is this course important?
- Many applications
  - over 30 machines in house - where?
  - industry
  - transportation
  - positioning
  - generation
    - Do you know forms of electrical energy generation without using an electrical machine?

Generation

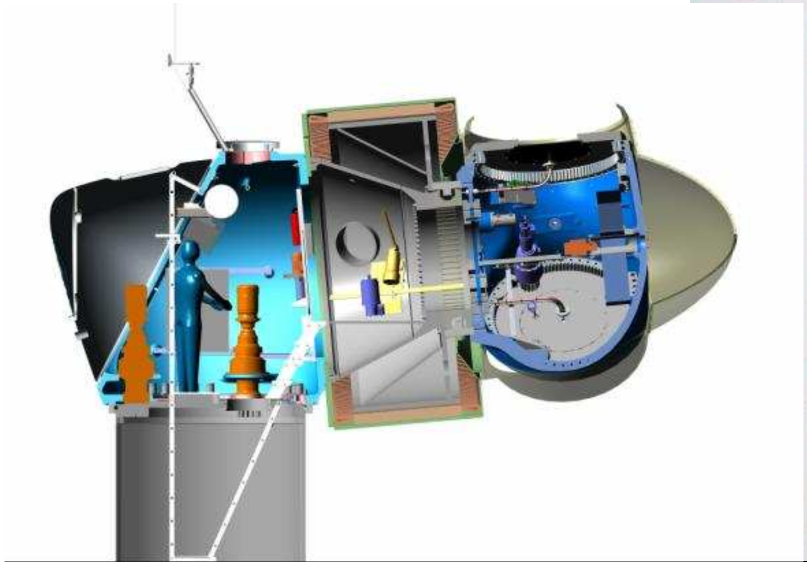
Transportation

Domestic

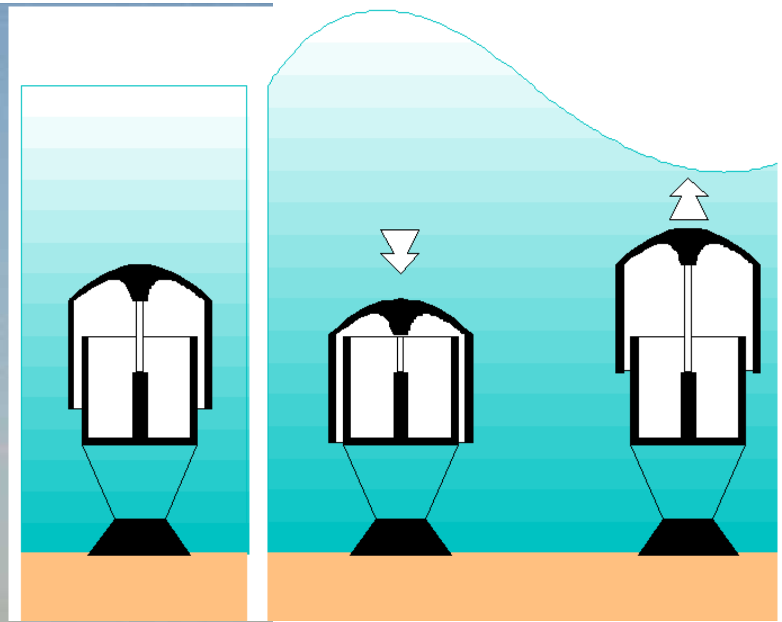
High speed generator and flywheel for hybrid vehicles



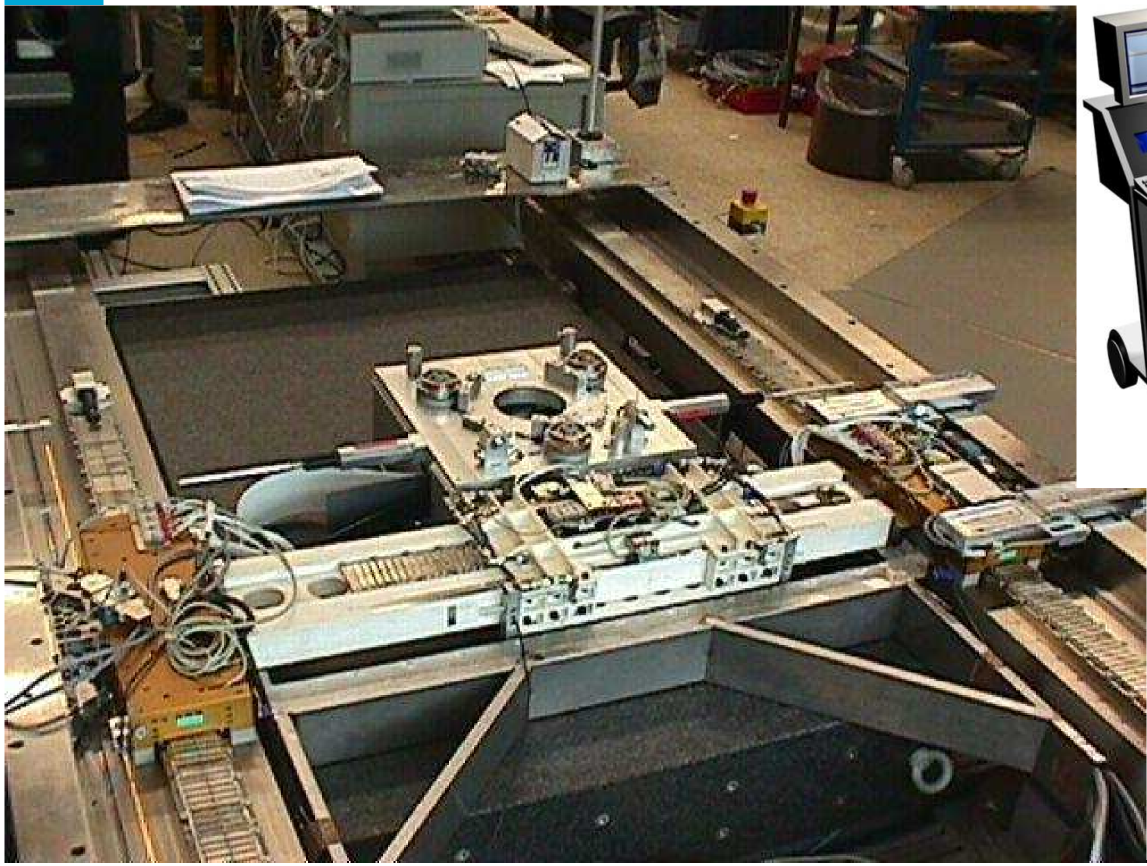
Generators for (direct-drive) wind turbines

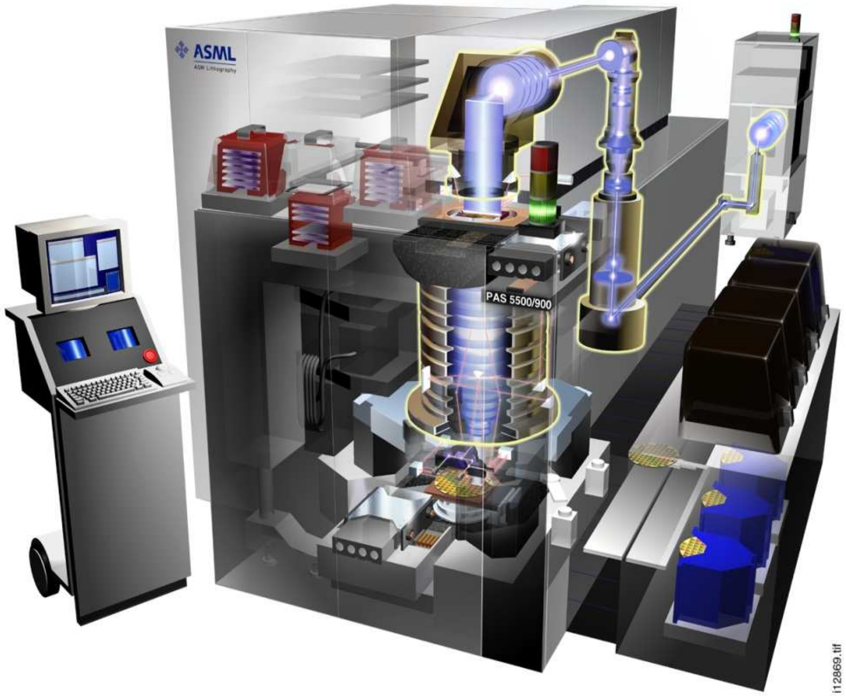


Archimedes Wave Swing



Actuators for wafer steppers





Extremely wide variety

- Power levels 10^{-6} – 10^{9} W (watch – power station)
- Torque levels 10^{-9} – 10^{7} Nm
- Speed range 10 rpm – 300.000 rpm (wind turbine – spindle)
- Positioning accuracies to below 1 nm = 10^{-9} m
- Different types

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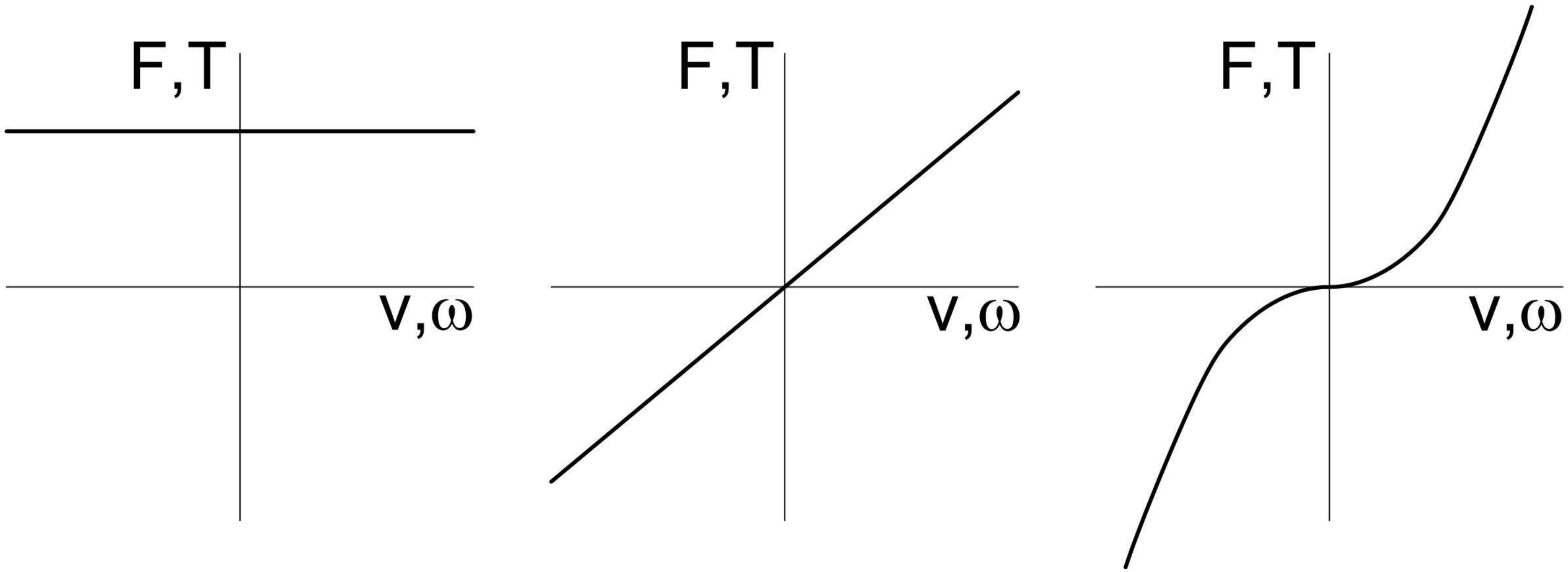
Characterisation of mechanical loads



lift, crane,
friction in bearings

viscous friction

aerodynamic friction
fluid friction,
pump, fan, vehicle

NB: 4 quadrants

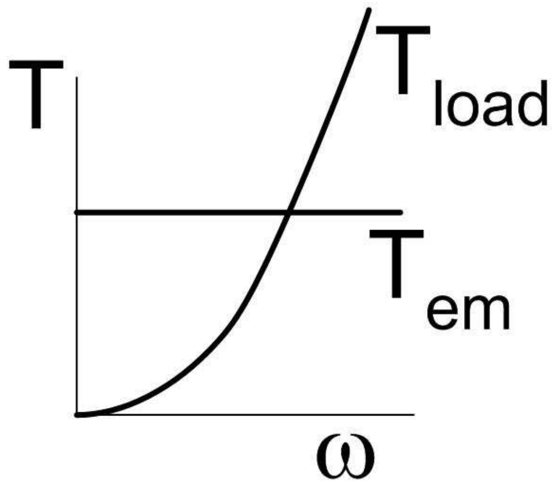
relations linear and rotating $v = \omega r \quad ; \quad T = Fr \quad ; \quad P = Fv = T\omega$

Equations of motion

$$m\frac{\mathrm{d}v}{\mathrm{d}t} = \sum F = F_{em} - F_{load}$$

$$J\frac{\mathrm{d}\omega}{\mathrm{d}t} = \sum T = T_{em} - T_{load}$$

Example: sketch speed as a function of time for the sketched electromechanic and load torque



Position / speed control

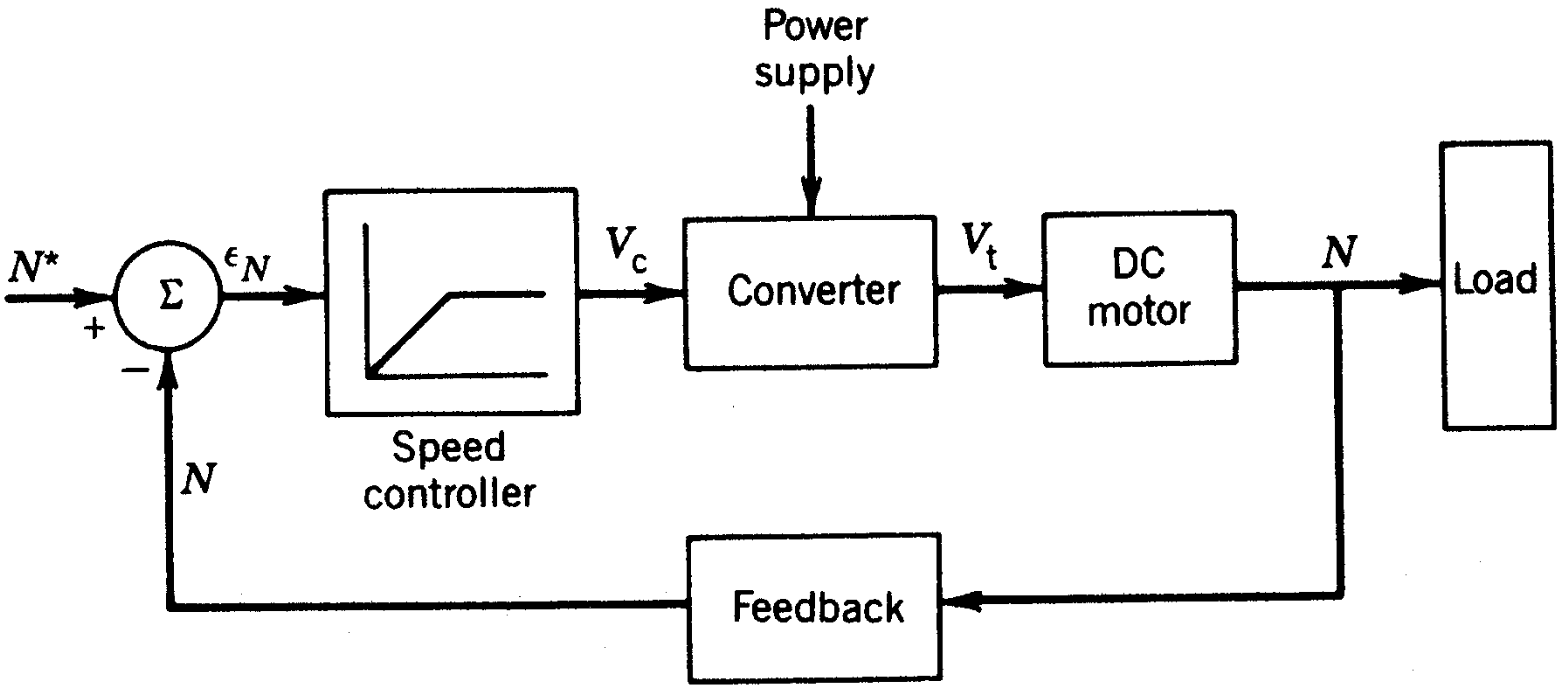


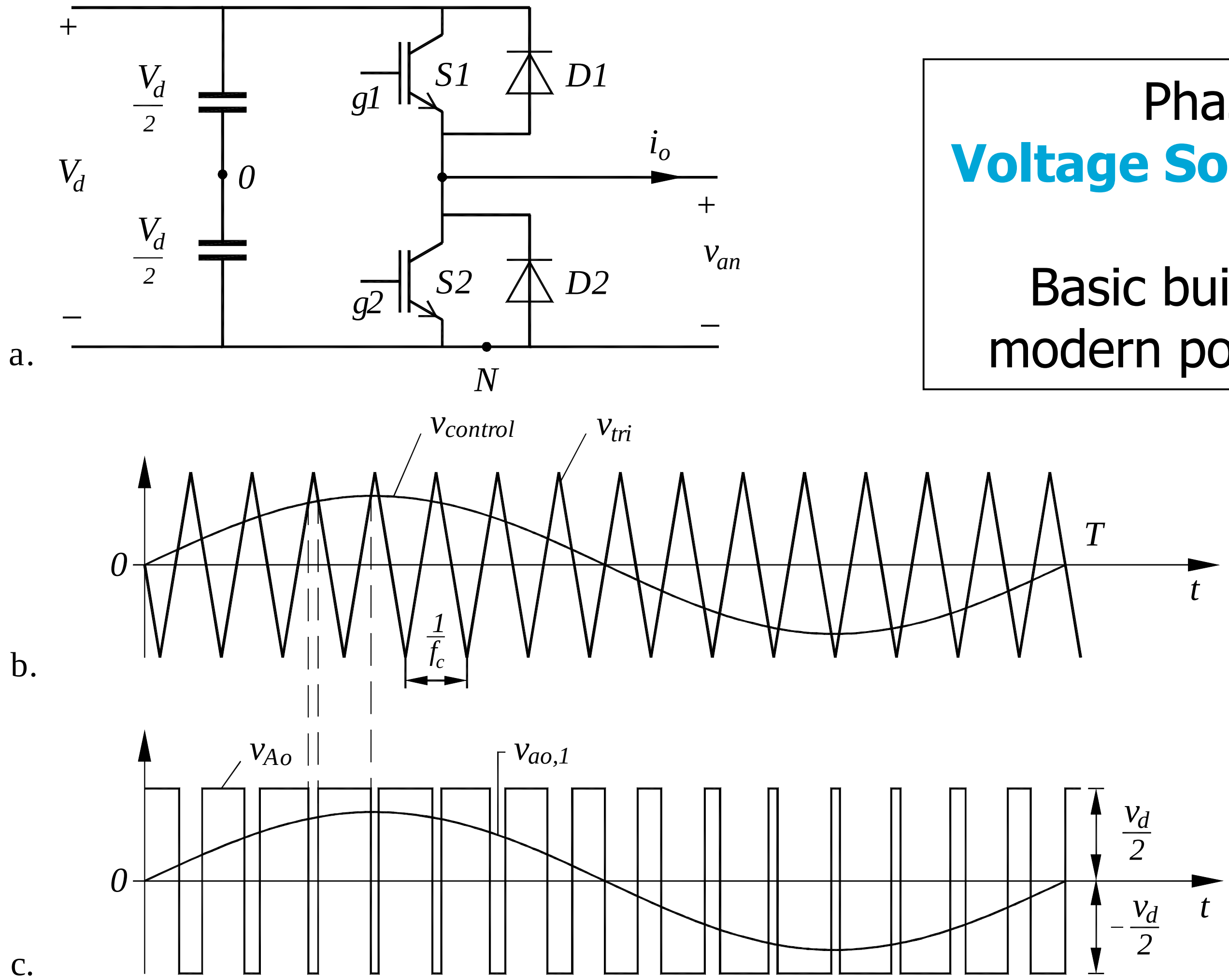
FIGURE 4.63 Closed-loop speed control system.

Power electronics

- Why power electronics?
  - to change speed and torque of machines, voltages, currents and frequencies on the machine terminals have to be changed
  - very precise and efficient control
  - possibilities of PE continuously increase
  - PE continuously becoming cheaper

- What do students have to know in this course?
  - most important converter types (rectifier, chopper, inverter)
  - which type is most suitable to drive a specific machine type
  - how any desired voltage or current waveform can be realized

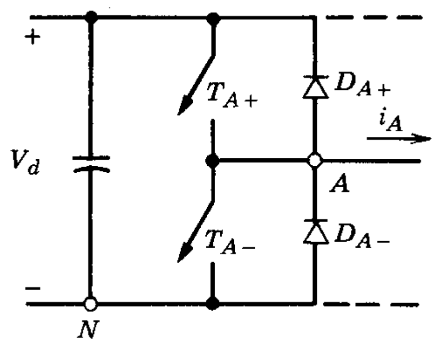
Principle of voltage source converter

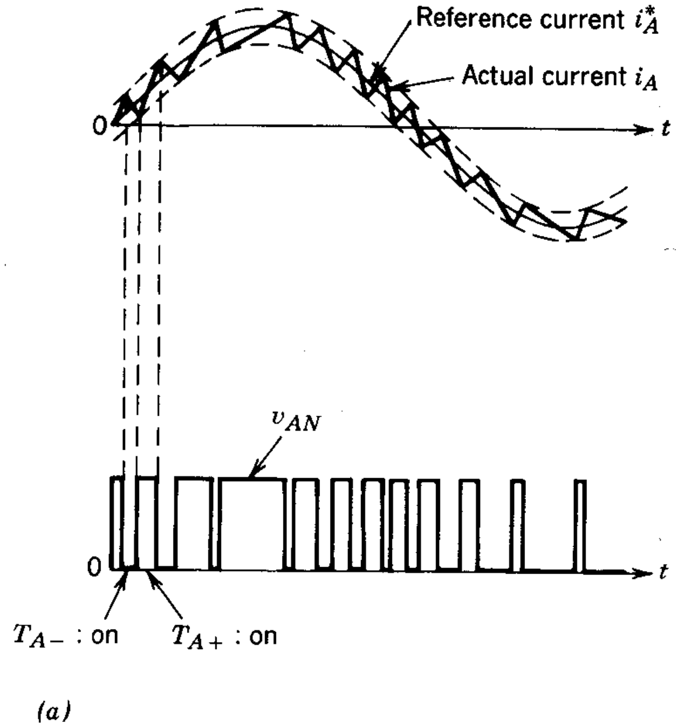


Phase leg of
Voltage Source Converter
=
Basic building block of modern power electronics

Average output voltage is a replica of $v_{control}$

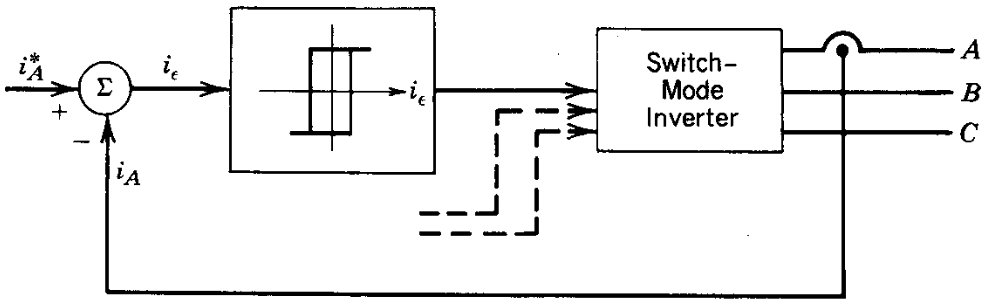
VSC as current source





The reason that the current increases with a limited rate is that there is a coil

$$u_L(t) = L\frac{\mathrm{d}i_L(t)}{\mathrm{d}t}$$



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Maxwell’s equations / magnetic circuits

- Introduction of Maxwell’s equations (for quasi-static fields)
- Ampere’s law used to calculate flux densities (1.1)
  - Around a wire in air
  - In magnetic circuit
  - In a magnetic circuit with an gap
- Second of Maxwell’s equations used to calculate voltages (1.1)
- Soft magnetic materials: hysteresis and eddy currents (1.2)
- Hard magnetic materials: permanent magnets (1.4)

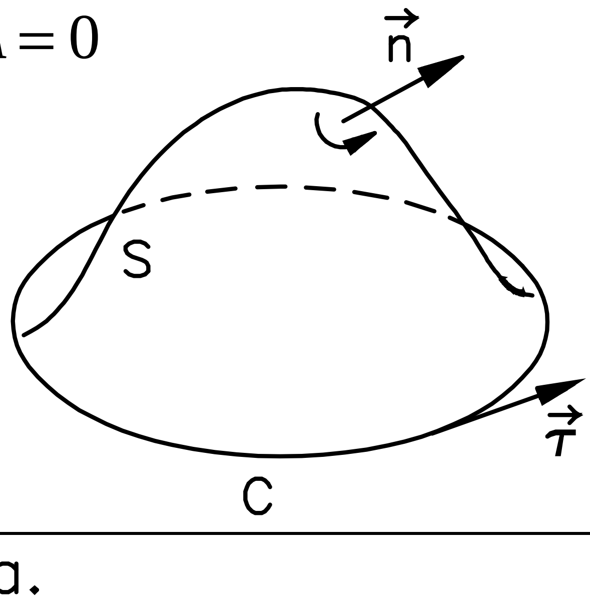
Maxwell's equations for quasi-static fields: Know by heart!

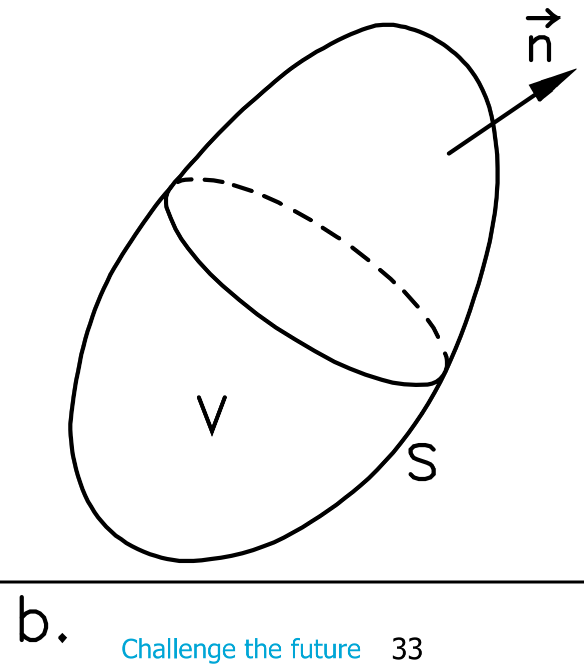
$$\oint_{C_m} \vec{H}\cdot\vec{\tau}\,\mathrm{d}s = \iint_{S_m} \vec{J}\cdot\vec{n}\,\mathrm{d}A$$

$$\oint_{C_e} \vec{E}\cdot\vec{\tau}\,\mathrm{d}s = -\frac{\mathrm{d}}{\mathrm{d}t}\iint_{S_e} \vec{B}\cdot\vec{n}\,\mathrm{d}A$$

$$\oiint_{S} \vec{B}\cdot\vec{n}\,\mathrm{d}A = 0$$

H : magnetic field intensity
J : current density
E : electric field intensity
B : magnetic flux density
n, τ: unit vectors





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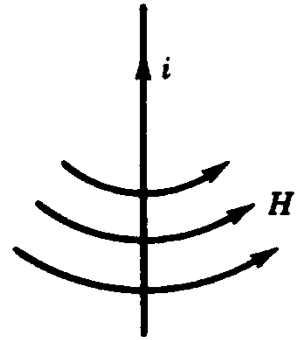
Magnetic field around a wire in air

Contour follows magnetic path.
Take a circular path around a wire:

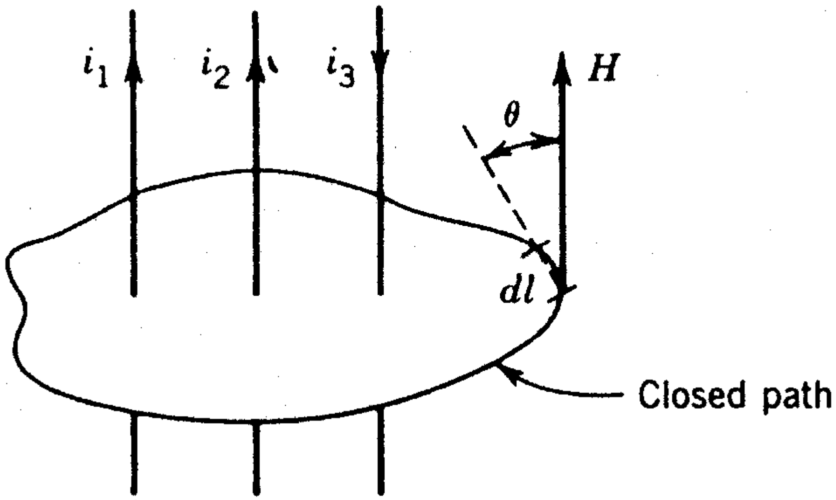


$$\oint_{C_m} \vec{H} \cdot \vec{\tau} \, \mathrm{d}s = \iint_{S_m} \vec{J} \cdot \vec{n} \, \mathrm{d}A = \sum i$$

because $i = \iint_{S_{Cu}} \vec{J} \cdot \vec{n} \, \mathrm{d}A$

$$H 2\pi r = i \quad \Rightarrow \quad H = \frac{i}{2\pi r}$$

$$B = \mu_0 H = \mu_0 \frac{i}{2\pi r}$$



Magnetic field in a magnetic circuit

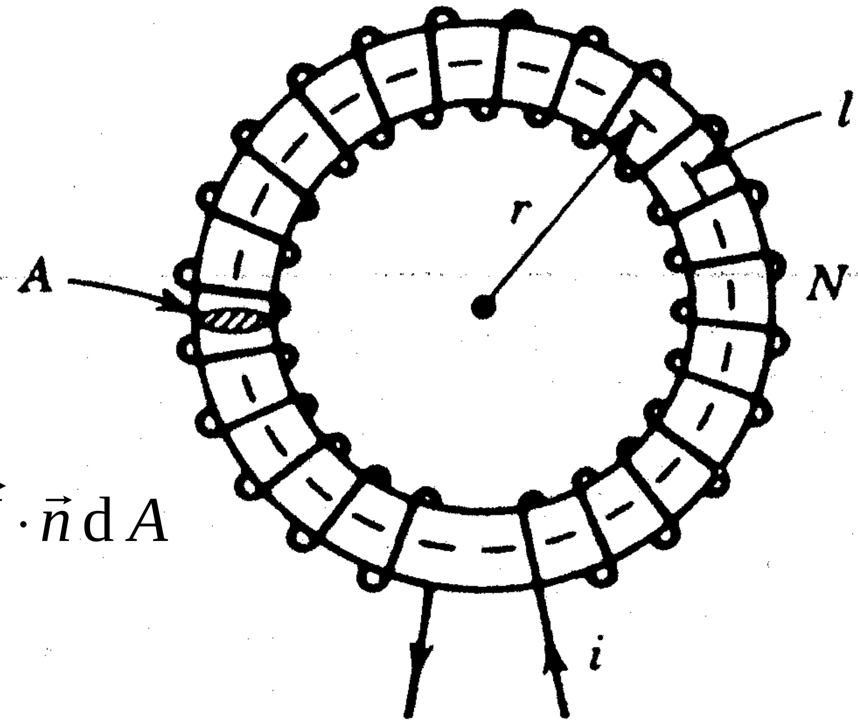
Contour follows magnetic path:

$$\oint_{C_m} \vec{H} \cdot \vec{\tau}\, \mathrm{d}s = \iint_{S_m} \vec{J} \cdot \vec{n}\, \mathrm{d}A$$

$$\oint_{C_m} \vec{H} \cdot \vec{\tau}\, \mathrm{d}s = Hl$$

$$\iint_{S_m} \vec{J} \cdot \vec{n}\, \mathrm{d}A = Ni \qquad i = \iint_{S_{Cu}} \vec{J} \cdot \vec{n}\, \mathrm{d}A$$

$$Hl = Ni \quad \Rightarrow \quad H = \frac{Ni}{l}$$



Assumption: symmetry, radius
Vectors!

Calculation of circuit flux

For linear materials:

$$B = \mu_0 \mu_r H = \mu_0 \mu_r \frac{Ni}{l}$$

$$\mu_0 = 4\pi 10^{-7}\,\mathrm{H/m}$$

$$\mu_r = 1 \ldots 100000$$

$$\Phi = \iint_{A_{core}} \vec{B} \cdot \vec{n}\, \mathrm{d}\,A$$

$$\Phi = BA_{core} = \mu_0 \mu_r \frac{Ni}{l} A_{core}$$

Alternative calculation of flux

Magnetomotive force Ni

Reluctance $R_m = \frac{l}{\mu_0 \mu_r A_{core}}$ $R = \frac{l_{Cu}}{\sigma_{Cu} A_{Cu}} = \frac{\rho_{Cu} l_{Cu}}{A_{Cu}}$

Flux $\Phi = \frac{Ni}{R_m}$ $i = \frac{u}{R}$

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