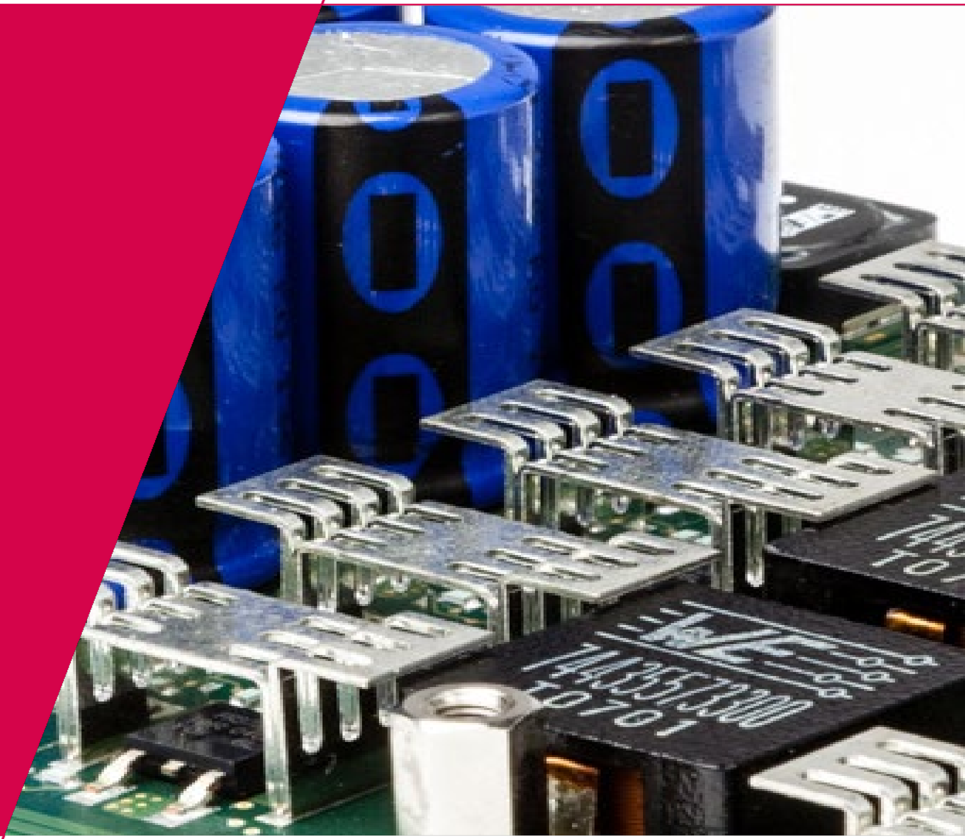
4AT060 Sustainable Vehicles (ED)
5AT010 Electrical Components

Power Electronics

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.	Recap / Q&A
7th: 15:45-16:30 8th: 16:45-17:30	Instructions Q&A					~~No lecture 20th Dec.~~		~~No instructions 17th Jan~~

Make sure you monitor CANVAS for updates etc.

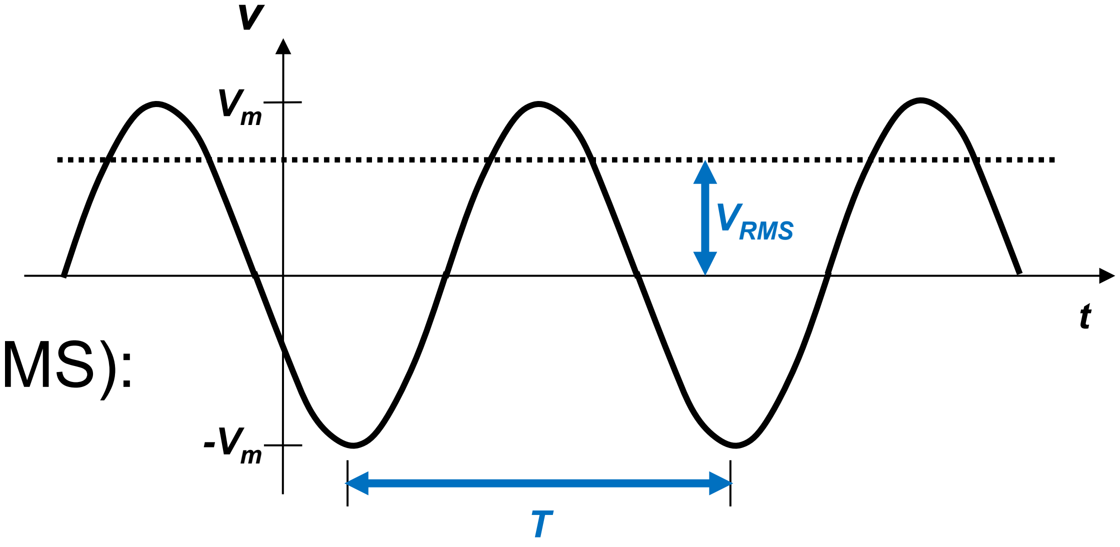
Agenda

- Electrical Machines
  - Recap Lecture 2
  - EM Efficiency/Power loss maps
- Introduction to Power Electronics
- DC-DC Converters
- DC-AC Converters (Inverter)

Electric circuits: AC signals (time-dependent), RMS (effective) voltage and current (recap Week 2)

- 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

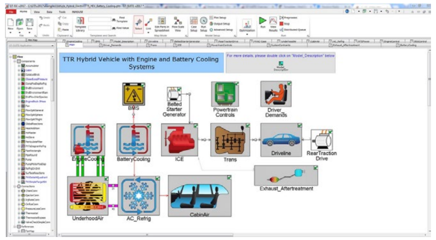
- If v(t) is non-sinusoidal, the RMS value V can/will be different!
- RMS: equivalent voltage/current for AC, giving same power calculation as for DC (mean, average…)

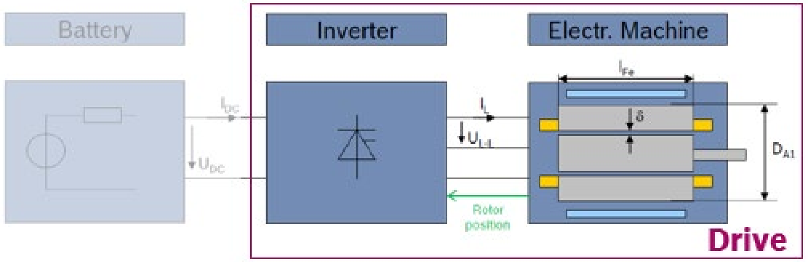
Note: EM electrical speed [rad/s] $\omega_{ele} = p * \omega_{mech}$, where p[-] is EM pole pair number, ω_{mech} [rad/s] is EM mechanical speed

EM EFFICIENCY / POWER LOSS MAPS

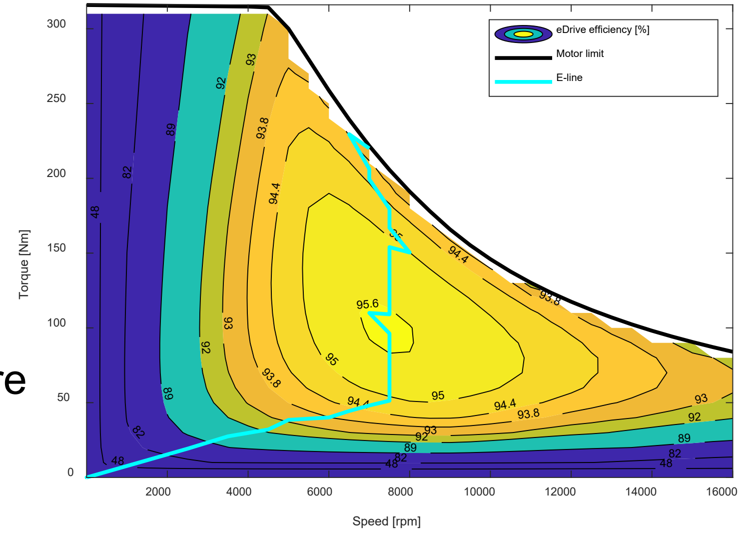
From EM design to powertrain system level

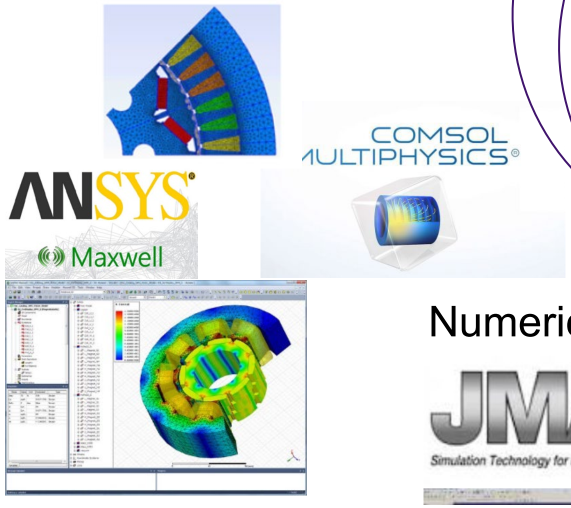
Vehicle simulations

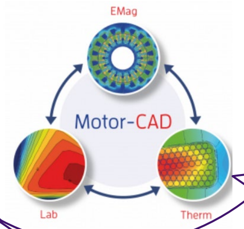




E-drive (EDR) map







Numerical & analytical software

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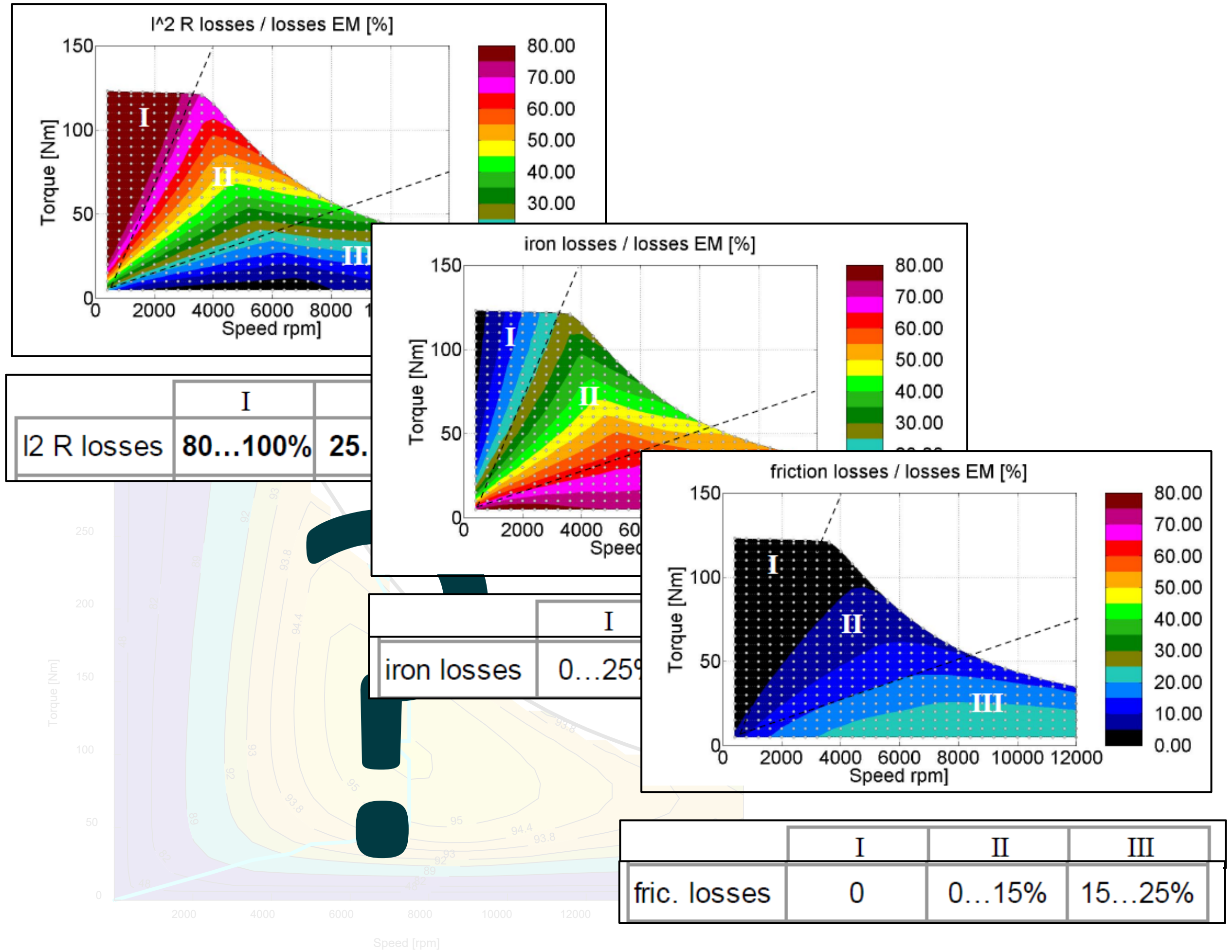
Electromechanics & Power Electronics

EM Efficiency & power loss maps: Example PMSM

- Motor efficiency maps play a key role in system design
- Motor maps are for steady-state:
  - e.g. Udc=360V, Tr=80C, Ts=80C
- Dynamic modelling should include (rotor) inertia, temperature effects…

- Let us highlight the losses in the motors
  - Copper (I^2 R, Joule, DC/AC) losses
  - Iron losses
  - Friction (bearing+windage) losses



	I	
I2 R losses	80…100%	25.

	I
iron losses	0…25%

	I	II	III
fric. losses	0	0…15%	15…25%

For motor operation:

$$P_{el} = P_{mech} + P_{loss} \rightarrow \text{eff.} = 100 * P_{mech} / P_{el}$$

$$v * i = T_{EM} * w_{mech} + P_{loss}$$

[V] [A] = [Nm] [rad/s] + [W]

In EM maps, rotational speed is shown as *n [rpm]* instead of w_{mech} *[rad/s]!* w_{mech} *= 2 pi n / 60*

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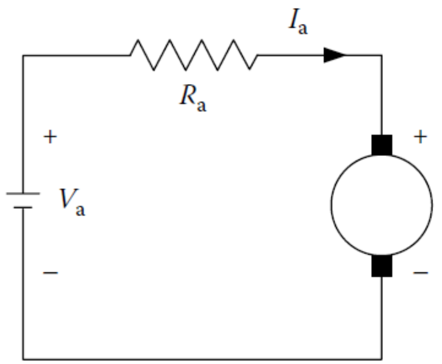
Electromechanics & Power Electronics

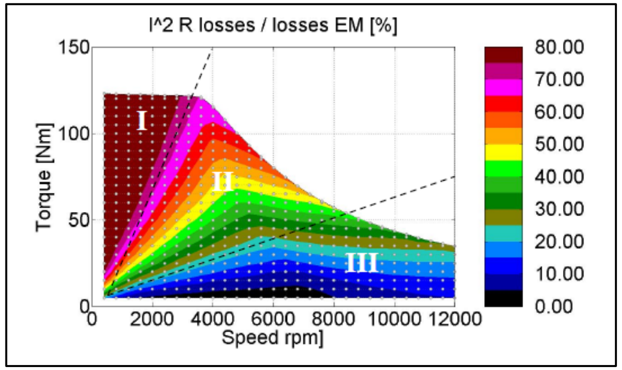
Copper losses (DC)



- The armature (stator for PMSM) can be considered to have a resistance. All wires/phases can be considered to cause power losses*

$$\boxed{P = I^2 R}$$

- **Copper losses** collectively group these losses, where the current generates heat



	I	II	III
I2 R losses	**80…100%**	**25…75%**	10…30%

- Torque and current are proportional,

$$\boxed{Copper\ Losses = k_c T^2}$$

  - where k_c depends on winding (coil) and its magnetic flux ϕ

(DC) Copper losses are dominant in constant torque region

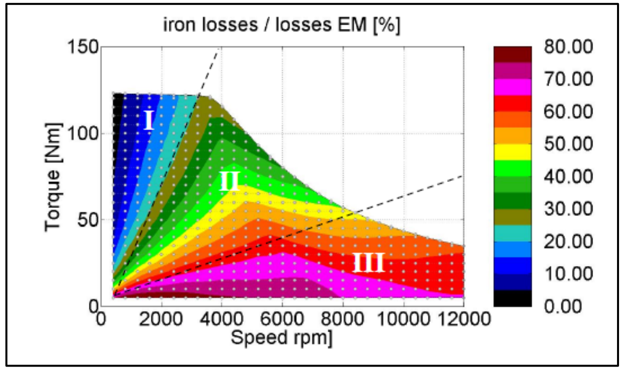
* For multi-phase circuits, the total loss would be a multiple by the number of the phase, e.g. for 3-phase: $\mathrm{P} = 3\, I^2 R$, where I is RMS vale of the AC signal

Iron losses

- Changing magnetic field creates these losses as rotor rotates:

$$\boxed{Iron\ Losses = k_i\omega}$$

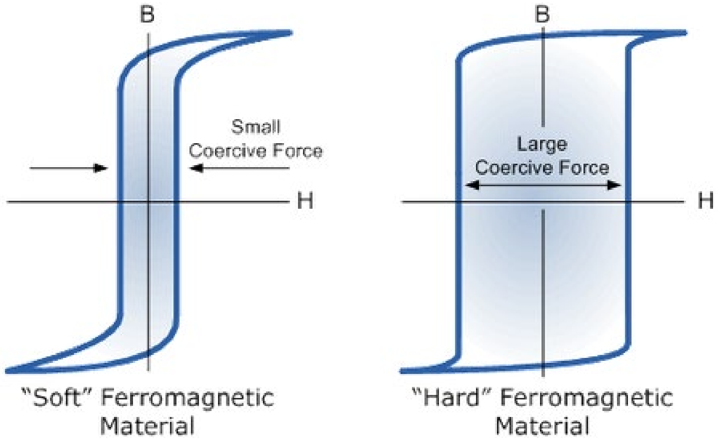
  - k_i depends on magnetic flux → Look-up table is used in VCU*



	I	II	III
iron losses	0…25%	**25…55%**	**60…80%**

1. Hysteresis loss is the energy required to continuously magnetize and demagnetize the iron

- A soft iron can be used to reduce, but not remove this effect



*VCU : Vehicle Control Unit

Iron losses

- Changing magnetic field creates these losses as rotor rotates:

$$\boxed{Iron\ Losses = k_i \omega}$$

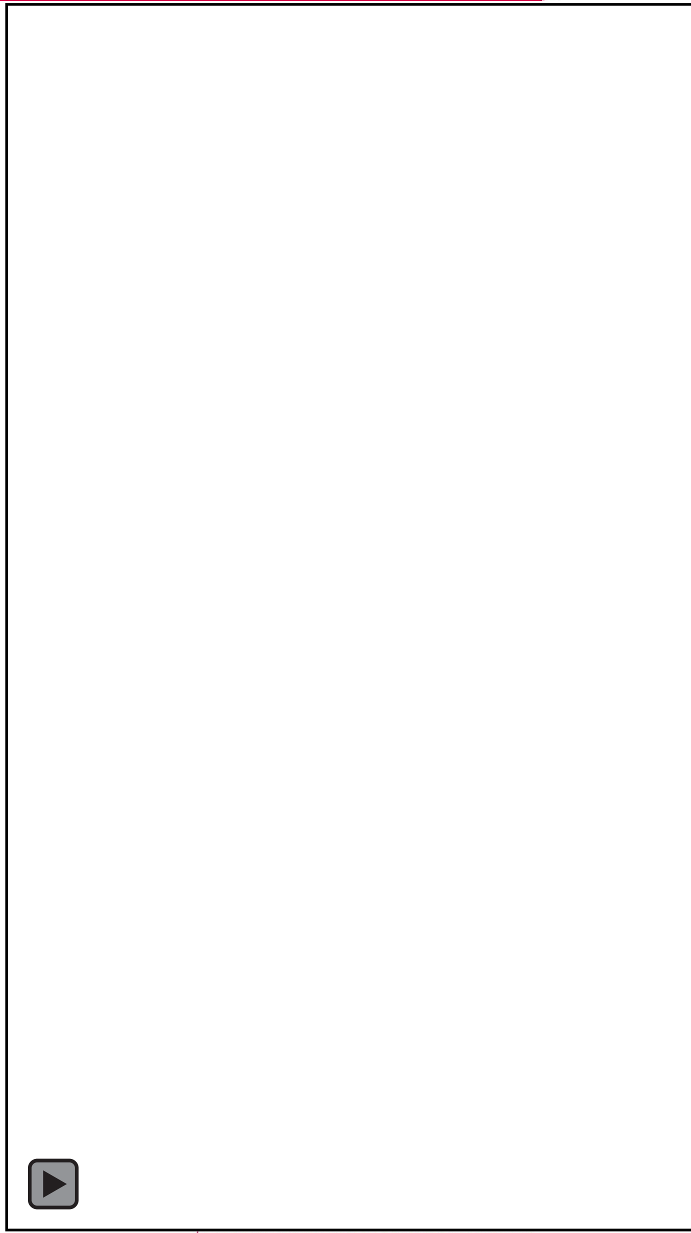
  - k_i depends on magnetic flux → Look-up table is used in VCU*

1. Hysteresis loss is the energy required to continuously magnetize and demagnetize the iron

  - A soft iron can be used to reduce, but not remove this effect

2. Changing fields will induce a current in the iron via electromagnetic induction (called '**eddy currents**' which generate heat)

  - Reduced by creating the iron out of laminated sheets



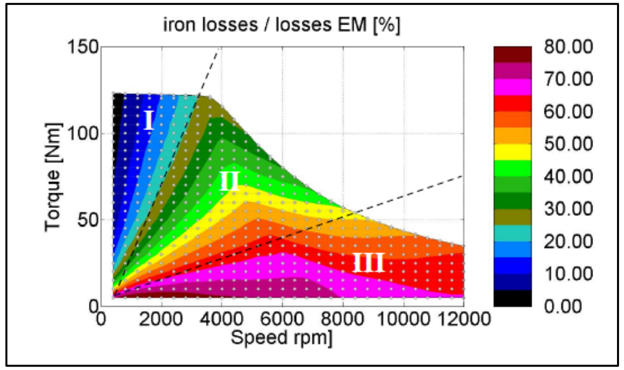
Iron losses

- For the ED Interim Assignment:
  - These losses are given

- Changing magnetic field creates these losses as rotor rotates:

$$\boxed{Iron\ Losses = k_i\omega}$$

- k_i depends on magnetic flux → Look-up table is used in VCU*



	I	II	III
iron losses	0…25%	**25…55%**	**60…80%**

1. Hysteresis loss is the energy required to continuously magnetize and demagnetize the iron

- A soft iron can be used to reduce, but not remove this effect

2. Changing fields will induce a current in the iron via electromagnetic induction (called '**eddy currents**' which generate heat)

- Reduced by creating the iron out of laminated sheets
- **Bosch: Iron stack Production**

Left: Stator stack of laminations
Right: Rotor stack of laminations

Iron losses are dominant in constant power region

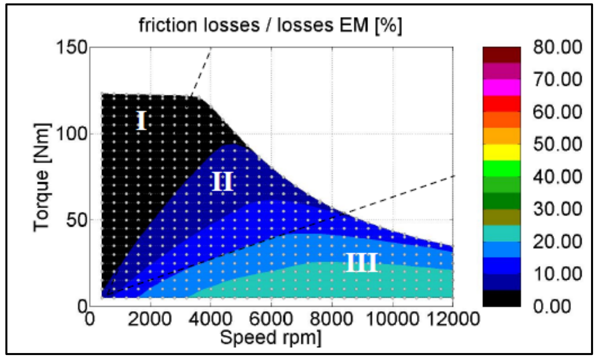
Friction (Bearing + Windage) lo

- For the ED Interim Assignment:
  - These losses are given

- Mechanical losses, also referred as spin loss
- Windage (air, wind resistance, air turbulence) force ~ ω^2

$$Bearing\ Losses = T_f\omega$$

$$Windage\ Losses = k_w\omega^3$$

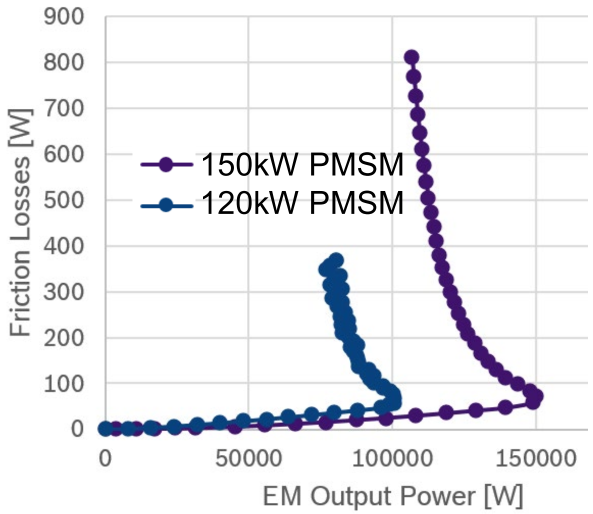


	I	II	III
fric. losses	0	0…15%	15…25%

- Difficult to estimate realistically:
  - Add certain fixed** loss

  OR
  - Take over from previous hardware designs

  OR
  - Not include

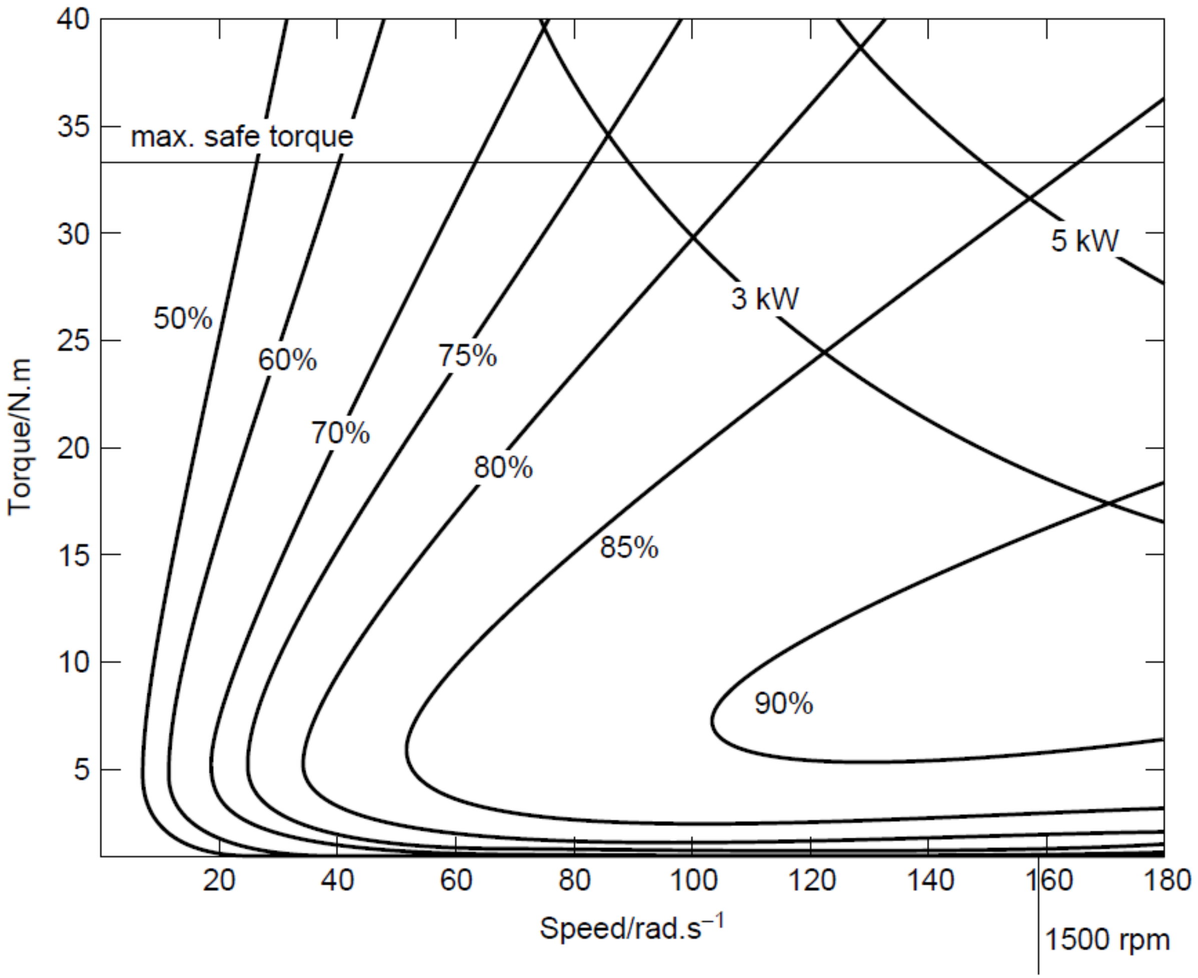


Friction losses are typically not included in EM optimization

** not exceeding e.g. 0.5% of P_{max} @ 10krpm

*speed dependent, not load dependent

Typical EM map



- Map covers a larger area than the actual operating ranges…
  … bounded by
  - maximum torque T_{max}
  - maximum power P_{max}
  - speed
- Machine parameters affect where the optimal efficiencies lay

Knowledge clips

- DC Machines:
- https://www.youtube.com/playlist?list=PLPpCFgQP7QKHUOFYvZhQ6ra5XrU3dN2dD
- AC Machines:
- https://www.youtube.com/playlist?list=PLPpCFgQP7QKEA0Mi9WKW_ywa0wIqx-2-w
- Magnetic forces, magnetic field
- https://www.youtube.com/playlist?list=PLqwfRVlgGdFCEf4WvyF0UThKTwiFxcVf4
- Electrical circuits:
- https://www.youtube.com/playlist?list=PLqwfRVlgGdFC7HLoajCVjUk23cqy4QvRL

Agenda

- Introduction to Power Electronics
- DC-DC Converters
- DC-AC Converters (Inverter)

Follow-up courses for power electronics:
EPE courses 5XWB0 Q3, 5LWE0 Q1, 5LWH0 Q1, 5APA0 Q2

Power Conversion

Introduction to Power Electronics

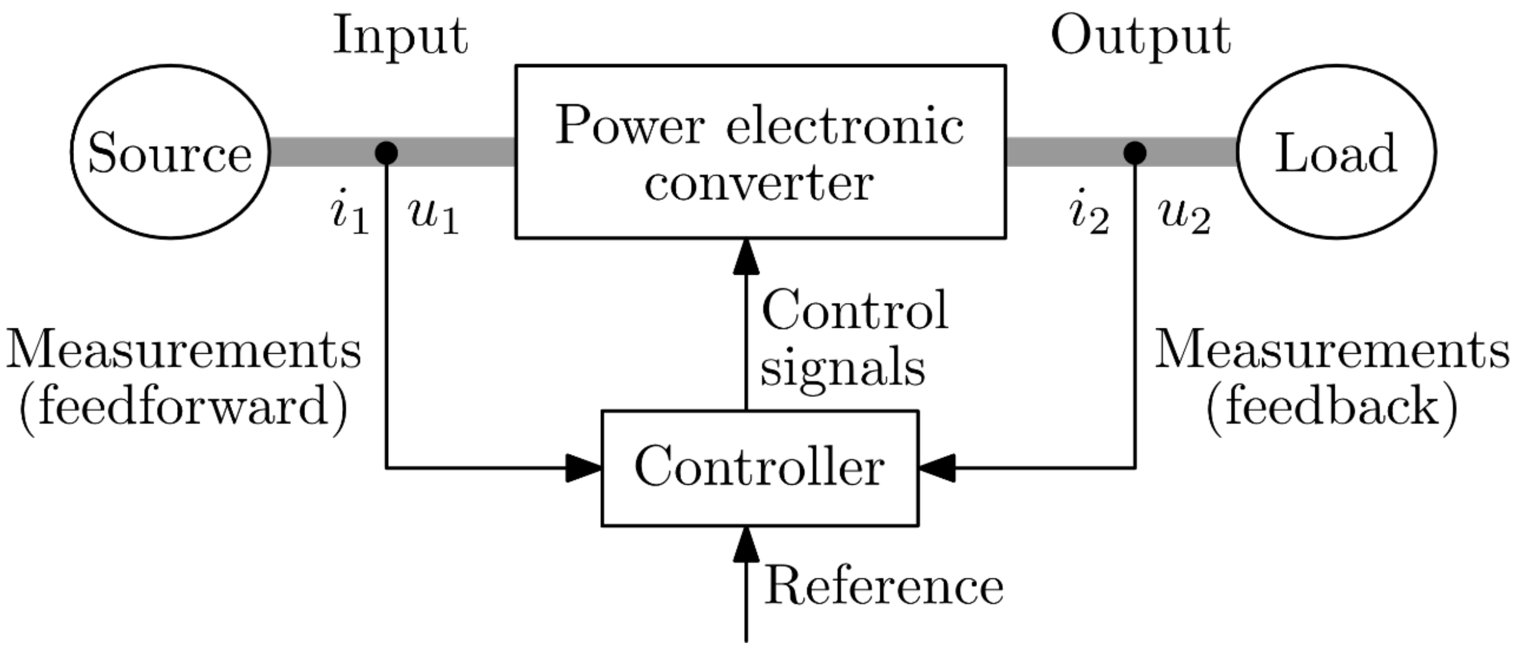
AC input power

DC output power

- Conversion of the (electrical) energy delivered by the power source into a form that is suitable for the respective load or consumer
- Grid (AC power) is very powerful→ source voltage RMS and frequency constant
- Battery (DC power)→ source voltage fluctuating (depends of State of charge)

Source: 5SWB0 Course

Types of Power Conversion



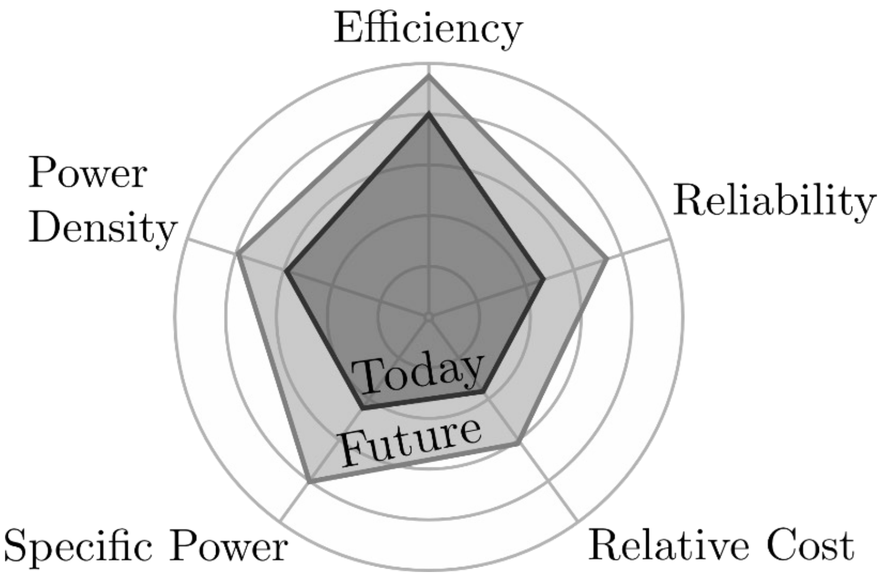
Conversion types

- AC-DC rectification: Possibly control DC voltage, AC current
- DC-AC inversion: Produce sinusoidal AC voltage/current of controllable magnitude and frequency
- DC-DC conversion: Change and control DC voltage/current magnitude
- AC-AC cyclo-conversion: Change and control AC voltage/current magnitude and frequency

Source: 5SWB0 Course

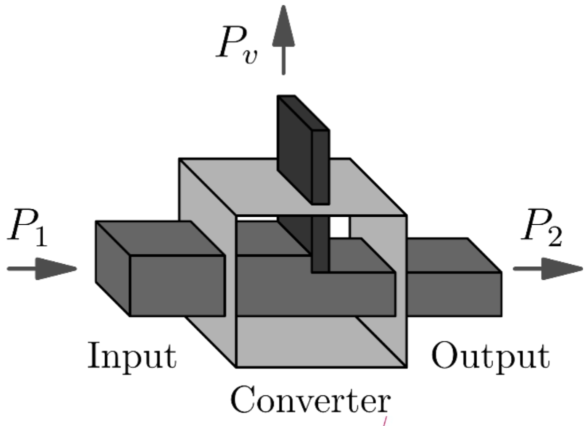
Key Performance Indicators (KPIs)

Efficiency:	$\eta = 100 \cdot \frac{P_2}{P_1}$	$[\%]$
Power density:	$\rho = \frac{P_{2,\mathrm{nom}}}{V}$	$[\mathrm{kW/liter, kVA/liter}]$
Specific power:	$\gamma = \frac{P_{2,\mathrm{nom}}}{W}$	$[\mathrm{kW/kg, kVA/kg}]$
Relative cost:	$\sigma = \frac{P_{2,\mathrm{nom}}}{C}$	$[\mathrm{kW/\$, kVA/\$, kW/€, kVA/€}]$



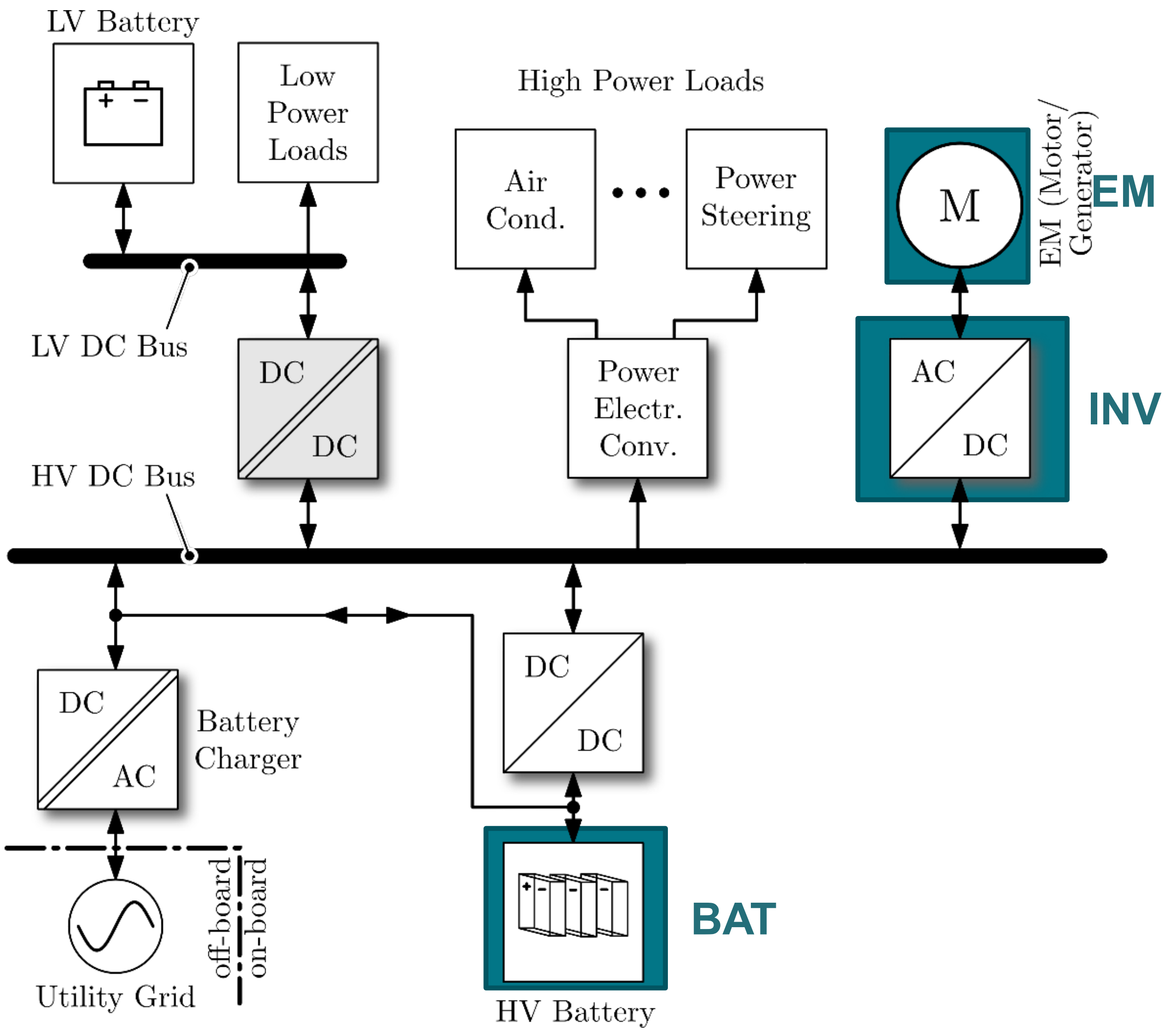
Design goals:
- small size & weight,
- low cost,
- high reliability,
- high efficiency

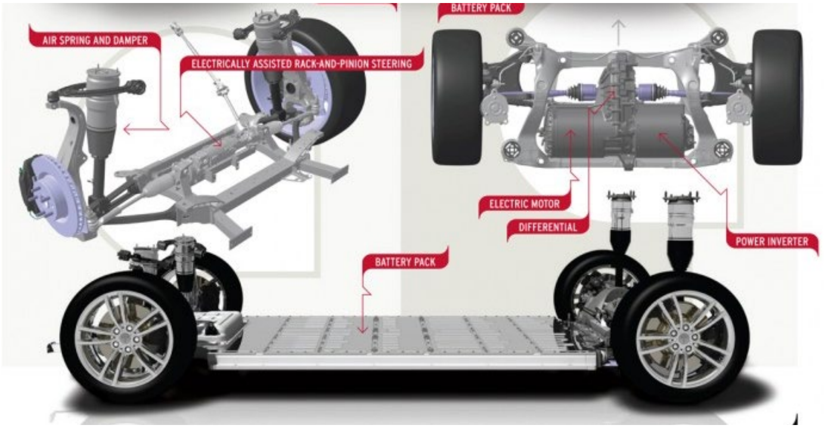
$$\eta = \frac{P_2}{P_1} = \frac{P_1 - P_\mathrm{v}}{P_1}$$



Source: 5SWB0 Course

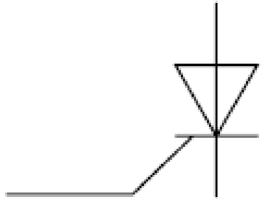
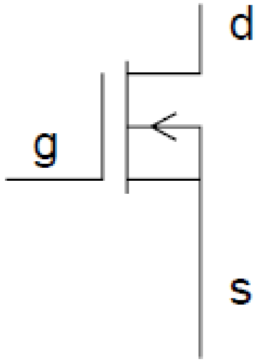
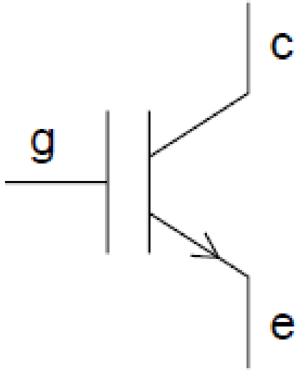
EV Power System





Source: 5SWB0 Course

Semi-conductor Switches

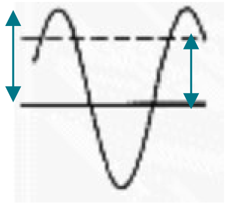
Type	Thyristor	MOSFET	IGBT
symbol			
Max. voltage (V)	4500	1000	1700
Max. current (A)	4000	50	600
Switching time (μs)	10–25	0.3–0.5	1–4

Recap Electrical Circuits

DC vs AC signals, their notations, anology

- Amplitude/magnitude current I_m,
- Amplitude/magnitude voltage V_m , U_m

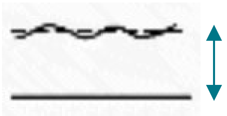
I_m, V_m or U_m



I, V or U

AC power, AC voltage*, AC current*

- RMS/effective current I_{rms}, I ,
- RMS/effective voltage U_{rms}, U or V_{rms}, V



I, V or U

DC power, DC voltage, DC current

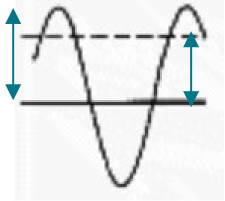
- Average/mean current <i>, I ,
- Average voltage, <u>, U or <v> , V

* Pure sinusoidal signal is assumed

*Arithmetic mean, average, $\overline{v_0} = < v_0 >$

DC vs AC signals, their notations, anology

I_m, V_m or U_m



I, V or U

AC power, AC voltage*, AC current*

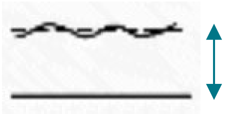
- RMS/effective current I_{rms}, I ,
- RMS/effective voltage U_{rms}, U or V_{rms}, V
- AC power:
  - Active power [W]: P = I * V* $\boxed{\cos\varphi}$ Power Factor
  - Apparent power [VA] : |S| = I * V

$$i = I_m \cos(\omega t + \theta_i) = \sqrt{2}\, I \cos(\omega t + \theta_i)$$

$$v = V_m \cos(\omega t + \theta_v) = \sqrt{2}\, V \cos(\omega t + \theta_v)$$

$$(\theta_v - \theta_i) = \varphi$$

* Pure sinusoidal signal is assumed



I, V or U

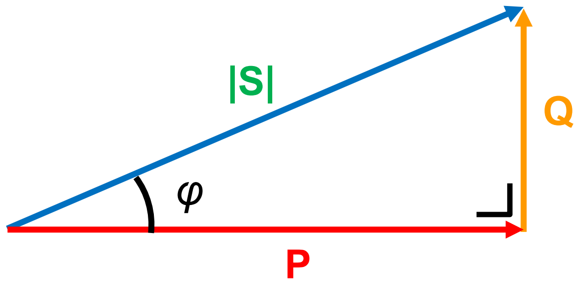
DC power, DC voltage, DC current

- Average/mean current <i>, I ,
- Average voltage, <u>, U or <v> , V
- DC power [W] : I * V

*Arithmetic mean, average, $\overline{v_0}$ = $< v_0 >$

Quality indicators for electrical power systems

- Power definitions:
  - *Average or active power P[W]*
  - *Reactive power Q[VAr]*
  - *Apparent power S [VA]*

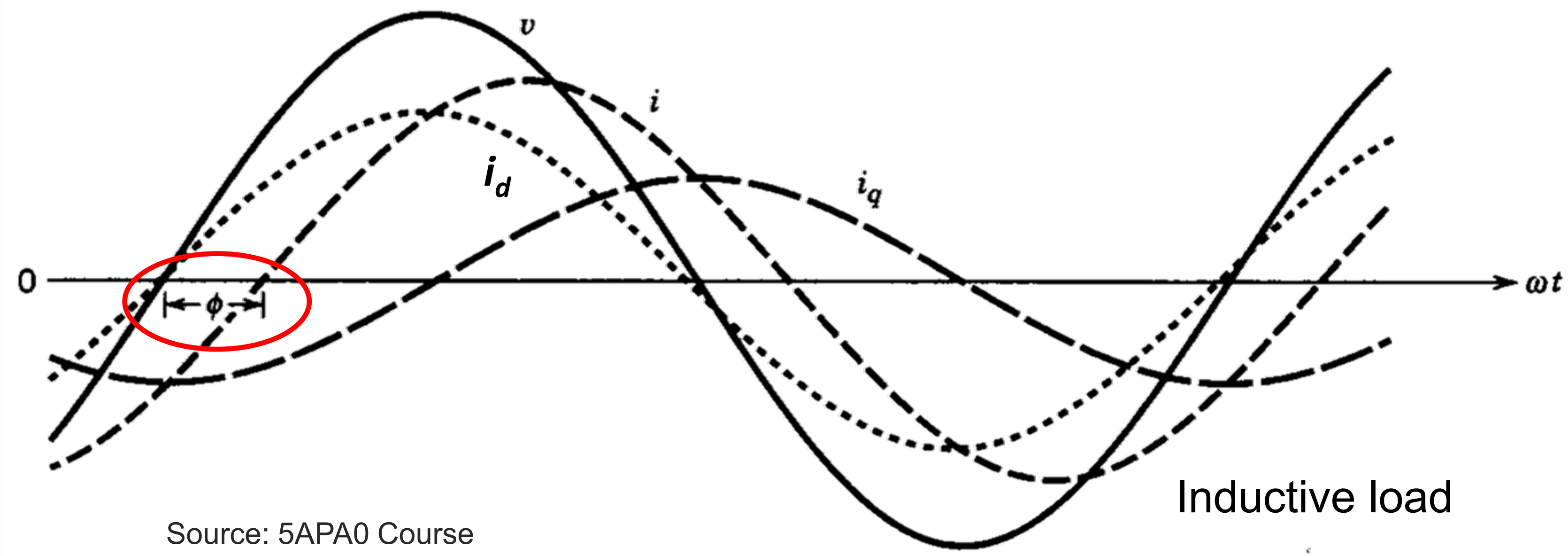


- Power Factor (PF): $\frac{P}{S}$ ($=\cos\varphi$ only if V & I are sinusoidal)
- Displacement power factor (DPF) or cos phi: $\cos\varphi$
- Total Harmonic Distortion (THD): For voltage or current

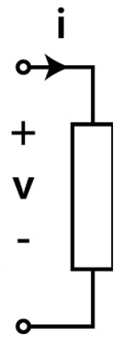
$$\mathrm{THD}(\%) = 100 \cdot \sqrt{\sum_{h=2}^{\infty} \left(\frac{I_{\mathrm{s,rms,h}}}{I_{\mathrm{s,rms,1}}} \right)^2}$$

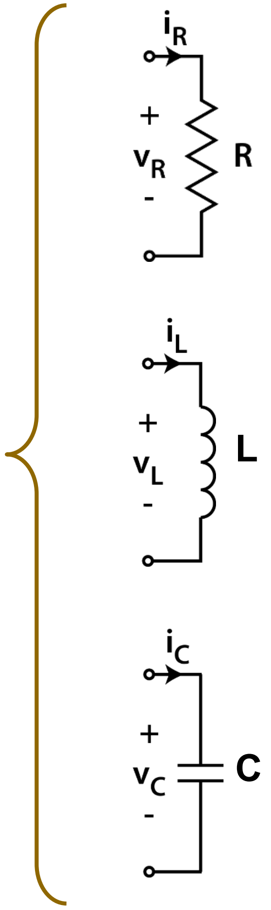
Resistive, inductive & capacitive loads (Recap Week 2)

- Sinusoidal steady-state condition
  - Linear systems do not change frequency, only amplitude and phase
  - We assume frequency (EM speed) not changing unless indicated otherwise
- Electrical loads can be…
  - Resistive load (v & i in same phase)
  - Inductive load (v & i not in same phase, phase shift)
  - Capacitive load (v & i not in same phase, phase shift)



Source: 5APA0 Course





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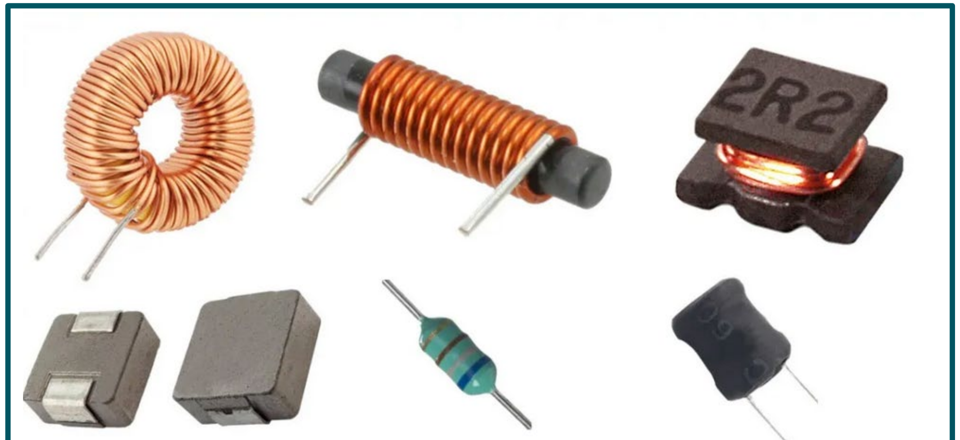
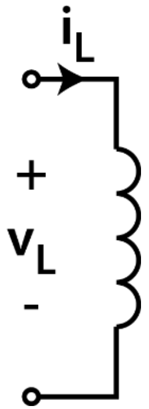
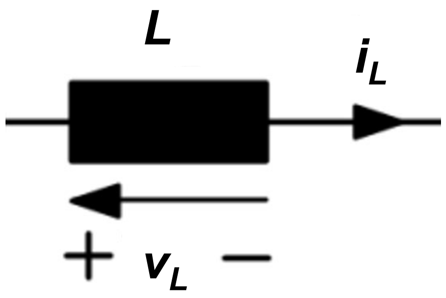
Electromechanics & Power Electronics

Passive components: Inductors



Inductors





$$v_L = L\, di_L/dt$$

- A passive electronic component designed to add *inductance* to a circuit
  - Characterized by its *inductance* L ([H], [Henry])
- 2-terminals
- Coil, choke, reactor…
- 2 inductors together→ transformer
- Delays the electrical current rise → Can store magnetic field (short-time)

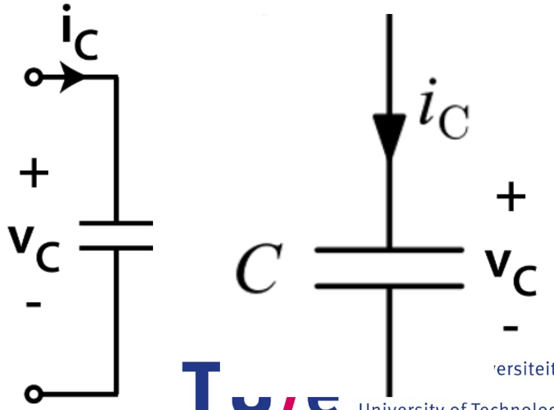
Passive components: Capacitors

- A passive electronic component designed to add *capacitance* to a circuit
  - Characterized by its *capacitance* C ([F], [Farad])
- 2-terminals
- Delays the electrical voltage rise→ Can store electric field/charge (short-time)

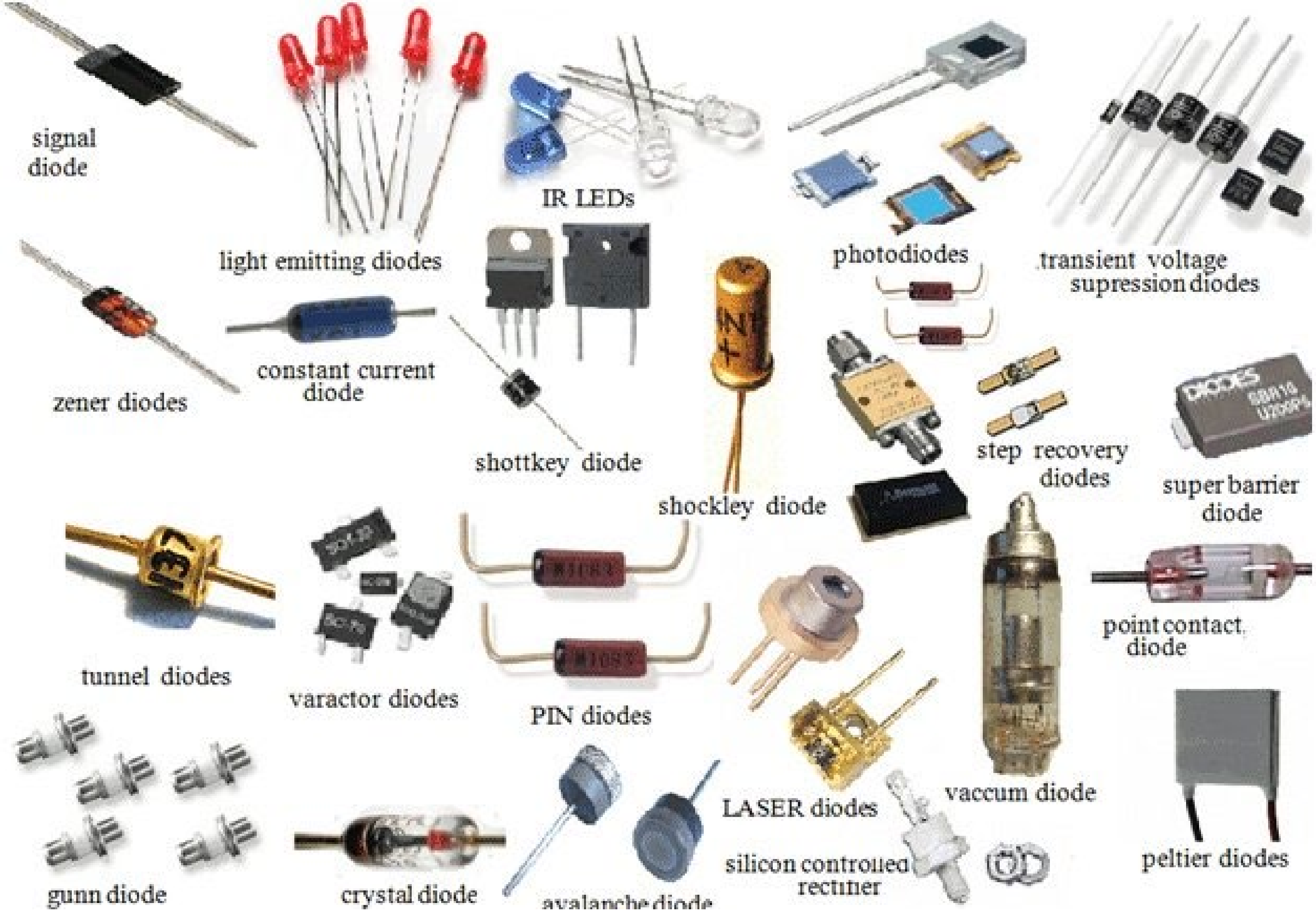
Capacitors

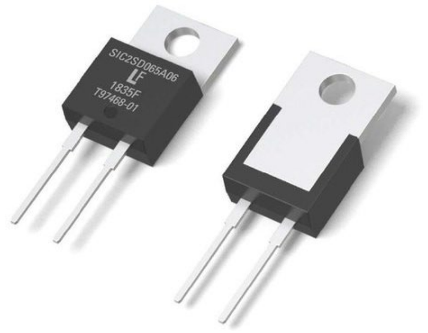
DC-link capacitor bank (in inverter (INV))

$$i_C = C\, dv_C/dt$$



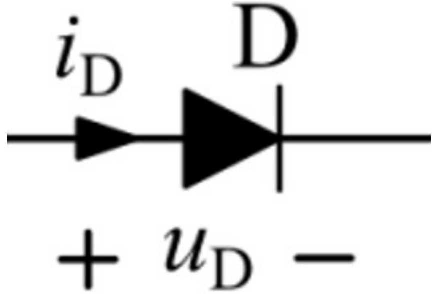
Passive components: Diodes





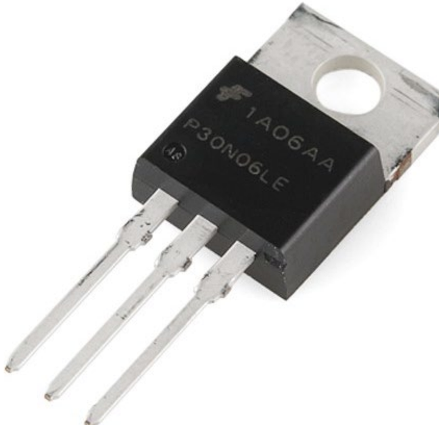
Diodes:

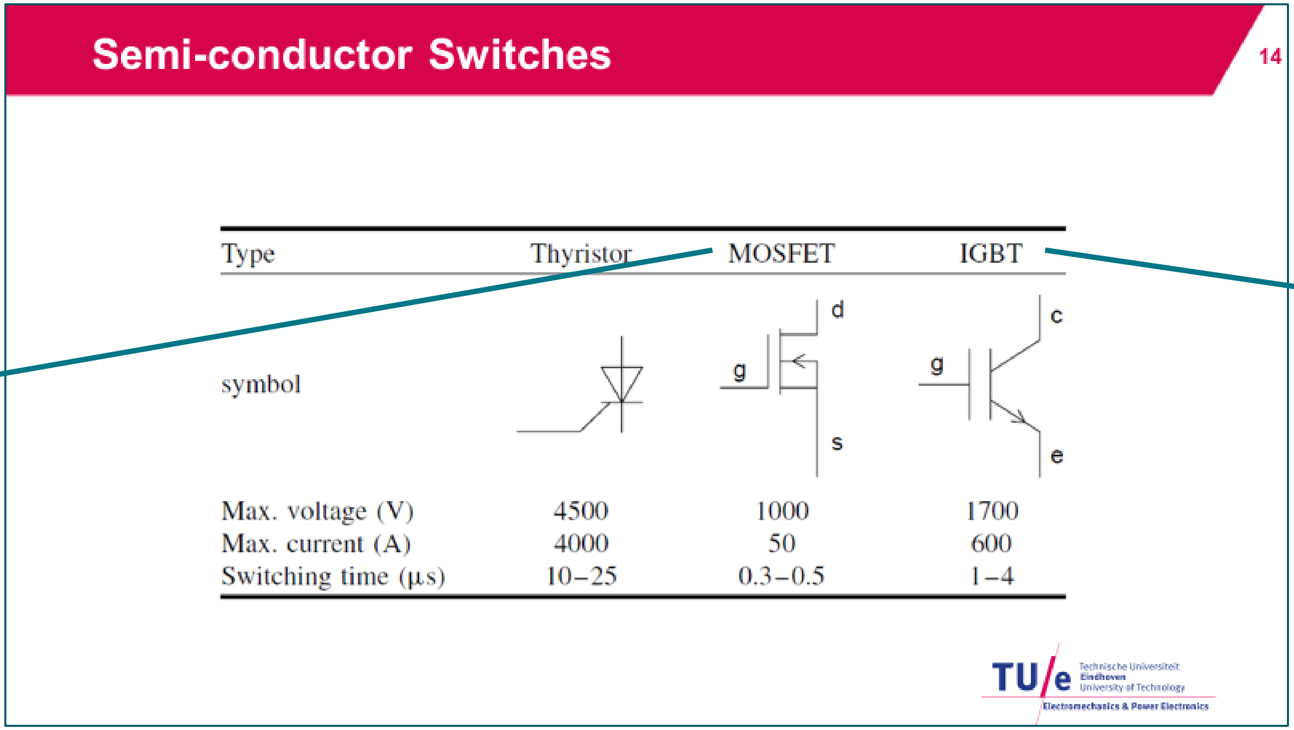
- Semiconductor switch
- 2-terminals
- One-way switch
- Allows current in one way



Active components: Semiconductor switches

- Typically, 3-terminals (2 for current, 1 for control)
- Characterized by its *voltage, current, switching speed*
- Multiple switches can form a **power module** (terminal number can be higher then 3)




Semi-conductor Switches

14

Type	Thyristor	MOSFET	IGBT
symbol			
Max. voltage (V)	4500	1000	1700
Max. current (A)	4000	50	600
Switching time (µs)	10–25	0.3–0.5	1–4

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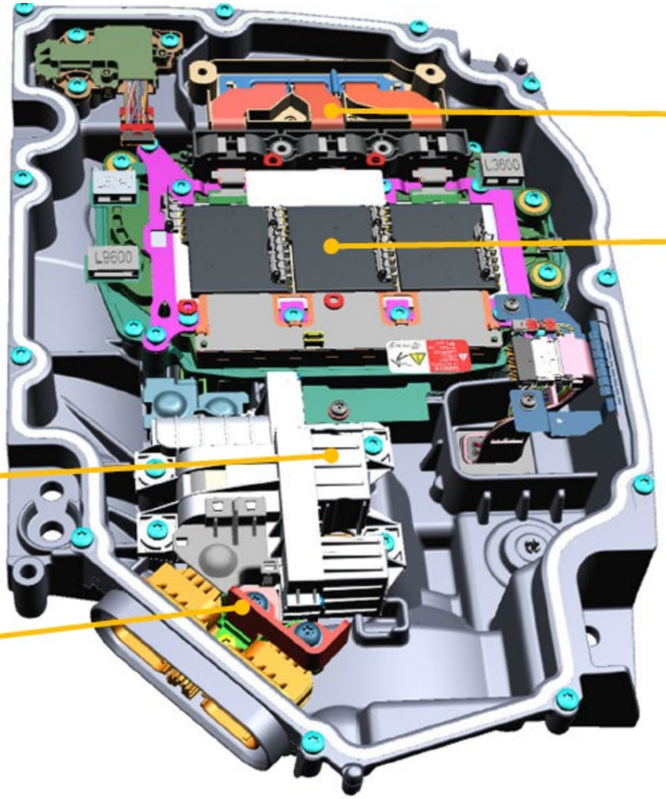
Example: Inverter (DC-AC) (for traction application)

TOP VIEW

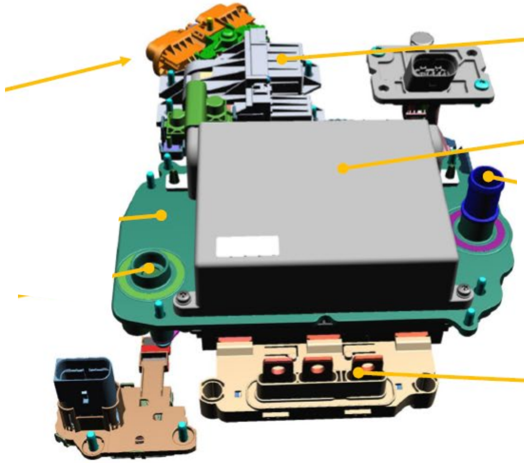


AC busbar
(Connection to EM)

IGBT Switch –
Power module

Filter
capacitor

DC busbar
(Connection to BAT)



Filter capacitor

DC busbar

DC-Link Capacitor

AC busbar

BOTTOM VIEW

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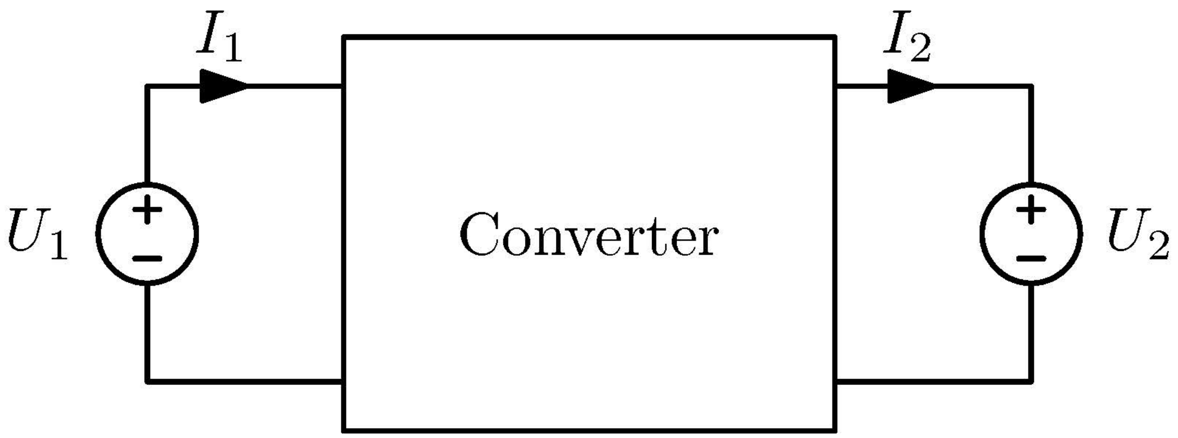
DC-DC Converters

What is a (switched) DC-DC converter?



+ High efficiency

+ Small volume, weight, cost (for small power applications of a couple of hundred watts)

+ Robust and reliable

- Typically, distorted (high ripples) output current and voltage characteristics due to switching action

- Noise (NVH)

- **In the following slides: assume lossless models**

$$P_1 = P_2$$

$$\rightarrow U_1 \cdot I_1 = U_2 \cdot I_2$$

$$\rightarrow \frac{U_2}{U_1} = \frac{I_1}{I_2}$$

Source: 5SWB0 Course

Examples of DC-DC converters

Constant output voltage

- Truck converter: $24V_{DC}$ battery to $12V_{DC}$
- EV power net: $400V_{DC}$ HV battery to $12V_{DC}$ LV battery
- Laptop / phone charging in car: $12V_{DC}$ LV battery to $5V_{DC}$ USB

Variable output voltage

- Car stereo: $12V_{DC}$ battery to $20\text{-}40V_{DC}$ internally
- DC motor/actuator drive: $12V_{DC}$ battery to $[-12V_{DC} \ldots +12V_{DC}]$

DC-DC converter in EV power net can be:
- standalone (right picture) or
- integrated unit with inverter (left picture)

Examples of DC-DC converters

CARTFT.COM
Shop for mobile
PC- and GPS-Solutions

CTF-Truck-DC-8A (24V to 12V Converter, 8A)
[http://www.cartft.com/catalog/il/816]

49.95 EUR
incl. 19% VAT, plus shipping

- Truck Converter
- 8A Max !
- Fanless !

This adapter converts 24V (22V-32V) to 12V-carlike-level (13.8V) with a maximum output of 8A (110W). With this item you can operate 12V devices with 24V truck/lorry batteries.

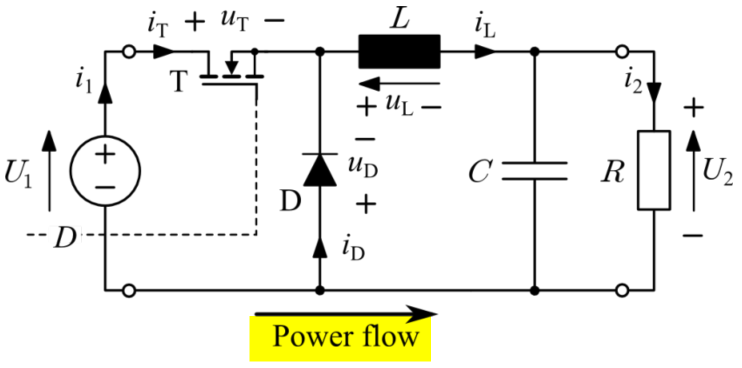
Technische Daten
Output: 12-15 V(DC) fixed (normal 13.8V)
Minimum current: 0A
Continuous current: 8A
Maximum watt: 110W
Input: 22-32V(DC)
Current: 5A/24VDC
Fuse rating: 8A
Working temperature: -10°C to 50°C
Dimensions (L x W x H): 95 x 93 x 40mm

Source: 5SWB0 Course

DC-DC Converter Topologies

DC-DC buck and boost converters

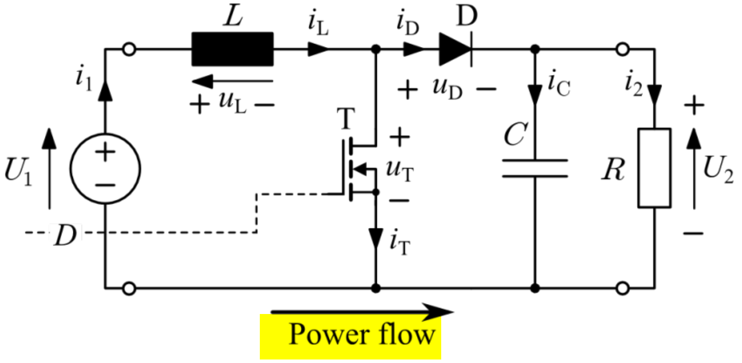
- **Buck converter** with power* MOSFET and diode



*The word "power MOSFET" is used since the semiconductor switch regulates electrical power flow (signal MOSFETs are not a part of this lecture)

Both cases provide **unidirectional** Electrical Power Flow, Power does not change its sign!

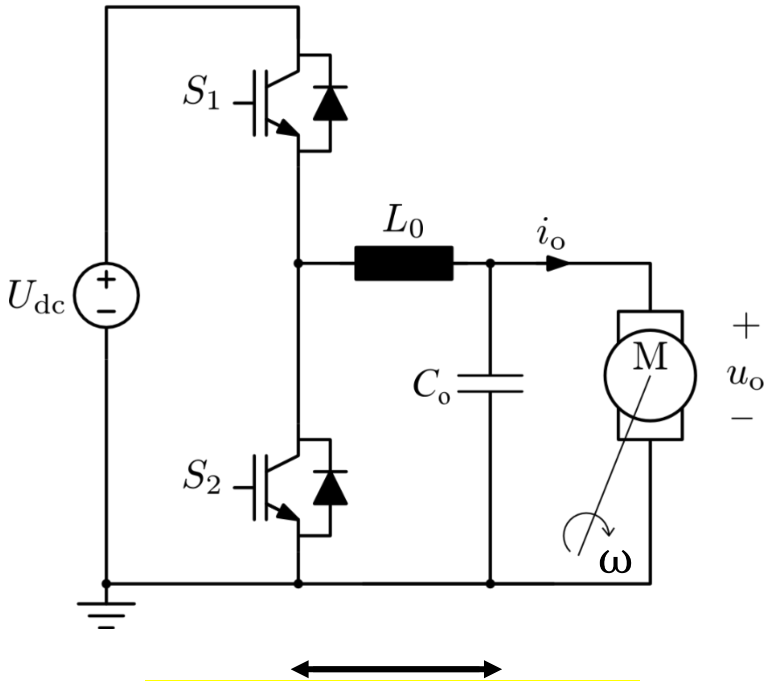
- **Boost converter** with power MOSFET and diode



Source: 5SWB0 Course

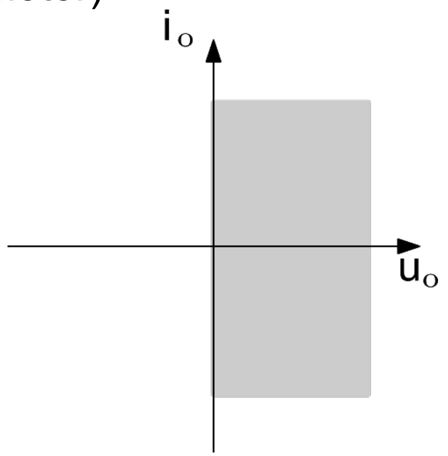
Half-bridge converter (Half H-bridge)

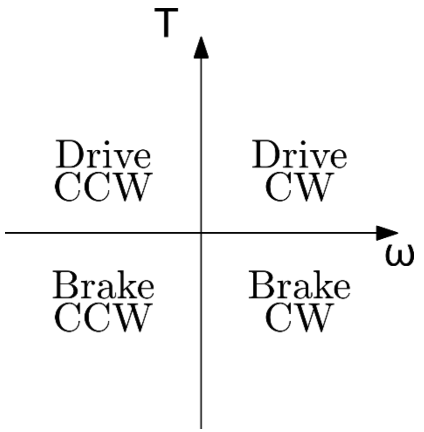
- Two quadrant (2Q) operation
  - Semi-conductor switches are denoted as S1 & S2
  - Positive output voltage u_0 , between 0 and $+U_{dc}$ → $0 \leq u_0 \leq +U_{dc}$
  - Positive or negative output current (e.g. driving/braking a motor)
  - Makes use of a **Half H-bridge** configuration of switches



Bidirectional Power flow

Source: 5SWB0 Course





CW: Clockwise ($\omega > 0$)

CCW: Counter clockwise ($\omega < 0$)

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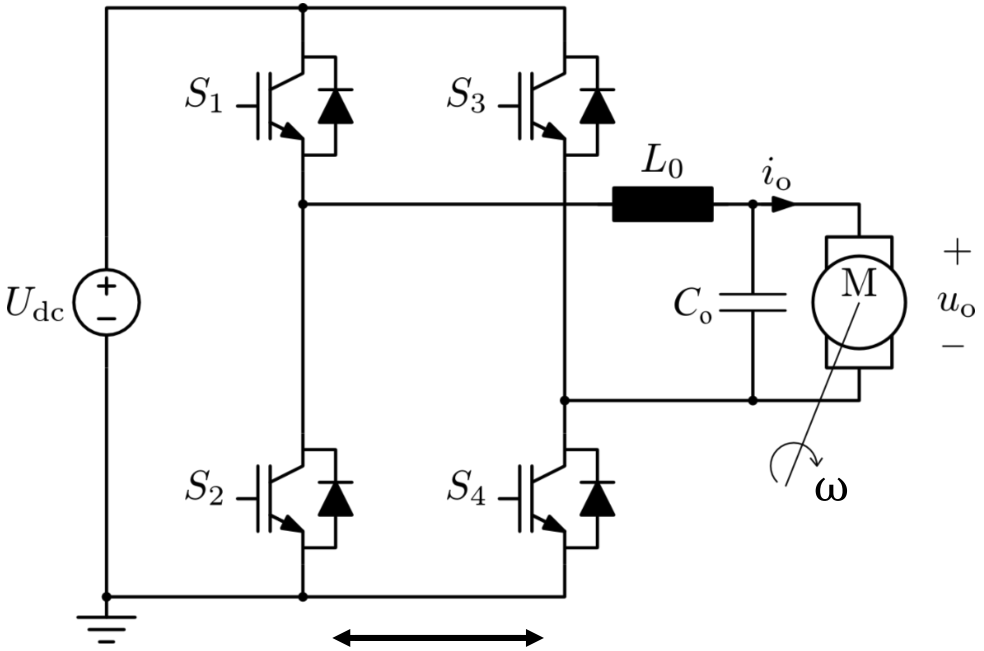
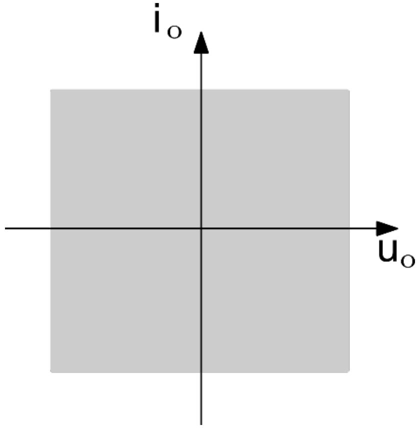
Full-bridge converter (Full H-bridge) (Week 2 → 4Q operation)

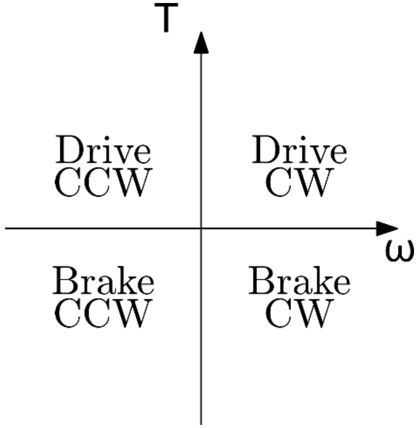
- Four quadrant (4Q) operation
  - Positive or negative output voltage, between -U_{dc} and + U_{dc} (CW or CCW rotation), $-U_{dc} \leq u_0 \leq +U_{dc}$
  - Positive or negative output current (e.g. driving/braking a motor)
  - Makes use of a **Full H-bridge** configuration of switches
- Example: motor drive



Bidirectional Power flow

Source: 5SWB0 Course





CW: Clockwise ($\omega > 0$)

CCW: Counter clockwise ($\omega < 0$)

After break…

- DC-DC Converters: Operation
- DC-AC Converters (Inverters)