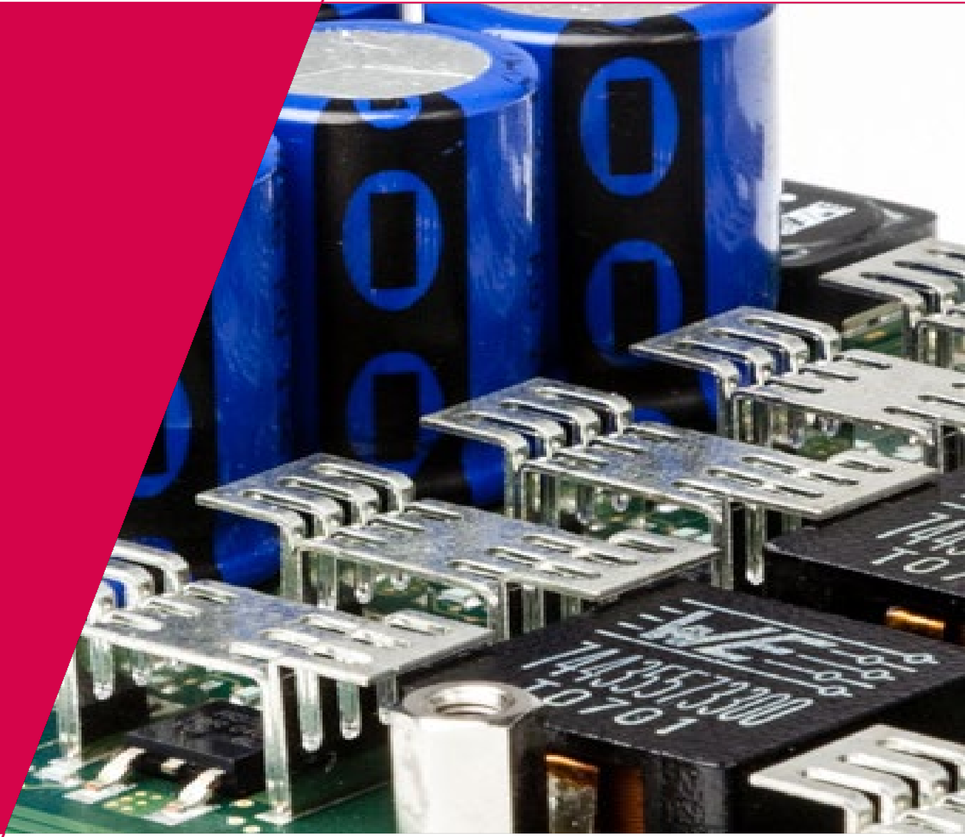
4AT060 Sustainable Vehicles (ED)
5AT010 Electrical Components

Electrical Machines

Dr. Esin Ilhan Caarls



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Where innovation starts

4AT060 & 5AT010 - 2.5ECTS

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
3rd: 10:45-11:30 4th: 11:45-12:30	Powertrain Topologies & Modeling	Electrical Machines	Power Electronics	Charging	Batteries	Powertrain Control	Fuel Cells and Aux. Systems	Reflection
7th: 15:45-16:30 8th: 16:45-17:30					Instructions: -Work on Assignments -Q&A	No instructions 20^{th} Dec.		No instructions 17^{th} Jan

<u>Make sure you monitor CANVAS for updates etc.</u>

ED Interim Assignment will be released today! Deadline 9 Dec!
Topics: Lecture Weeks 2-3

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MENTIMETER / PULSE CHECK!

https://www.menti.com/alba9o74rtep

Go to https://www.mentimeter.com/ → Menti Code 45 64 78 4

Agenda

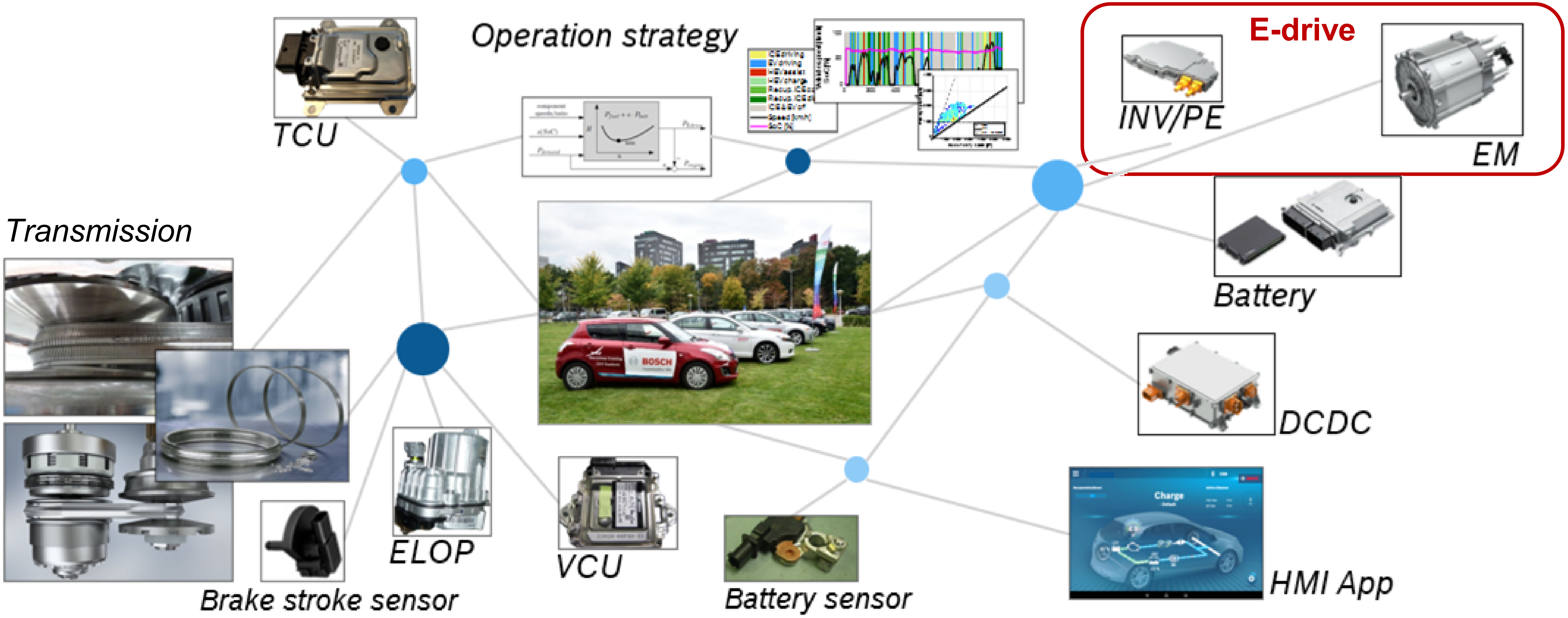
- Electrical drives (EPE courses 5XWB0 Q3, 5LWE0 Q1, 5LWH0 Q1)
- Electrical machines (EM) (EPE courses 5SWA0 Q2, 5LWF0 Q3)
  - Magnetism and Torque production
  - Electric and Magnetic Circuits → Break!
  - Synchronous permanent magnet (PM) machines
  - Control aspects
  - EM Efficiency/Power loss maps

Intended Learning outcomes:

- Identify the main working principles and constraints of the traction E-drives and E-machines
- Explain the basic concept for the E-machine control
- Describe the component-system level interactions

ELECTRICAL DRIVES (E-Drives)

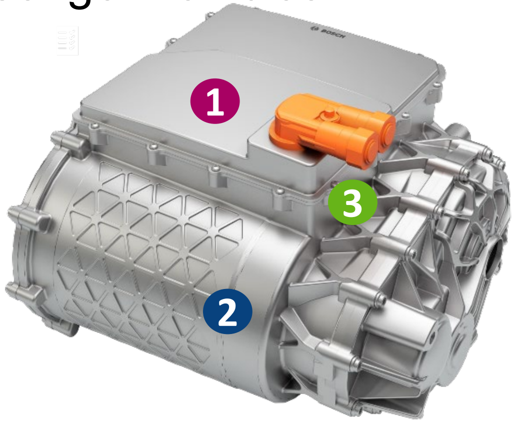
Automotive as an inter-connected system



EM: Electrical machine, INV: Inverter, PE: Power Electronics, TCU: Transmission control unit, VCU: Vehicle control unit, ELOP: Electrical oil pump, HMI: Human machine interface

Examples of system integration – eAxle

Source: Bosch eAxle for passenger vehicles



1 **Direct integrated power electronic**

Reduction of cost, weight & losses

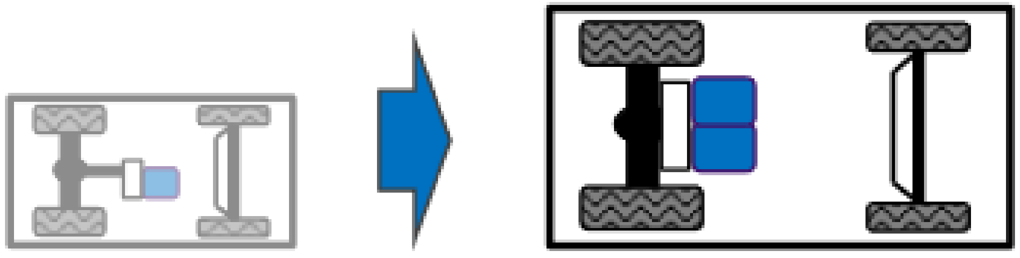
2 **One shared bearing shield for E-machine & Transmission**

Reduction of cost & weight

3 **One common cooling circuit for power electronics & e-machine**

Reduction of interfaces

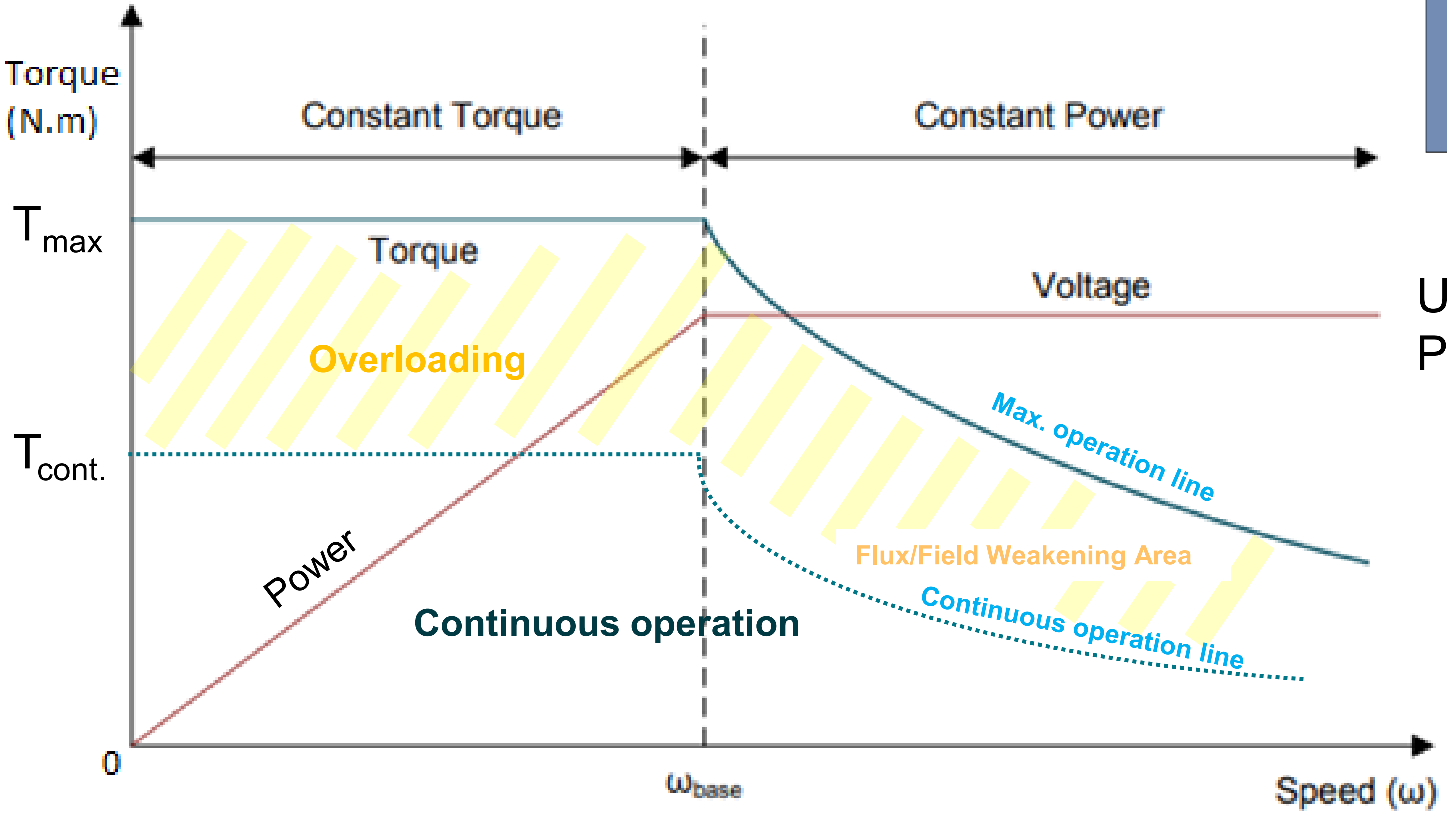
Topology scaling in Commercial Vehicles (heavy-duty applications)



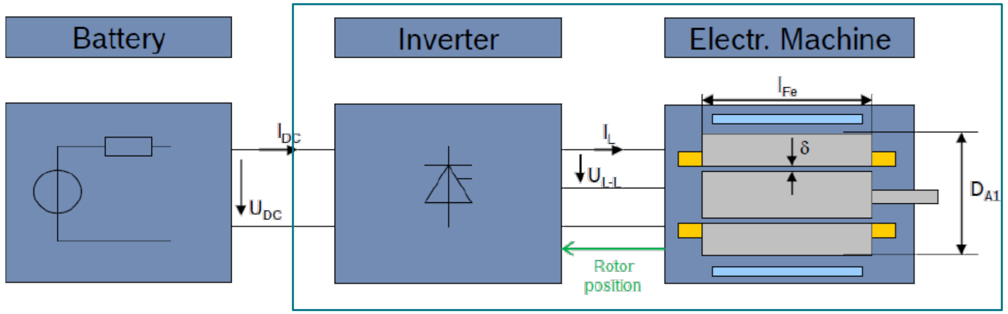
Main challenge is:

- Improved Motor Cooling (air+water) for better higher power/ better performance

EM & E-drive operation modes & terminologies



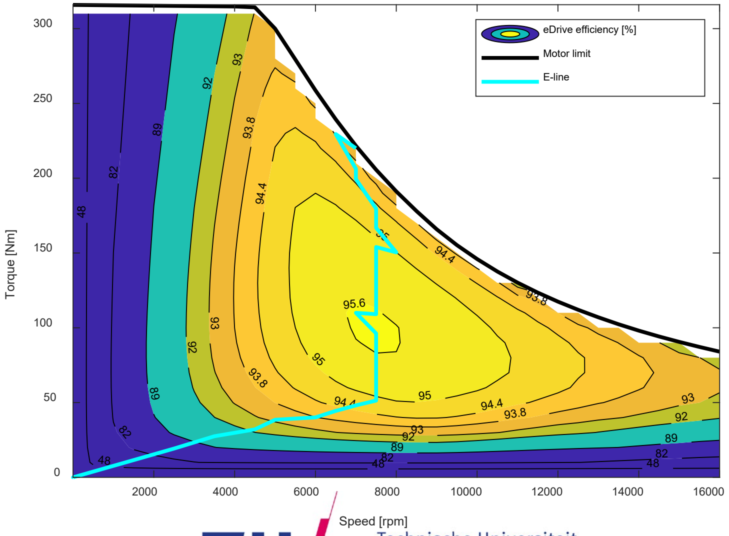
IDEALIZED CURVES



EM + INV = E-Drive / EDR

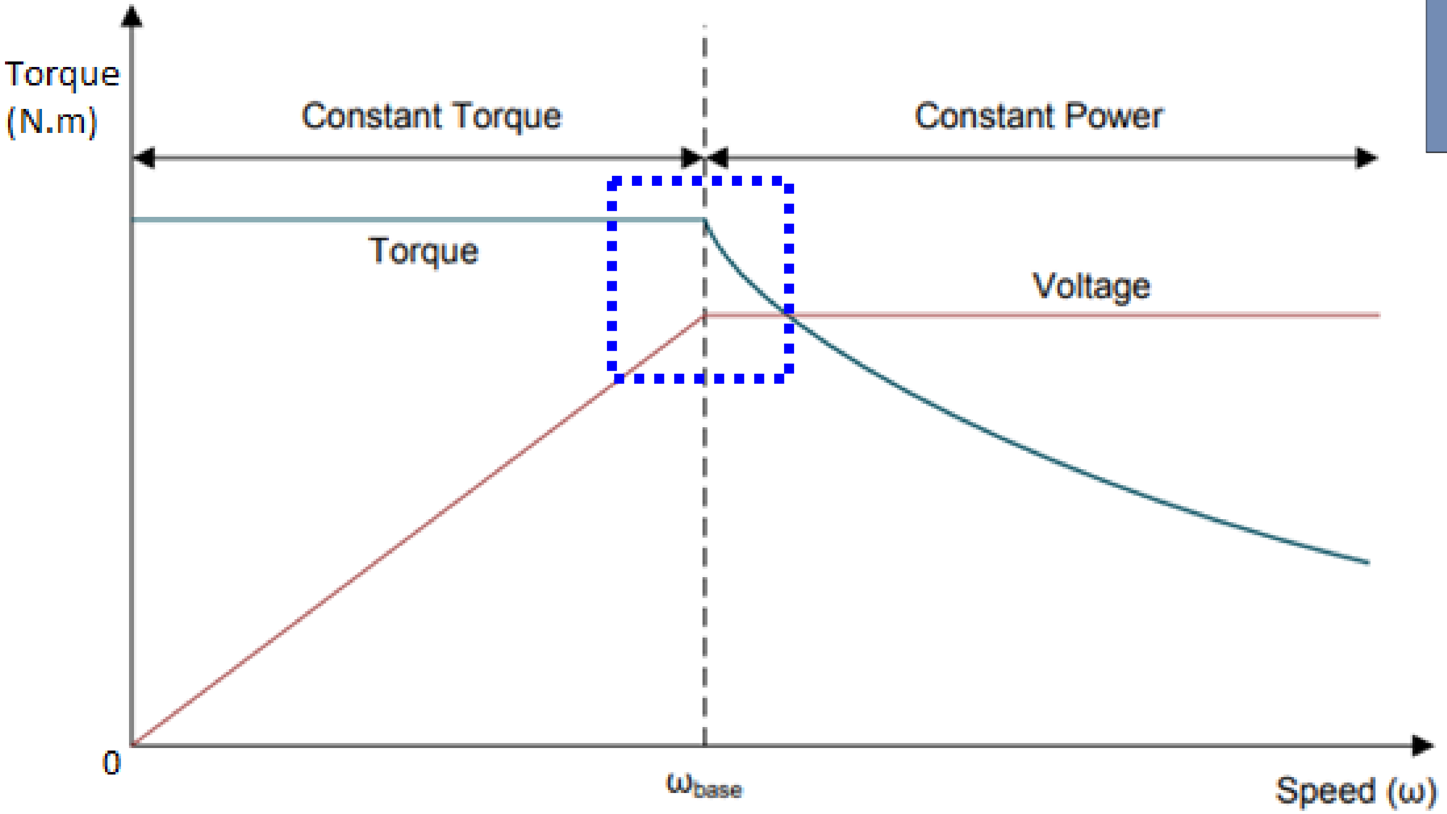
$U_{max} < U_{DC}$
P_{max}

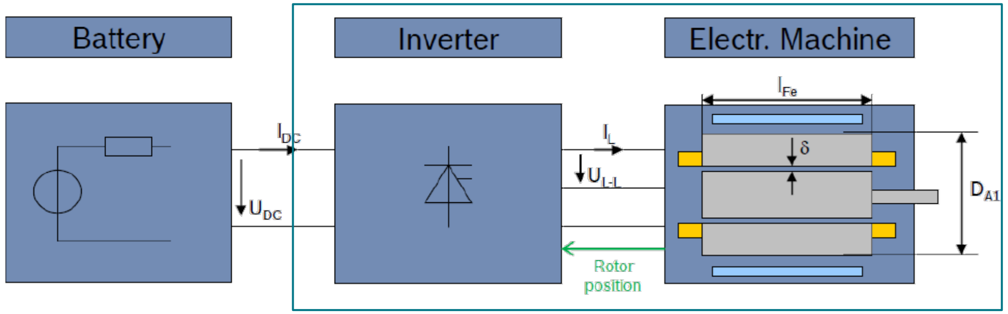
Efficiency / Power loss map



Important performance parameter: Cont-peak power ratios

EM & E-drive operation modes & terminologies





EM + INV = E-Drive / EDR

Corner point @base speed:

- Performance limited by allowed max. current (Torque) & max. voltage (Power),
- Control strategy changes
- Control strategy directly affects torque (torque control)
- The base speed definition can change if target is to maintain "max torque" or "max power".
- Where the actual "max" power & "max" torque are located can shift around the base speed.

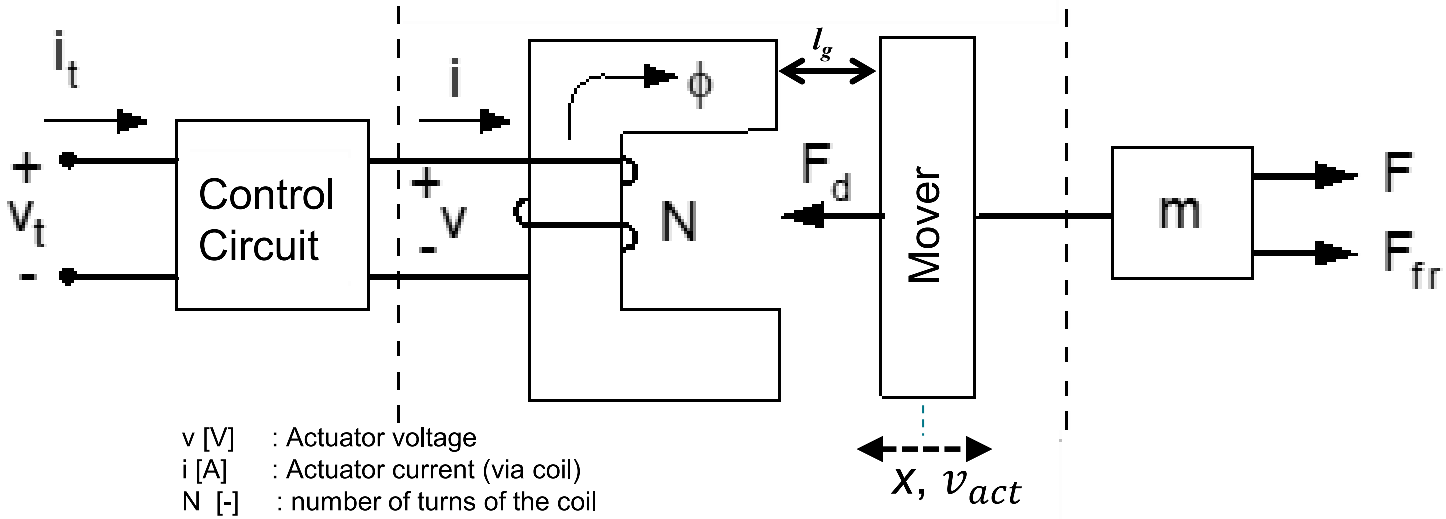
Idealized curves, Definitions can change depending on control strategies!

Electrical Machines (EM)
(Magnetism & Torque production)

Electromechanical Energy Conversion

- Multi-physical domain operation
- Example: An actuator

Electrical Energy Domain | Magnetic Energy Domain | Mechanical Energy Domain



v_t [V] : Input voltage to controller
i_t [A] : Input current to controller

v [V] : Actuator voltage
i [A] : Actuator current (via coil)
N [-] : number of turns of the coil

Φ [Wb] : Magnetic flux
F_d [N] : Electromagnetic drive force
l_g [m] : Length of the airgap between the moving part (mover) of the actuator and its stationary part

x : Axis of the movement
v_{act} [m/s] : Actuator velocity

m [kg] : mass of the mechanical load
F [N] : load force
F_{fr} [N] : Friction force (loss)

Fnet [N] :Total force acting in actuator (mover)

$$F_{net} = F_d - F - F_{fr}$$

T_{net} [Nm] : Net torque
w_{act} [rad/s] : Actuator angular velocity

If no internal losses → $P_{el} = P_{mech}$

$$v_t * i_t = v * i = F_{net} * v_{act} = T_{net} * w_{act}$$

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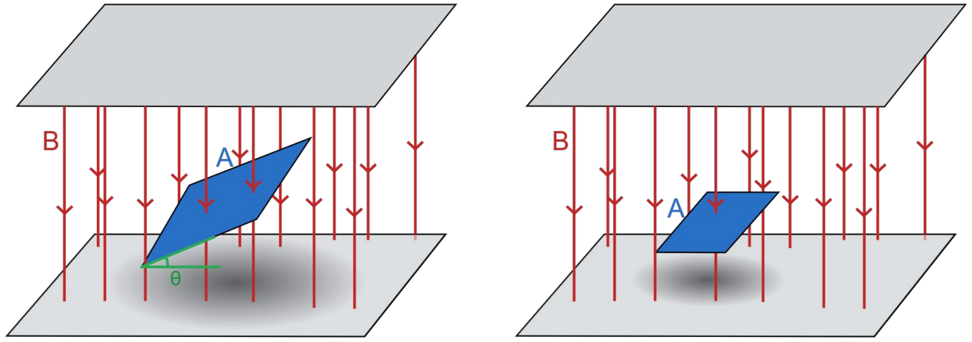
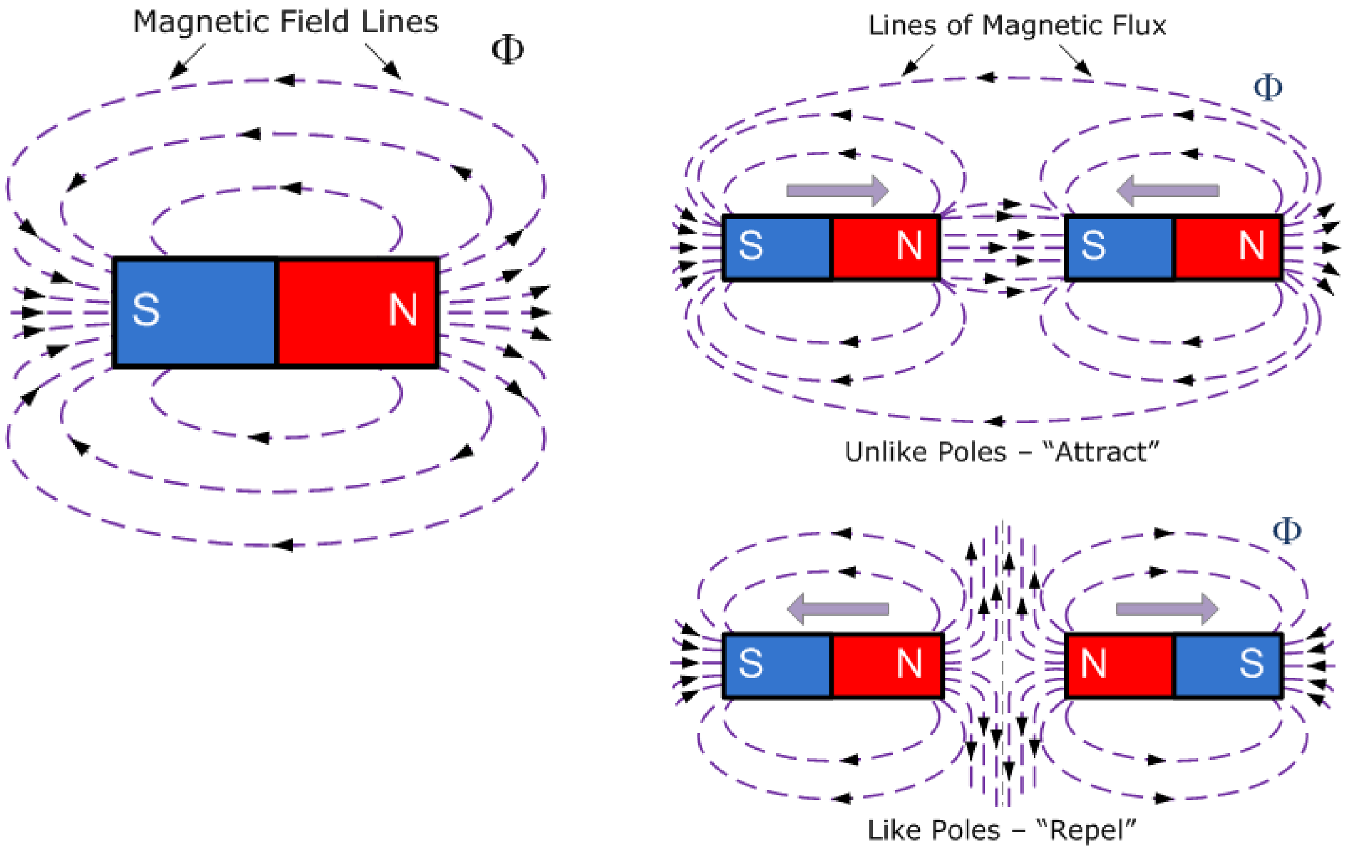
Magnetic Flux (Φ) and Magnetic Flux Density (B)

Magnetic flux Φ is a measurement of the total magnetic field



$\Phi = B.A.\cos\theta$ $\lambda = n.\Phi$



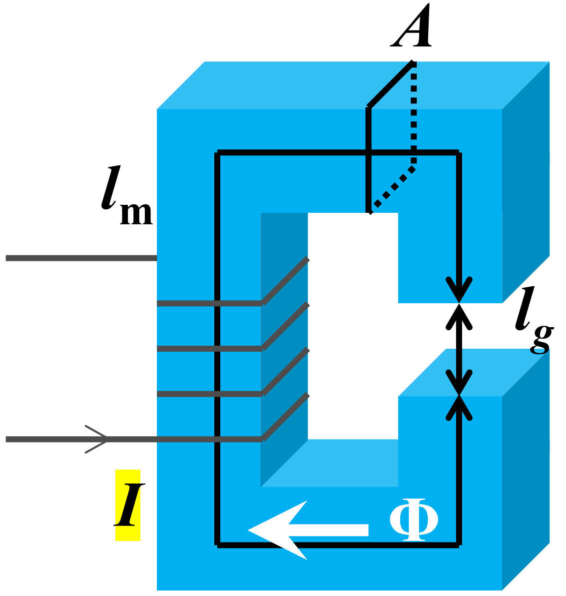
Where:

Φ : Magnetic Flux (Linkage) [Wb, Weber]
λ : Magnetic Flux Linkage [Weber-turns]
B: Magnetic Flux Density (Magnitude of the magnetic field) [Wb/m^2 or Tesla]
A: Area of surface [m^2]
θ: Angle between the magnetic field lines and the normal (perpendicular) to A [° or Degree].
n: number of turns of coil / conductor

Materials in the EM

EMs are constructed of

1. **(Magnetic) Field sources (Φ) :**
   - conductors, coils (copper, aluminum, etc.) carrying current I
   - magnets (permanent magnet (PM) as rare-earth (NdFeB, SmCo), ferrite, etc.)

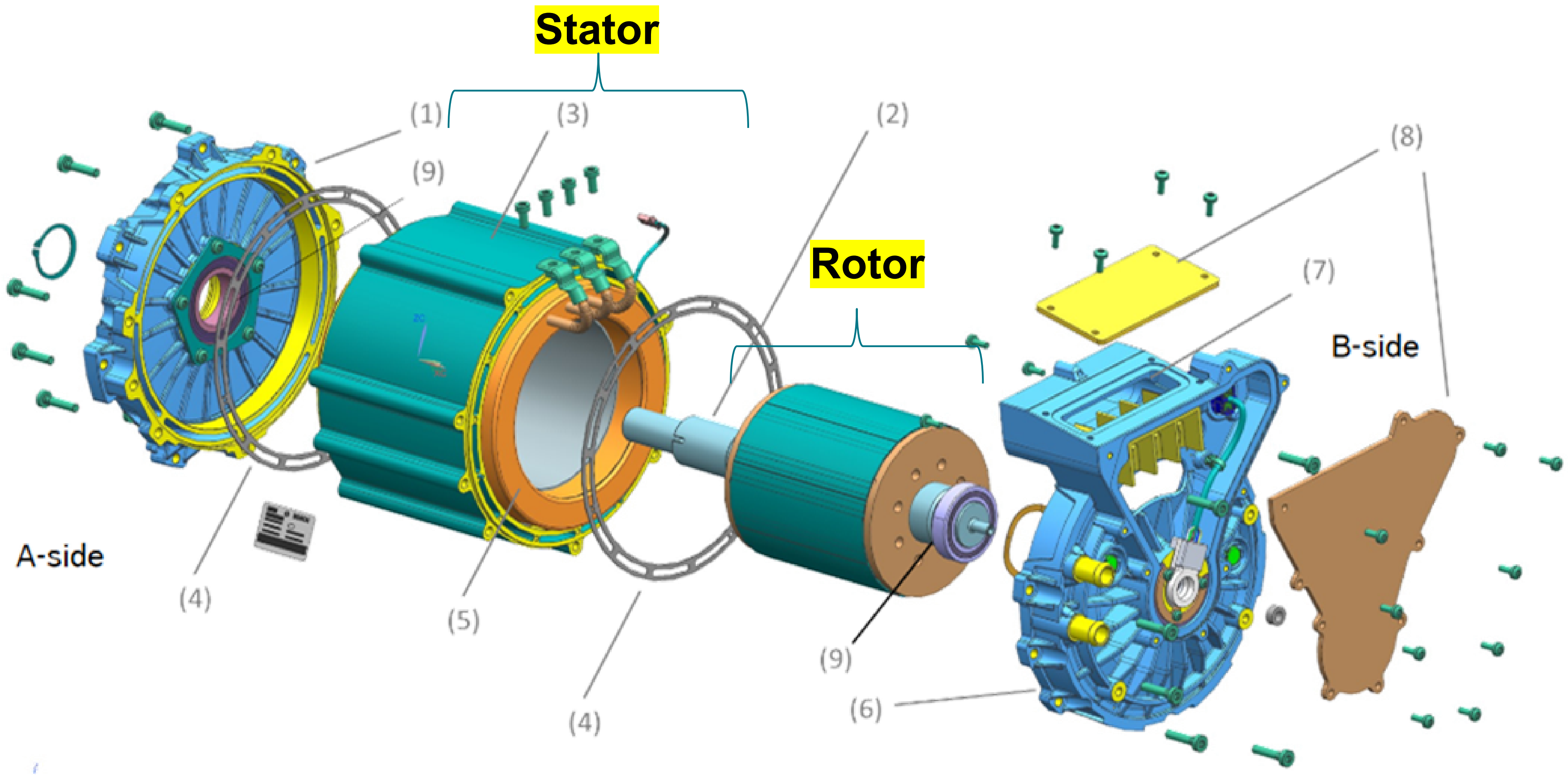


2. **(Soft) Ferromagnetic materials (l_m):** affected / magnetized by external magnetic field and provides flux paths (increases energy density in the device/EM)
   - Iron (core) with Silicon (SiFe), with cobalt (CoFe), with Nickel (NiFe)

3. **Air (l_g):** medium/airgap where energy conversion takes place (electrical energy ← → magnetic energy)

NdFeB: Neodymium Iron Boron
SmCo : Samarium Cobalt

Traction EM: Typical parts



1. End shield A-side
2. Shaft end
3. Housing
4. Sealing
5. Stator winding
6. End shield B-side
7. Terminal box
8. Cover of terminal box
9. Bearing

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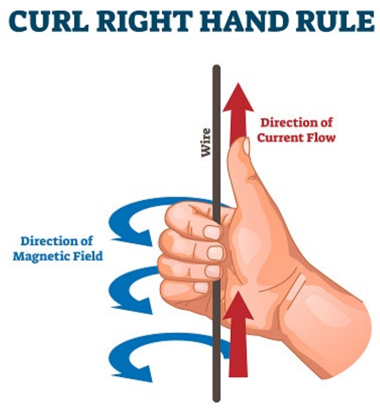
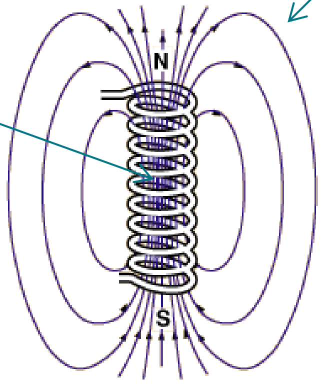
Field sources: Coils or Magnets

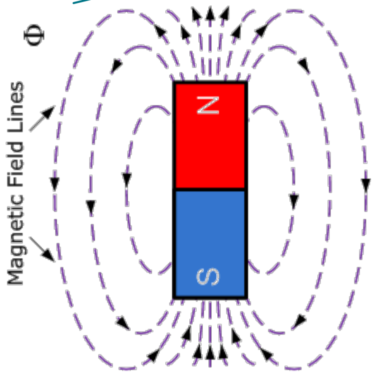


Current Carrying Coil / conductor

Magnetic field (flux) lines



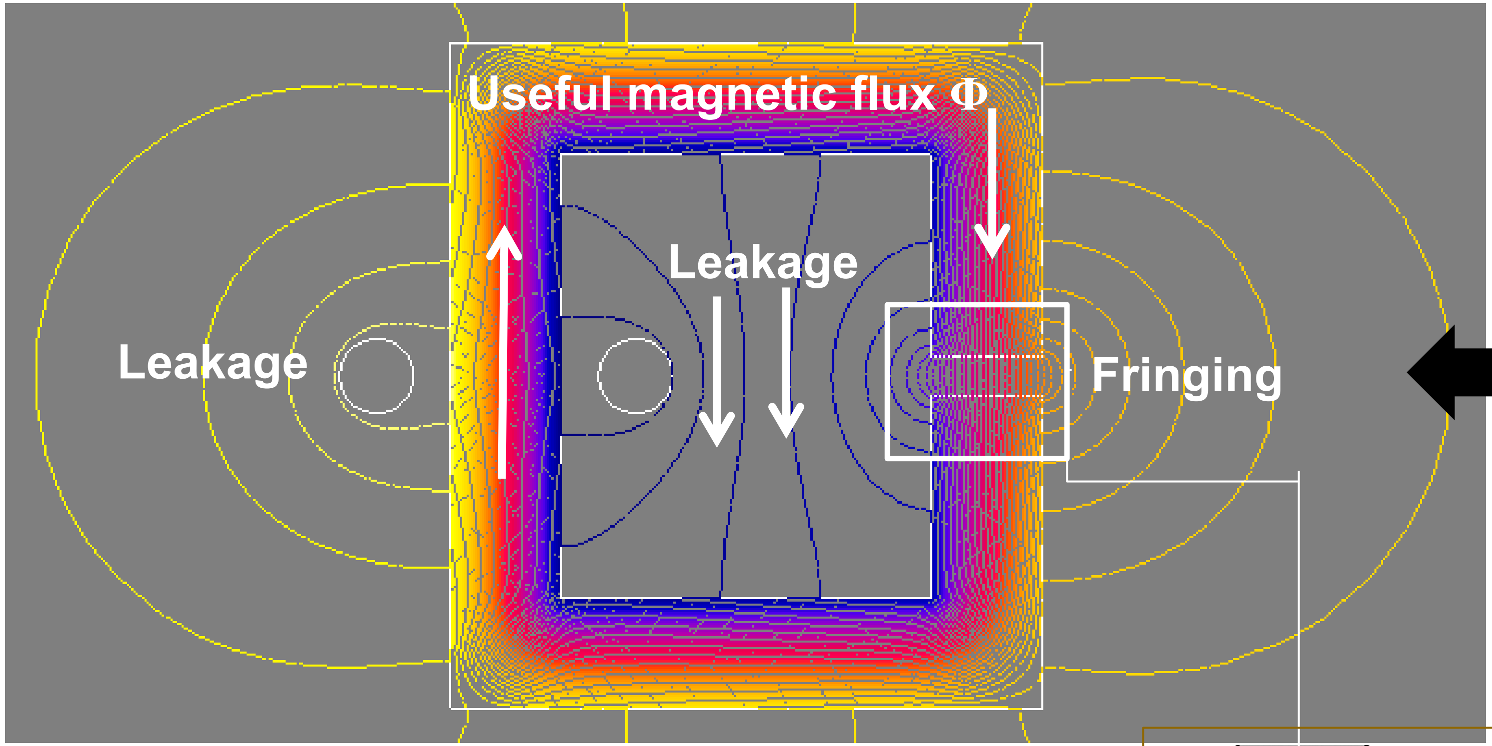
Electromagnet

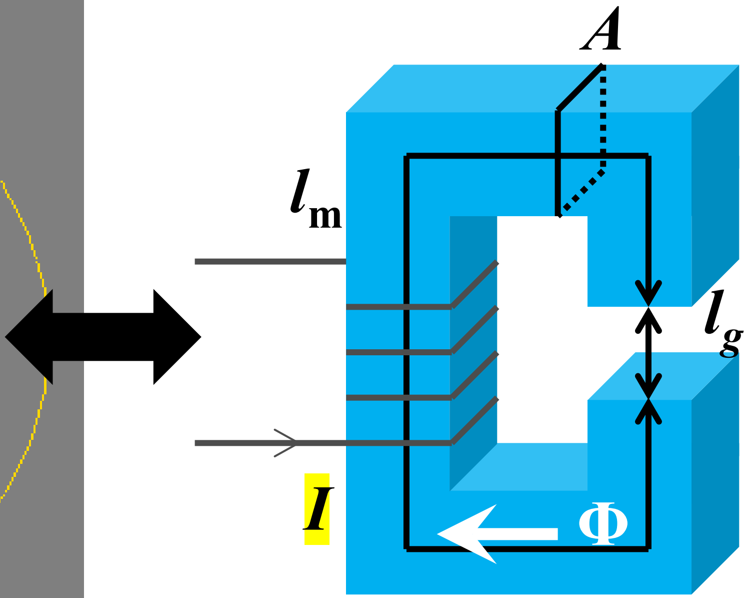


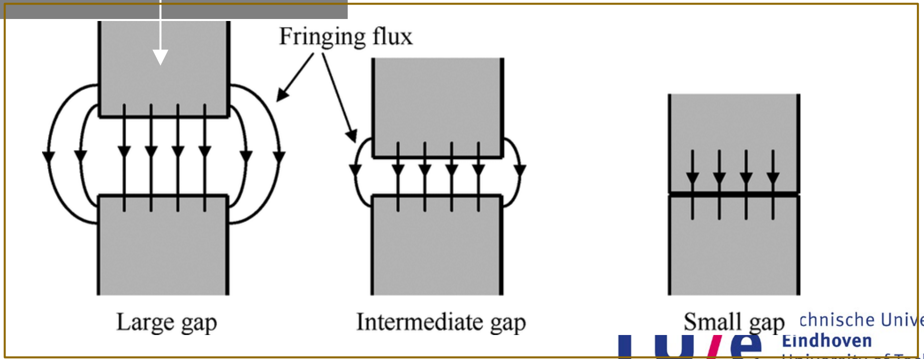
(Permanent) Magnet

EM with…	Coils	Magnet
Torque capability	Moderate	High
Efficiency	Moderate	High
Operational speed range	High (limited by thermal insulation of coil)	Low/moderate (limited by demagnetization)

Magnetic flux in ferromagnetic (iron) material



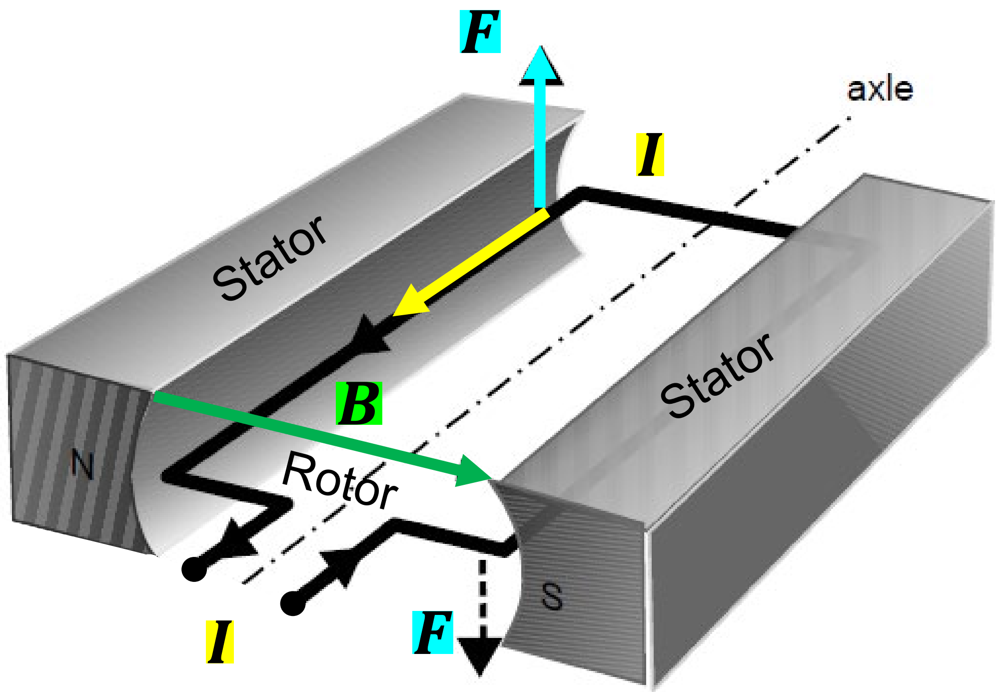




Torque production mechanism: Lorentz force

Example: Simplified DC Motor:

- Rotor: 1 coil conductor (wire) carrying current ***I***
- Stator: 1 magnetic pole pair (1PM with N-S) producing ***B***



•***Physical Law***: A force acts on a current (***I***) carrying conductor (coil) inside an external magnetic field ***B***

$$\mathbf{F} \sim \mathbf{I} \times \mathbf{B}$$

- ***B*** is the (stator) magnetic flux density [Wb m^{-2}]
- ***I*** is the (rotor armature) current [A]
- ***F*** is the Lorentz force [N]

Lorentz Torque

→ T ~ ***I*** x ***B*** **OR**

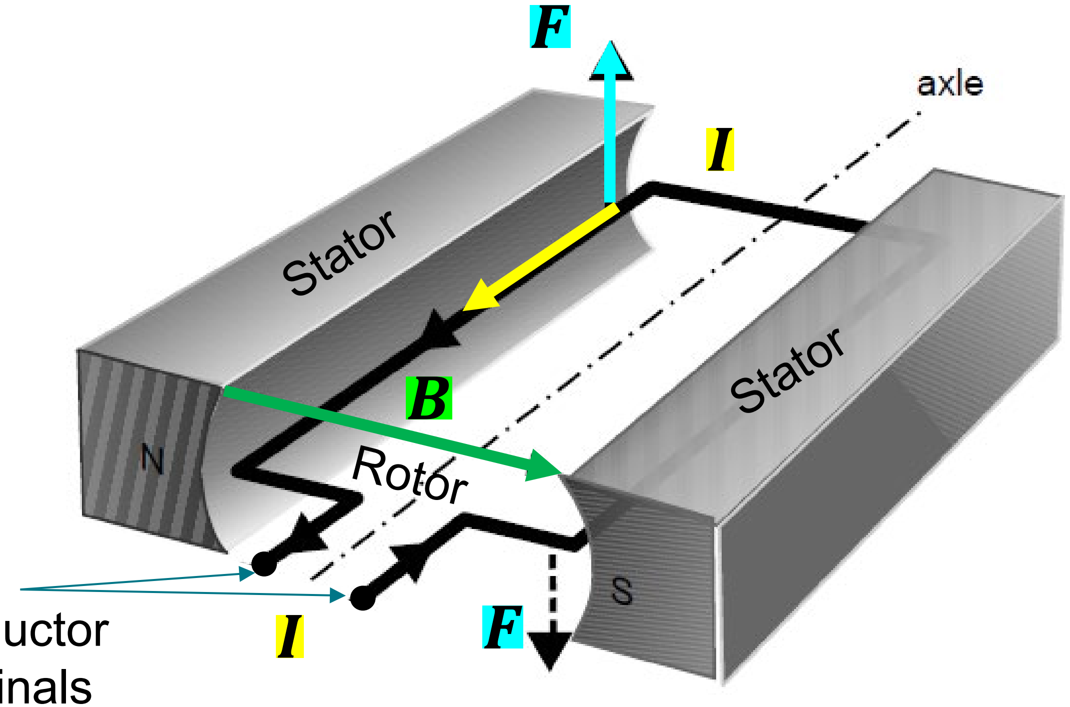
→ T ~ ***I*** x ϕ **OR**

→ T ~ ***I*** x λ

Torque production mechanism: back-EMF

Example: Simplified DC Motor:

- Rotor: 1 coil conductor (wire) carrying current ***I***
- Stator: 1 magnetic pole pair (1PM with N-S) producing ***B***



•***Physical Law****: Movement (speed v) of conductors (rotor winding) in an external magnetic field (stator magnetic field B) generates a voltage drop at its (rotor) terminals, i.e. back-EMF**

$$e_b \sim B\, v$$

$$e_b \sim \phi\, \omega$$

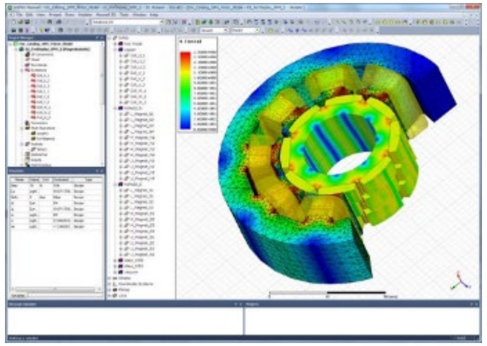
Note: Excitation/magnetic field B responsible for E_b can be created by magnets (PM) or current carrying conductor

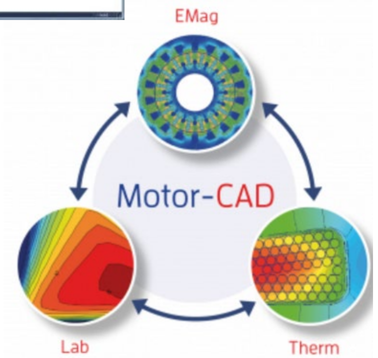
*Faraday and Lenz laws, ** EMF: Electro-motive force

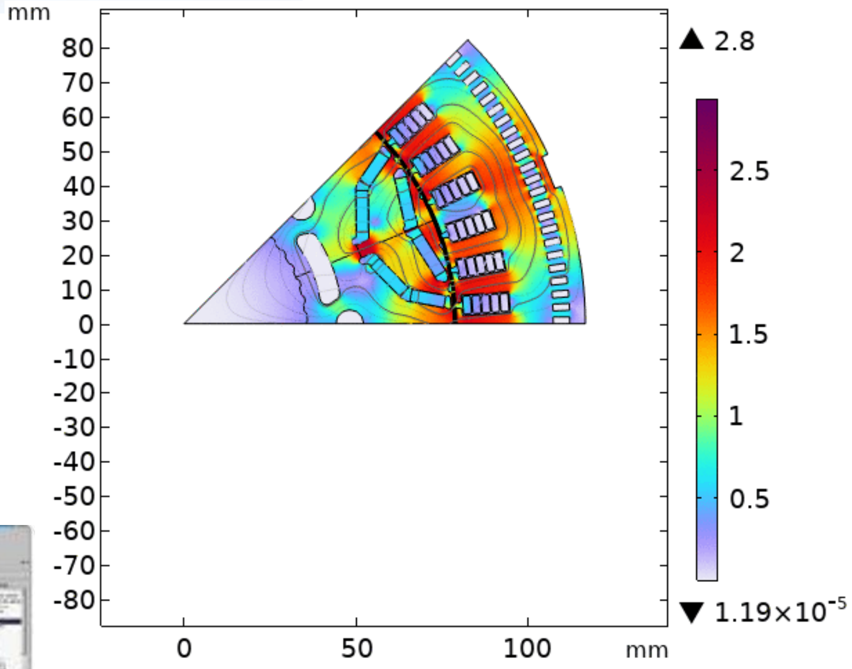
Electrical Machines (EM)
(Electric and Magnetic Circuits)

Modeling of EMs

Numerical approaches





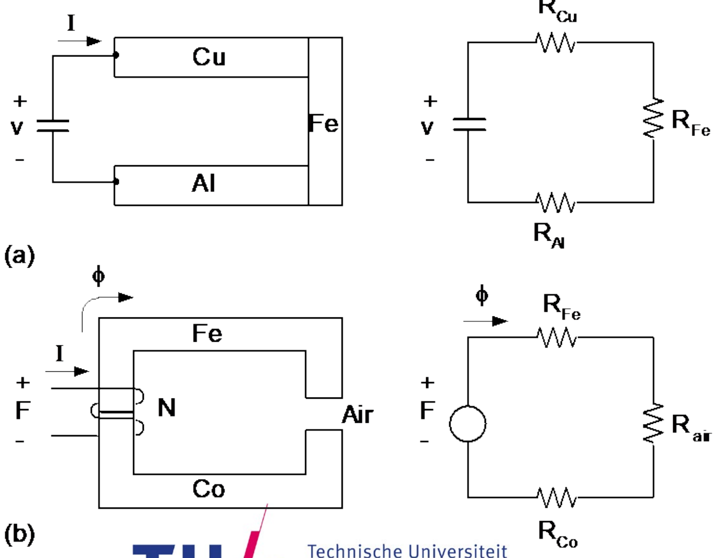


Analytical approaches

MATLAB

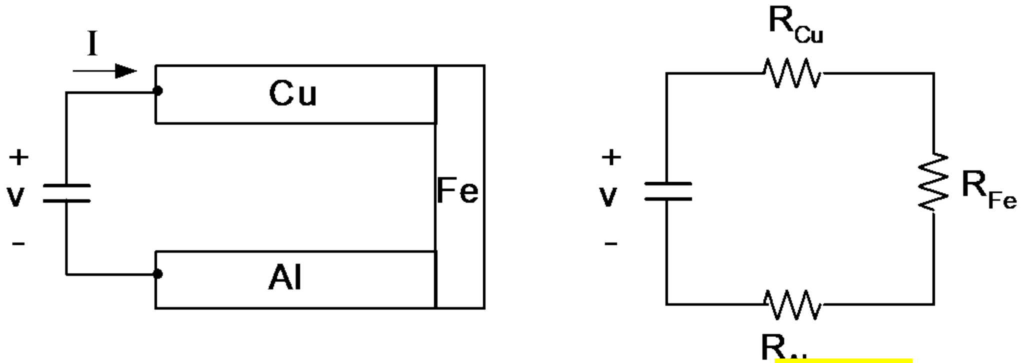
Harmonic series expansions

Equivalent circuits

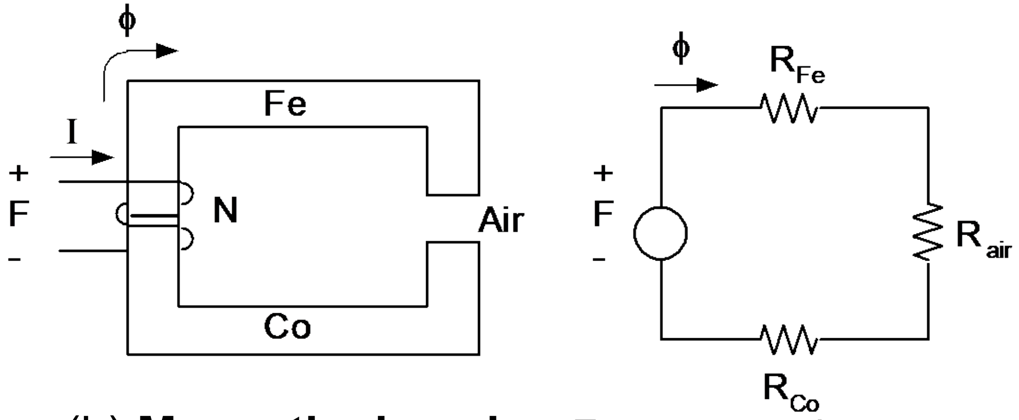


Modeling of materials

Electric		Magnetic	
Voltage	*V* (V)	MMF	*F* (A-t)
Current	*I* (A)	Flux (linkage)	ϕ * (or λ) (Wb)
Resistance	*R* (Ω)	Reluctance	*R* (H^{-1})



(a) **Electrical domain:** Direct and indirect electrical field sources are represented by voltage supply and electrical resistances of the used wires (Copper & Aluminum)



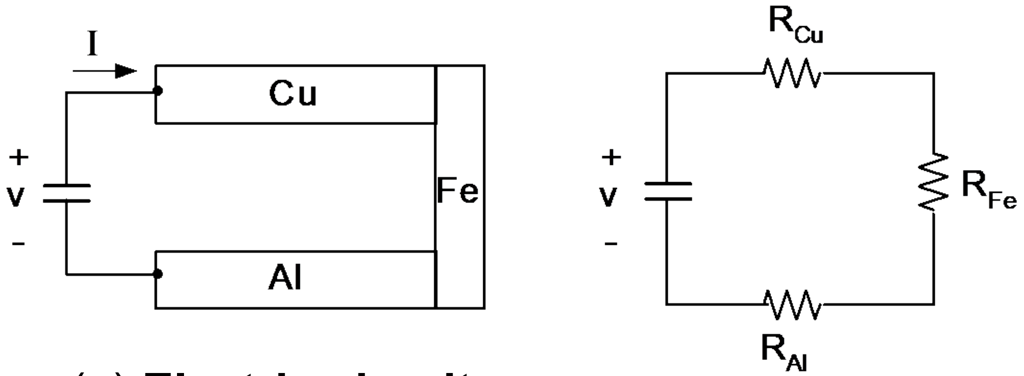
(b) **Magnetic domain:** Ferromagnetic core (Iron or Cobalt) shows a similar resistance to the magnetic field sources.

Note: An example indirect voltage source is the E_b back-EMF.

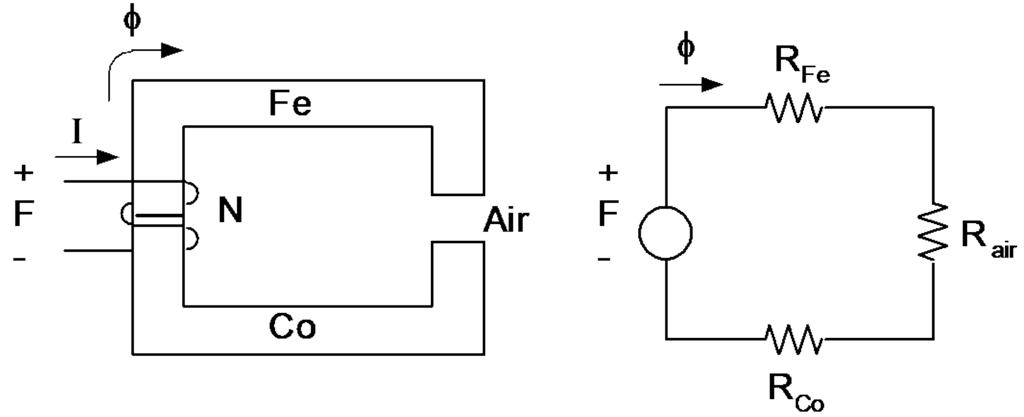
Analogy between electric and magnetic circuits

Electric		Magnetic	
Voltage	V (V)	MMF	F (A-t)
Current	I (A)	Flux (linkage)	ϕ * (or λ) (Wb)
Resistance	R (Ω)	Reluctance	R (H^{-1})
Conductance	G (S)	Permeance	P (H)
Electric field intensity	E (V/m)	Magnetic field intensity	H (A-t/m)
Current density	J (A/m^2)	Magnetic flux density	B (T OR Wb/m^2)
Conductivity	σ (S/m)	Permeability	μ (H/m)
$V = IR$ $J = \sigma E$ $R = \frac{l}{\sigma A} = \frac{1}{G}$		$F = \phi R$ $B = \mu H$ $R = \frac{l}{\mu A} = \frac{1}{P}$	

$$L = \frac{d\lambda}{di} = n\frac{d\phi}{di} = n\frac{dB \times A}{di}$$



(a) **Electric circuit** (Copper & Aluminium are typically used in windings)



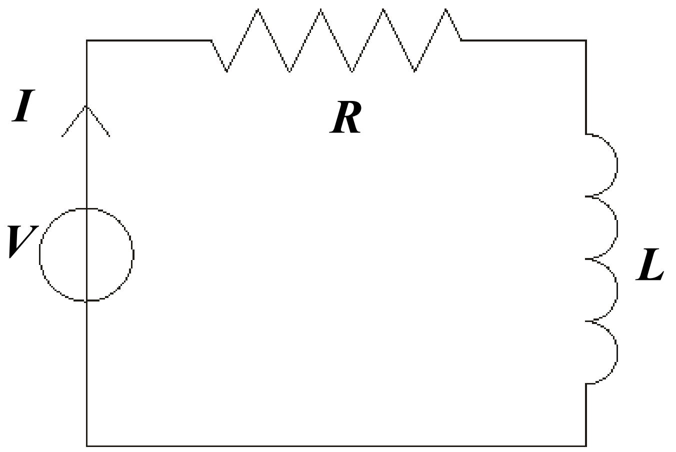
(b) **Magnetic circuit** (Iron & Cobalt are typically used in ferromagnetic core)

*λ flux linkage is number of turns (n) times Φ, therefore the same unit (Wb)

Electric circuits: Inductance

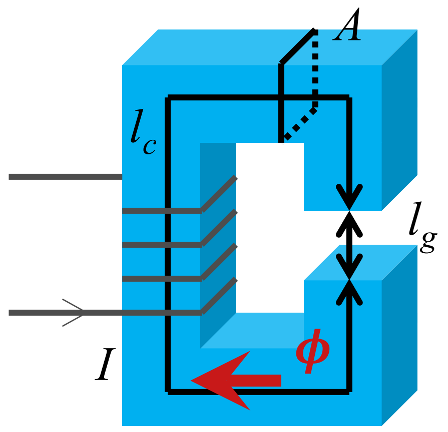
- The **inductance** (or coil) is an electric circuit variable that relates the magnetic field variable (**flux linkage λ**) to the electric circuit variable (**current i**).

Electric circuit



$$V = IR + L\frac{di}{dt}$$

Magnetic circuit



$$L = \frac{d\lambda}{di} = n\frac{d\phi}{di} = n\frac{dB \times A}{di}$$

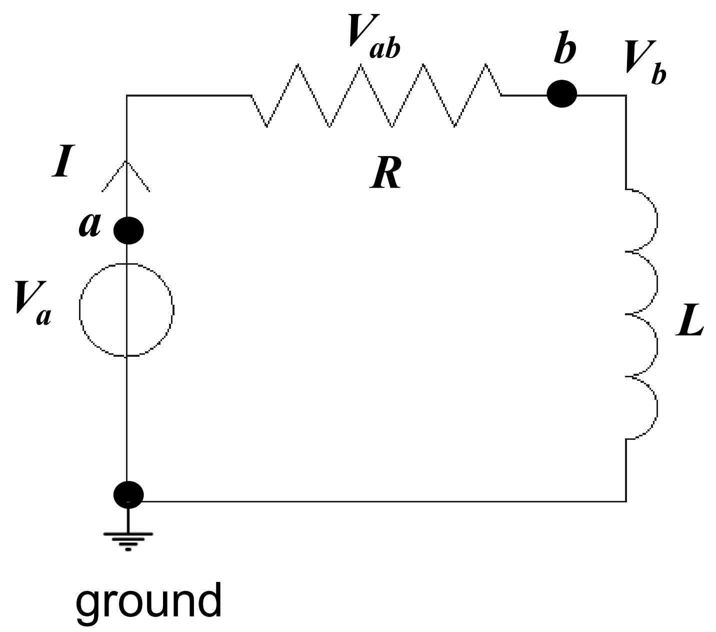
R [ohm] : wire resistance
L [Henry] : the wire inductance
n [-] : number of turns
A [m^2] : effective area where the magnetic flux ϕ passes

Note: In the EM circuit representation, winding-cables are represented by series connected R-L.

Electric circuits: Basic concepts

Voltages:

- V_a is the voltage of node a with respect to ground
- $V_{ab} = V_a - V_b$ refers to the voltage of node a with respect to node b



Source: V_a

Load: R-L,

$$V_{ab} = V_R = I\,R,$$
$$V_b = V_L = L\,di/dt$$

Typical Representation:

Lowercase letters (e.g. i): instantaneous value (time depending quantity)

Uppercase letters (e.g. I): average or RMS values

Electric circuits: AC signals (time-dependent), RMS (effective) voltage and current

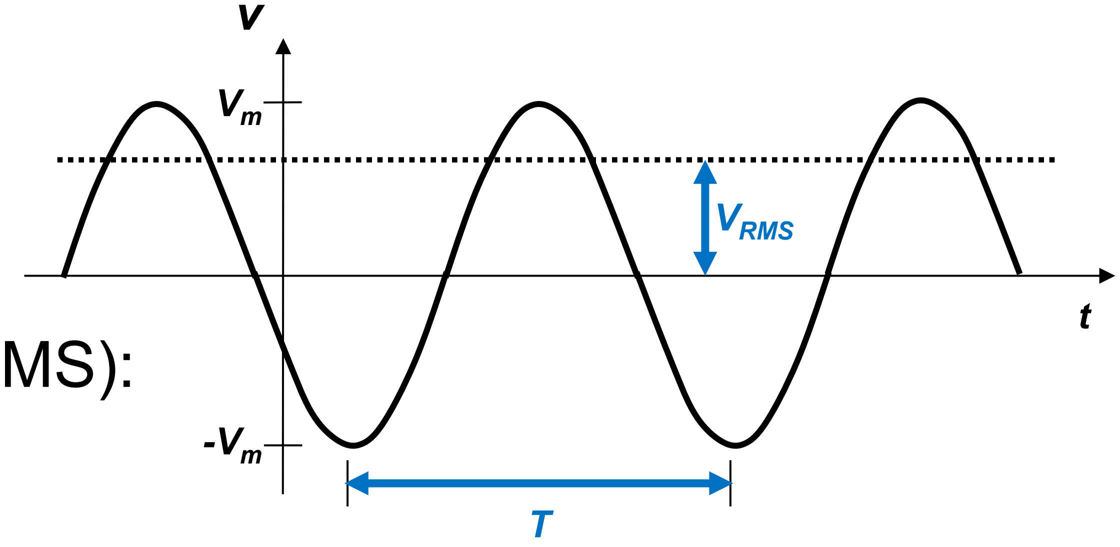
- Example: Sinusoidal voltage v(t):

$$v(t) = V_m \cos(\omega t + \phi)$$

- Apply definition of Root-Mean-Square (RMS):

$$V = \sqrt{\frac{1}{T}\int_{t_1}^{t_1+T} v^2(t)\mathrm{d}t}$$

$$V_{RMS} = \frac{1}{\sqrt{2}}V_m$$



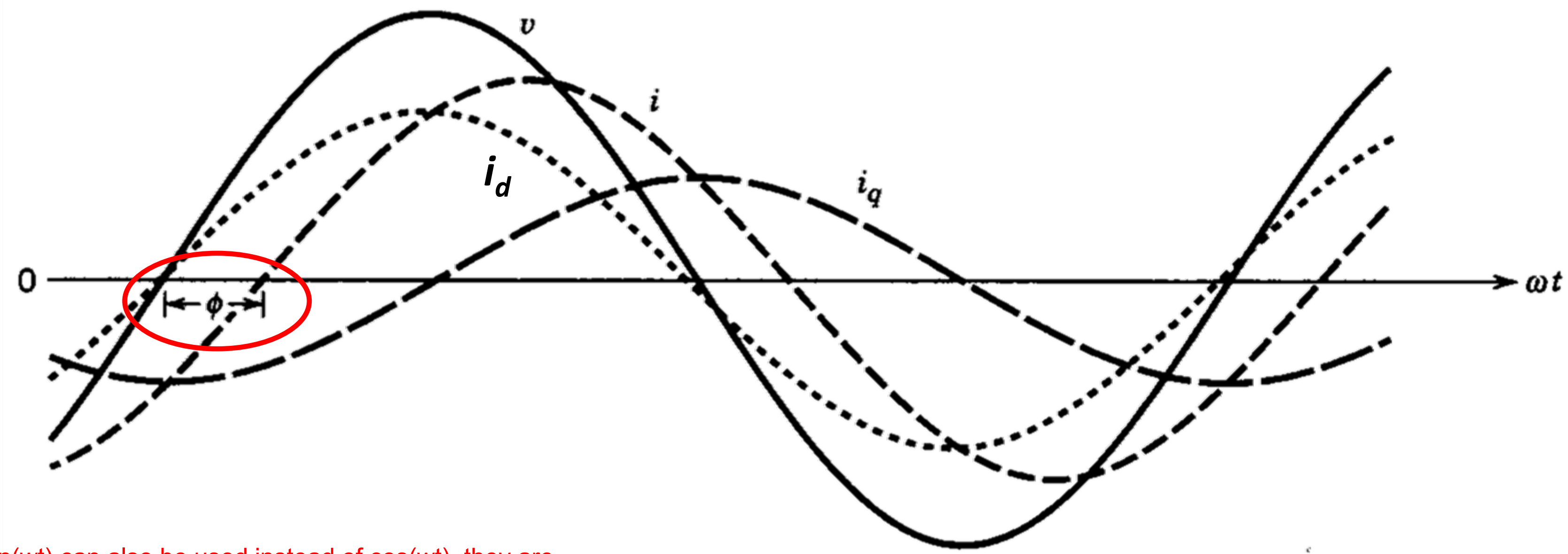
Electrical period / cycle [s] : T
Electrical frequency f [Hz]: $f = 1/T$
Electrical speed ω [rad/s]: $\omega = 2\pi f$
Time: t

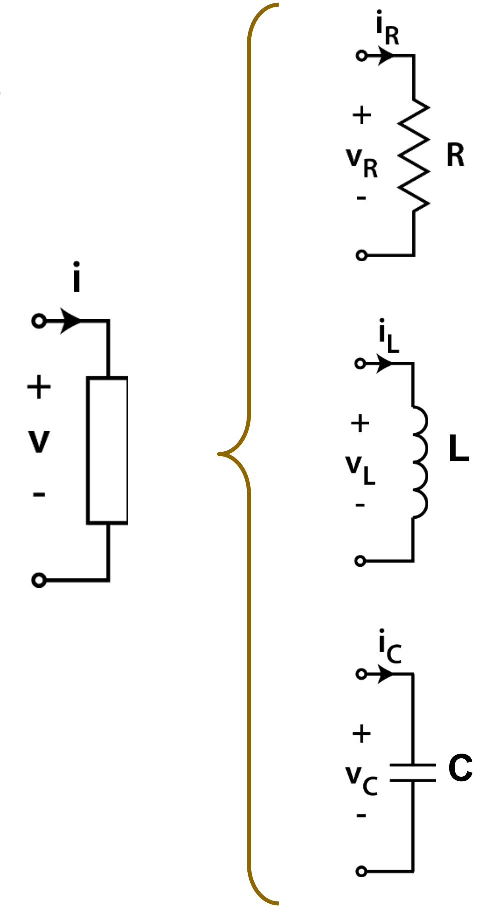
- If v(t) is non-sinusoidal, the RMS value V can/will be different!
- RMS: equivalent voltage/current for AC, giving same power calculation as for DC (mean, average…)

Note: EM electrical speed [rad/s] $\omega_{ele} = p * \omega_{mech}$, where p[-] is EM pole pair number, ω_{mech} [rad/s] is EM mechanical speed

Electric circuits: AC current (i) and AC voltage (v)

- Sinusoidal steady-state condition
  - Linear systems (v,i) do not change in frequency, but only in amplitude & phase
  - If EM speed changes → frequency also changes ($\omega = 2\pi f$)
- Electrical loads can be …
  - Resistive load (v & i in same phase)
  - Inductive load (v & i not in same phase, phase shift ϕ)
  - Capacitive load (v & i not in same phase, phase shift) → Not used in EM modeling

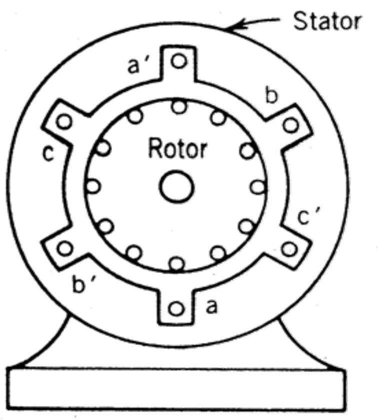




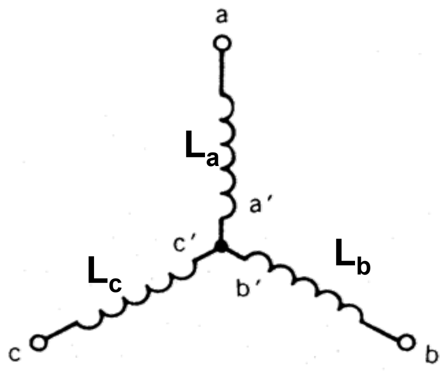
Note: sin(wt) can also be used instead of cos(wt), they are both sinusoidal functions!

Electric circuits: Multi-phase current and voltages

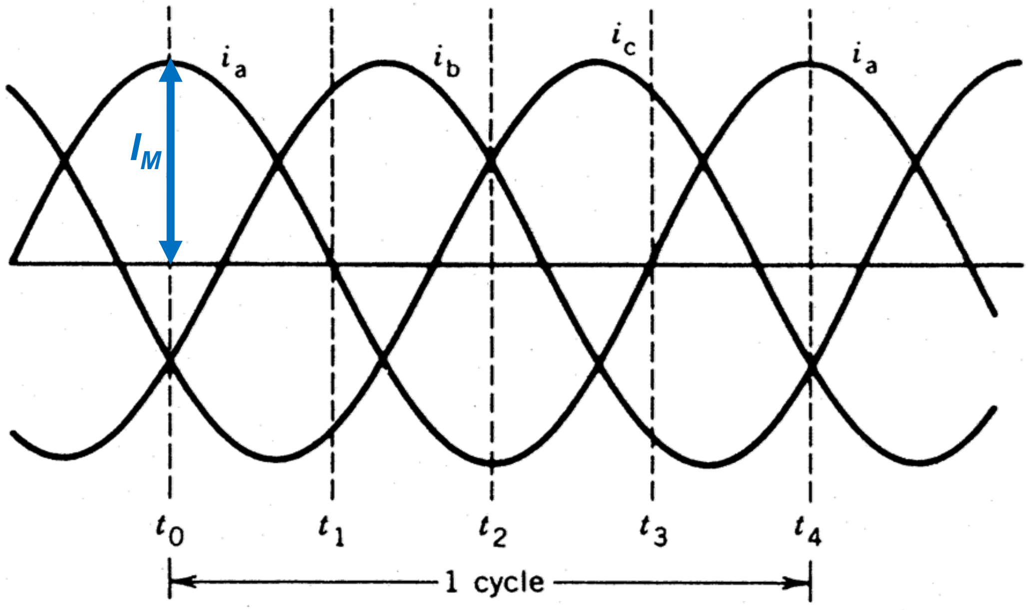
Example: 3-phase systems



Cross-sectional view of EM



Stator windings with **3-phase** currents i_a, i_b and i_c



$T = 360°[degree] = 2pi\ [radians]$

$$i_a = I_m \cos \omega\, t$$
$$i_b = I_m \cos(\omega t - 120°)$$
$$i_c = I_m \cos(\omega t + 120°)$$

$$i_a = I_m (t = t_0 = 0)$$
$$i_b = -\frac{I_m}{2}$$
$$i_c = -\frac{I_m}{2}$$

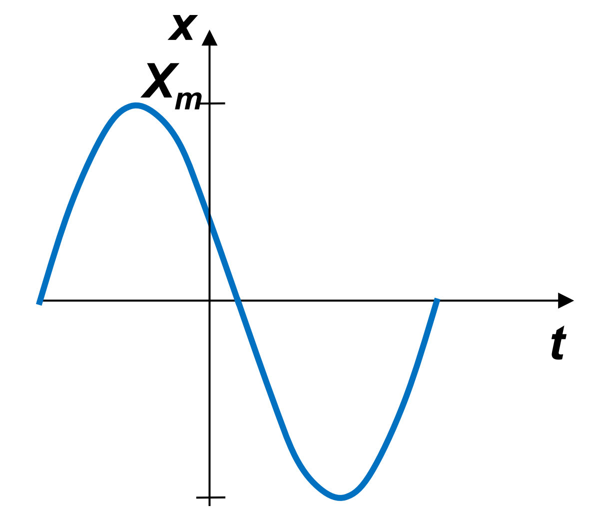
At a given time :

$i_a + i_b + i_c$ = 0 → Balanced system

Electric circuits: Phasors (Phase+Vector)

- Time-dependent signal

$$x(t) = \sqrt{2}X\cos(\omega t + \phi)$$



Waveform *x*(*t*):

- Time dependent
- Always real quantity

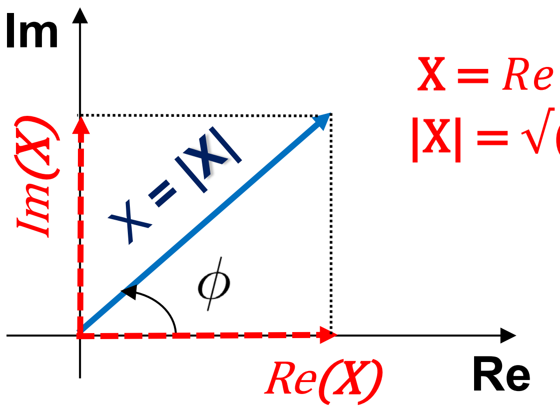
$$v = \sqrt{2}V\cos(\omega t)$$

$$i = \sqrt{2}I\cos(\omega t - \phi)$$

- Phasor representation

$$\mathbf{X} = Xe^{j\phi} \qquad \mathbf{X} = \bar{X} = \vec{X}$$

$$x(t) = \sqrt{2}\mathrm{Re}\left(\mathbf{X}e^{j\omega t}\right)$$



$$\mathbf{X} = Re(\boldsymbol{X}) + \boldsymbol{j}\, Im(\boldsymbol{X})$$

$$|\mathbf{X}| = \sqrt{(Re(\boldsymbol{X})^2 + Im(\boldsymbol{X})^2)}$$

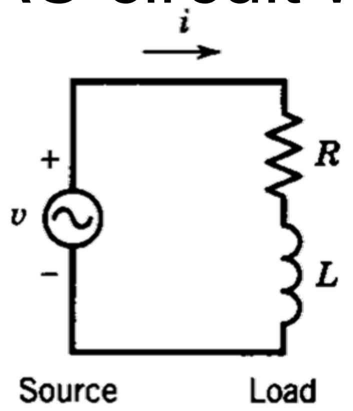
Phasor X

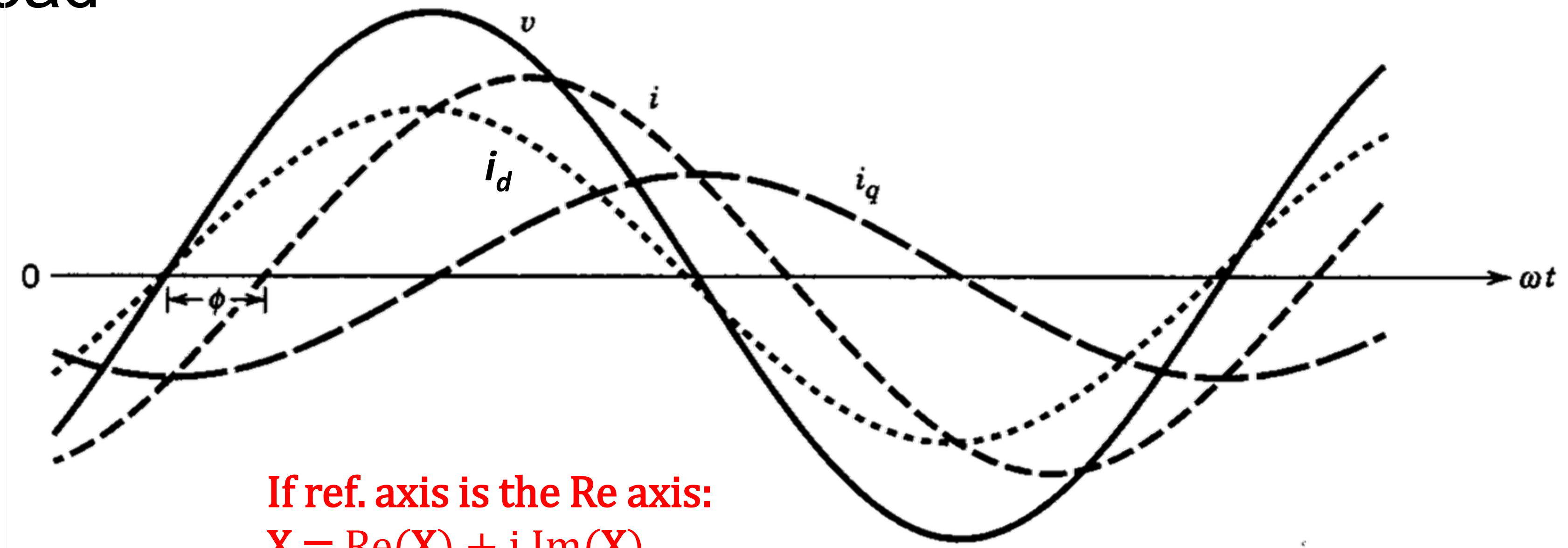
- Time independent
- Complex quantity

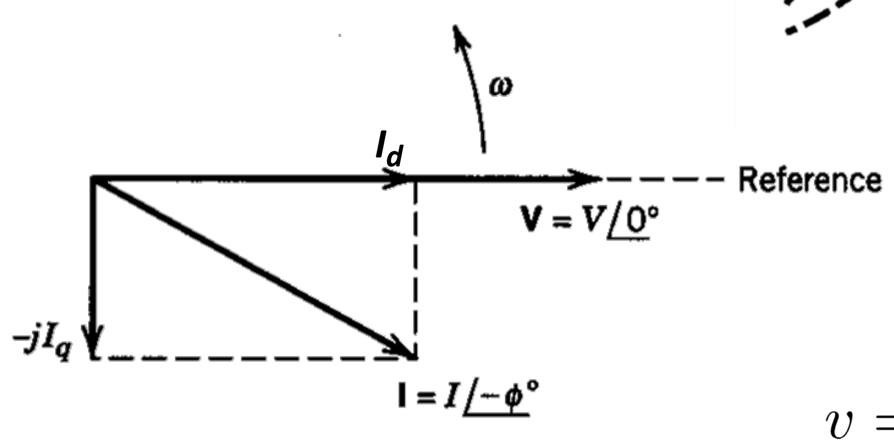
Note: sin(wt) can also be used instead of cos(wt), they are both sinusoidal functions!

Electric circuits: Steady-state sinusoidal voltages & currents

- AC circuit with R-L load







If ref. axis is the Re axis:

$\mathbf{X} = \mathrm{Re}(\mathbf{X}) + j\,\mathrm{Im}(\mathbf{X})$

$\mathbf{V} = V + j * 0, \quad |\mathbf{V}| = V$

$\mathbf{I} = I_d - j * I_q, \quad |\mathbf{I}| = |I_d - j * I_q| = \sqrt{(I_d^2 + I_q^2)}$

$$v = \sqrt{2}V\cos(\omega t)$$

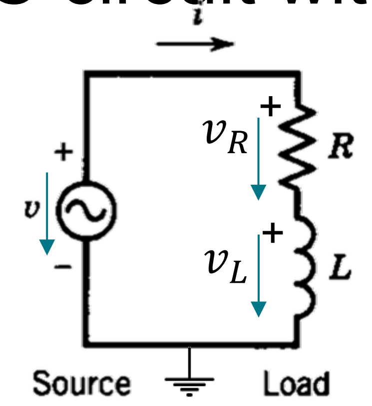
$$i = \sqrt{2}I\cos(\omega t - \phi)$$

Note: sin(wt) can also be used instead of cos(wt), they are both sinusoidal functions!

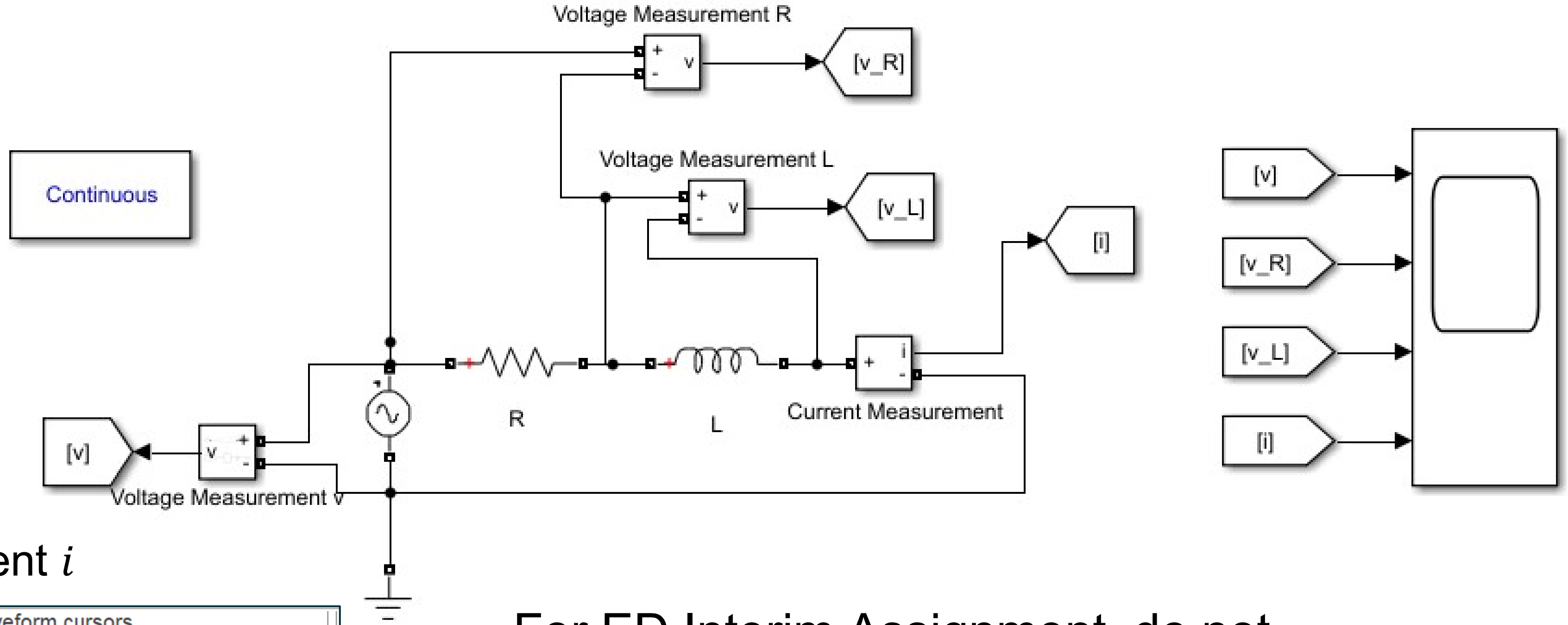
Electric circuits:
Simulation (Simulink, Simscape, Simscape Electrical)

- AC circuit with R-L load

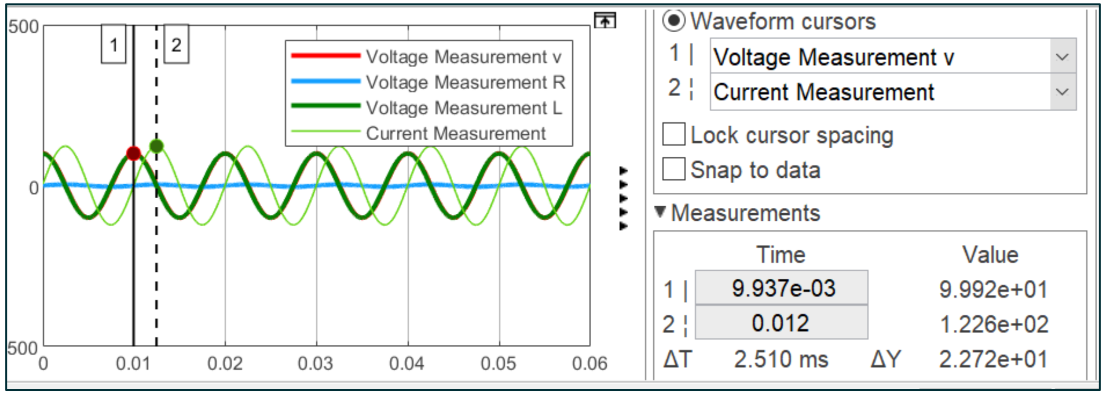
See the example file: RL_circuit_R2023b.slx



$$v(t) = v_R + v_L = Ri(t) + L\frac{di(t)}{dt}$$



Inductor voltage v_L -Current i



For ED Interim Assignment, do not forget to install Simulink Simscape, Simscape Electrical packages !

Electrical Power for AC quantities/circuits

Sinusoidal voltage and current

$$v = \sqrt{2}V\cos(\omega t + \theta_v) \qquad \mathbf{V} = V\angle\theta_v$$

$$i = \sqrt{2}I\cos(\omega t + \theta_i) \qquad \mathbf{I} = I\angle\theta_i$$

Complex power*

$$\mathbf{S} = \mathbf{V}\mathbf{I}^* = VI\angle(\theta_v - \theta_i) \quad \text{[VA]}$$

$$= P + jQ$$

Apparent power is the length of S

$$S = |\mathbf{S}| = VI = \sqrt{P^2 + Q^2} \quad \text{[VA]}$$

Average (real, active) power

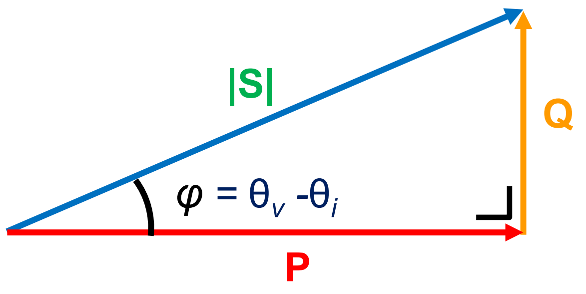
$$P = \mathrm{Re}(\mathbf{S}) \quad \text{[W]}$$

$$= VI\cos(\theta_v - \theta_i)$$

Reactive power accounts for the difference between P and S

$$Q = \sqrt{S^2 - P^2}$$

$$= VI\sin(\theta_v - \theta_i) \quad \text{[VAr]}$$



If we are talking on power flow between powertrain elements of the vehicle (wheel, transmission, etc,), this power is considered !

* Since the considered voltage phasor **V** and current phasor **I** are sinusoidal the angle difference between them is also the angle φ between P & Q.

Source: 5APA0 Course