Power Electronics for Decentral Energy Systems

Friedrich-Alexander-Universität Erlangen-Nürnberg

Lecture Notes

Summer term 2025

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Content

Notes and Comments

These lecture notes belong to: ....

Ideas, suggestions and hints (in particular to any found errors) are welcome. Please address them to:

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Erratum

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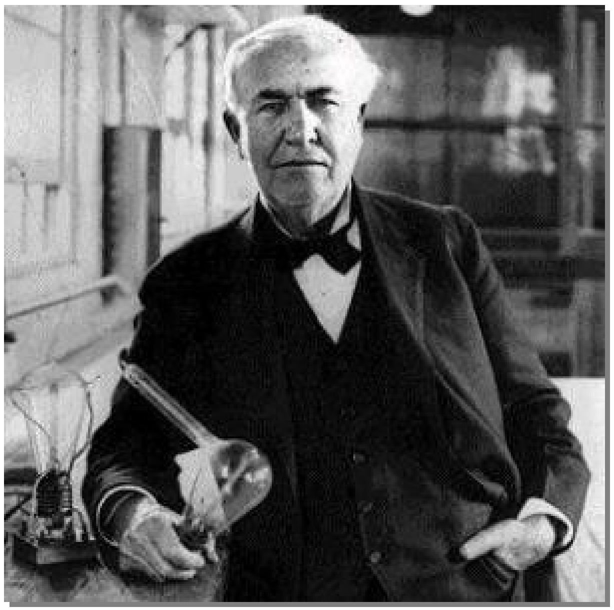
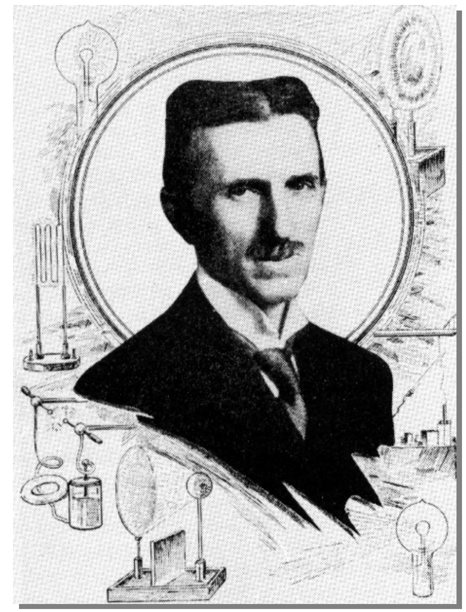
The beginnings of electrification - two important protagonists

Thomas Alva Edison
1847 - 1931



Nikola Tesla
1856 - 1943

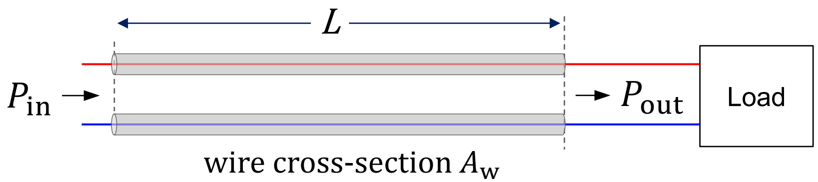


DC

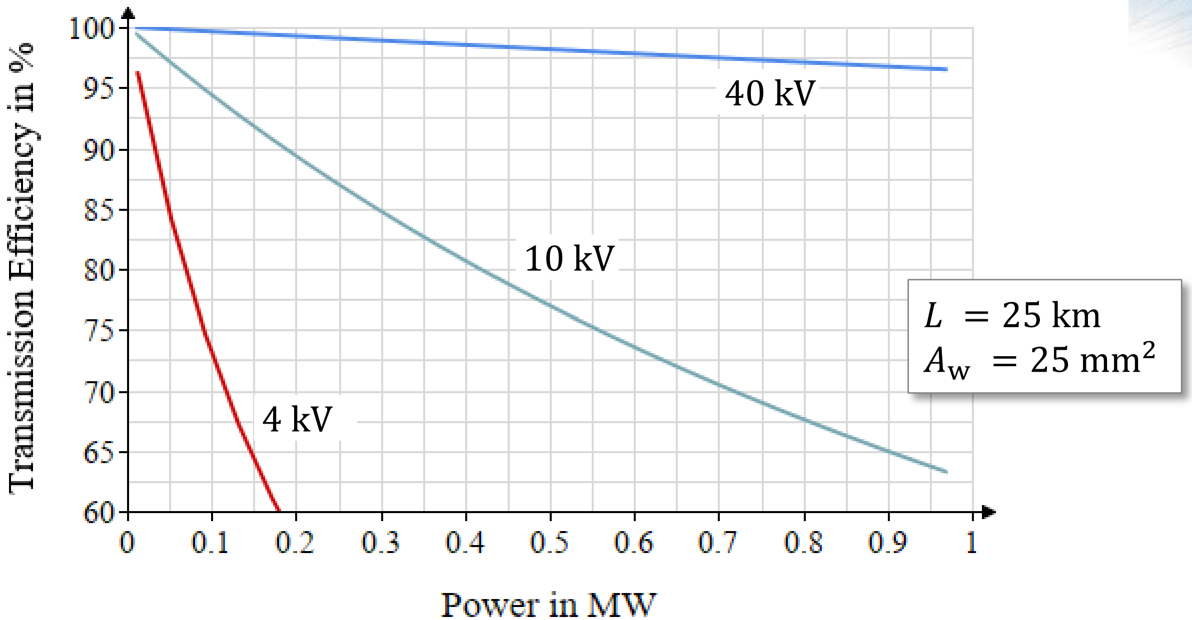
» war of currents «
1885 - 1891

AC

Electrical Power Transmission



$$\eta = \frac{P_{out}}{P_{in}}$$



↳ The transmission of high electrical power over large distances requires significantly higher voltages than would be acceptable in a domestic environment!

The beginnings of electrification

1885 — 1960 — 1970 — 1980

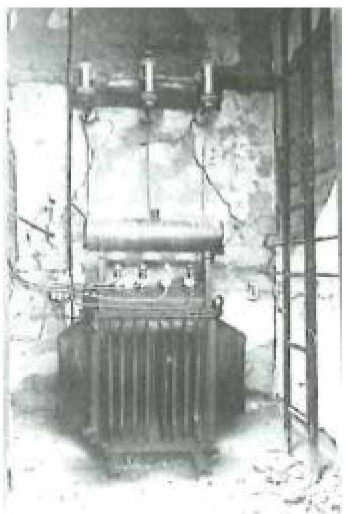
Si power diodes

Bipolar power transistors

Power modules

Power MOSFET

IGBT



Transformer

For a long time the only static option for voltage adaption (only works with alternating voltage)

Power electronics

today allows the flexible and highly efficient conversion of electrical energy from any into any desired form.

Basic technical boundary conditions have changed!

Was this the breakthrough for AC power or just a stage win?

DC

Decentral grids
Many individual producers, grid buffering by batteries

AC

High security of supply through overland/interconnected grid and availability of practically any amount of energy from central large power plants

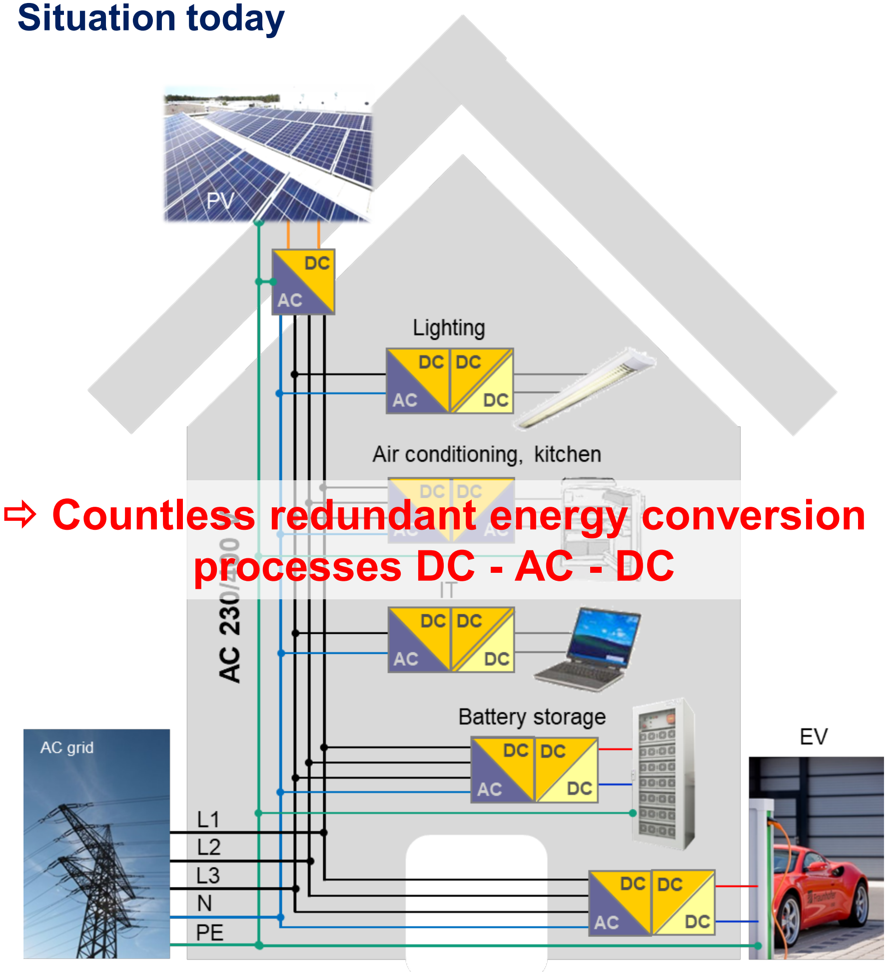
AC ? DC

Sustainable energy supply
Central and decentralized producers interacting with storages and consumers/prosumers within an intelligent power grid (smart grid)

1900 **1950** **2000**

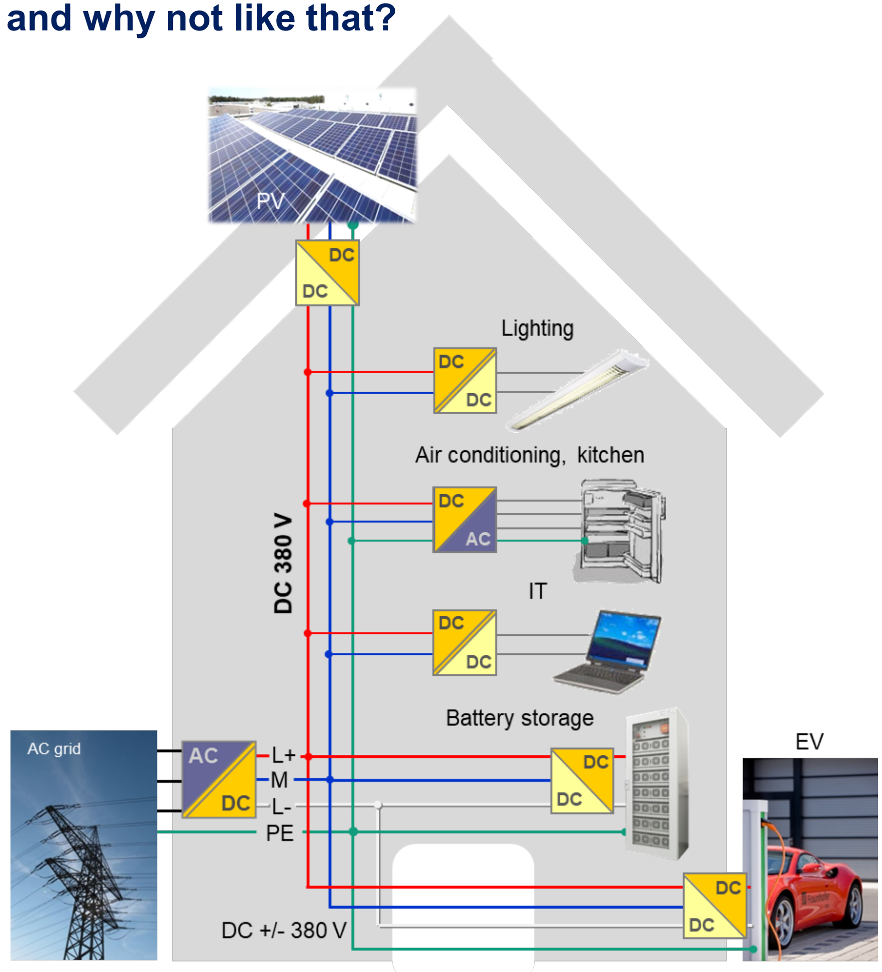
Why DC-Grids?

Situation today



⇨ Countless redundant energy conversion processes DC - AC - DC

... and why not like that?



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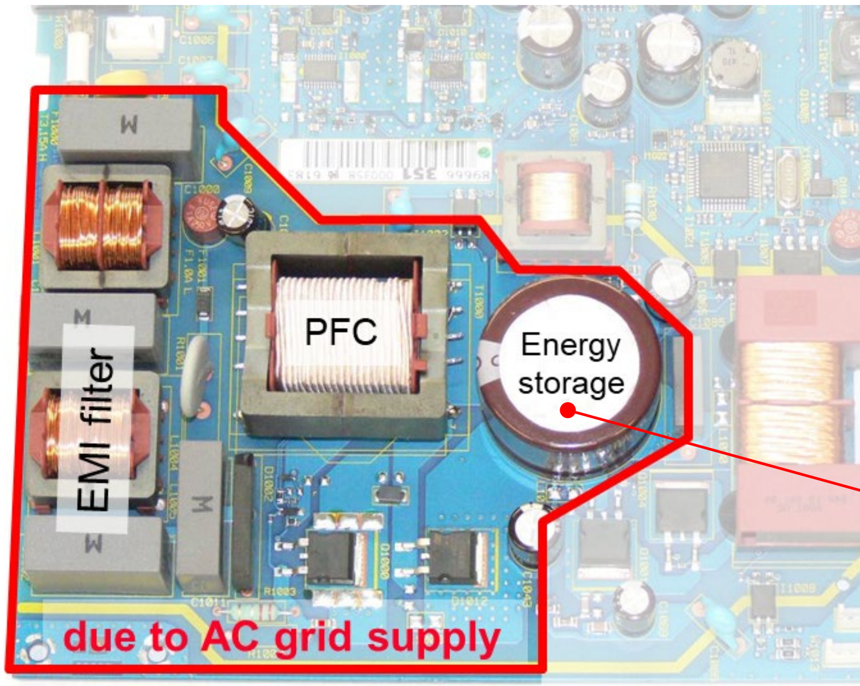
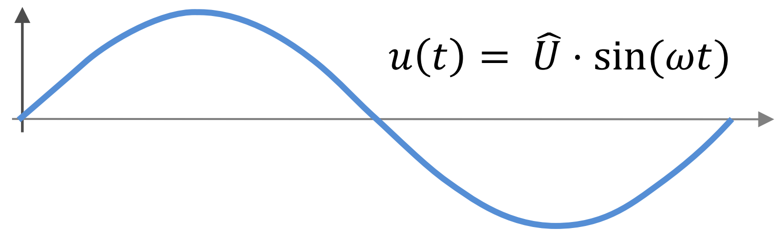
DC Grids for Decentral Energy Systems

A typical AC power suppy

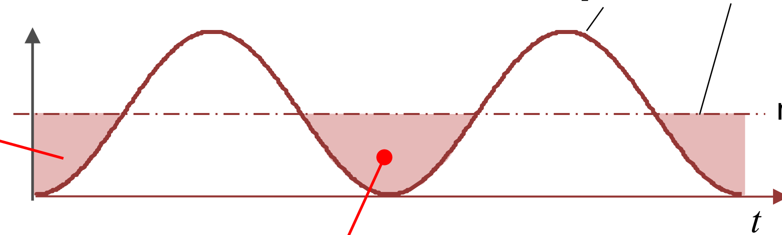


AC grid voltage

50(60) Hz



AC grid power



One hundred supply gaps per second require a considerable amount of energy storage capacity in each power supply!

⇨ With a drastic impact on **Size**, **Cost** and **Energy efficiency**

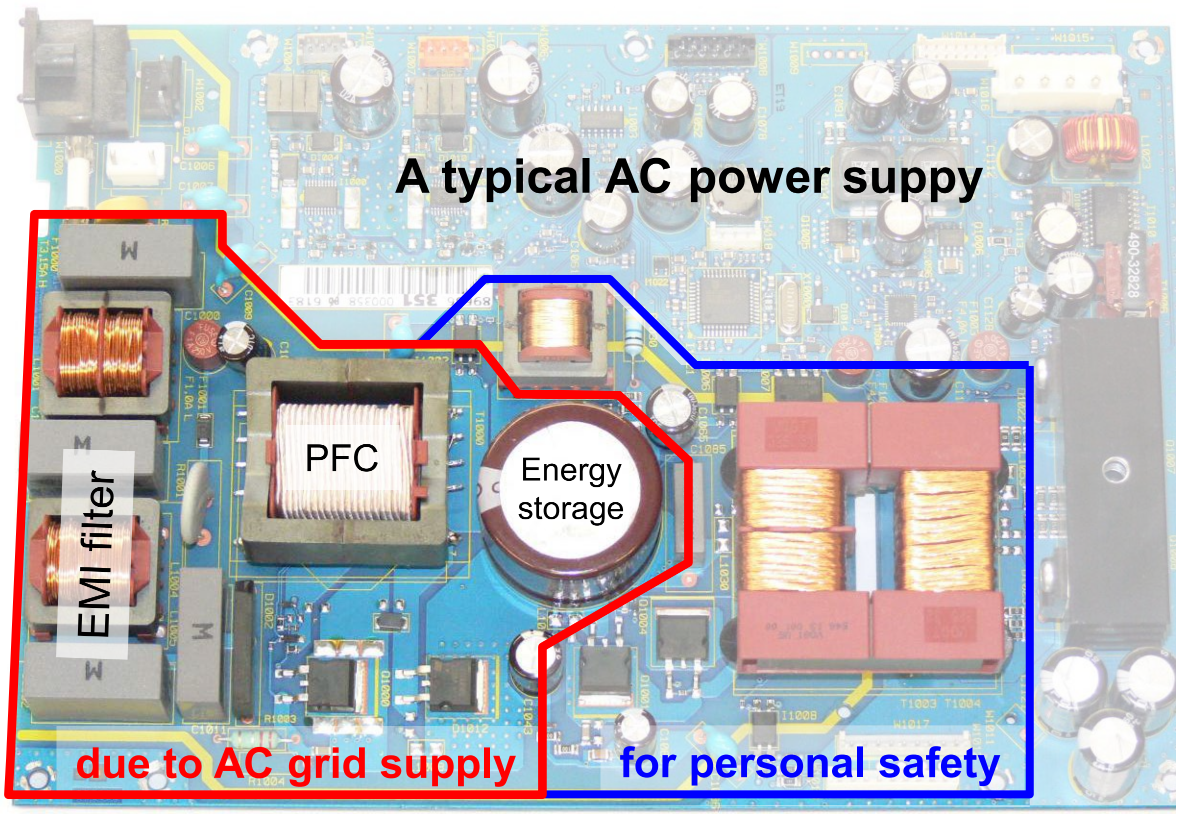
All the advances in power electronics (e.g. miniaturization by increasing the switching frequency) cannot take effect here, as the AC-grid frequency is fixed!

Equipment Power Supplies and Line Adapters

Supply from AC grid is responsible for

- **40...80%** of **losses**
- **50...95%** of **weight**
- **50...95%** of **volume**

of the AC power supply
in each electronic equipment!

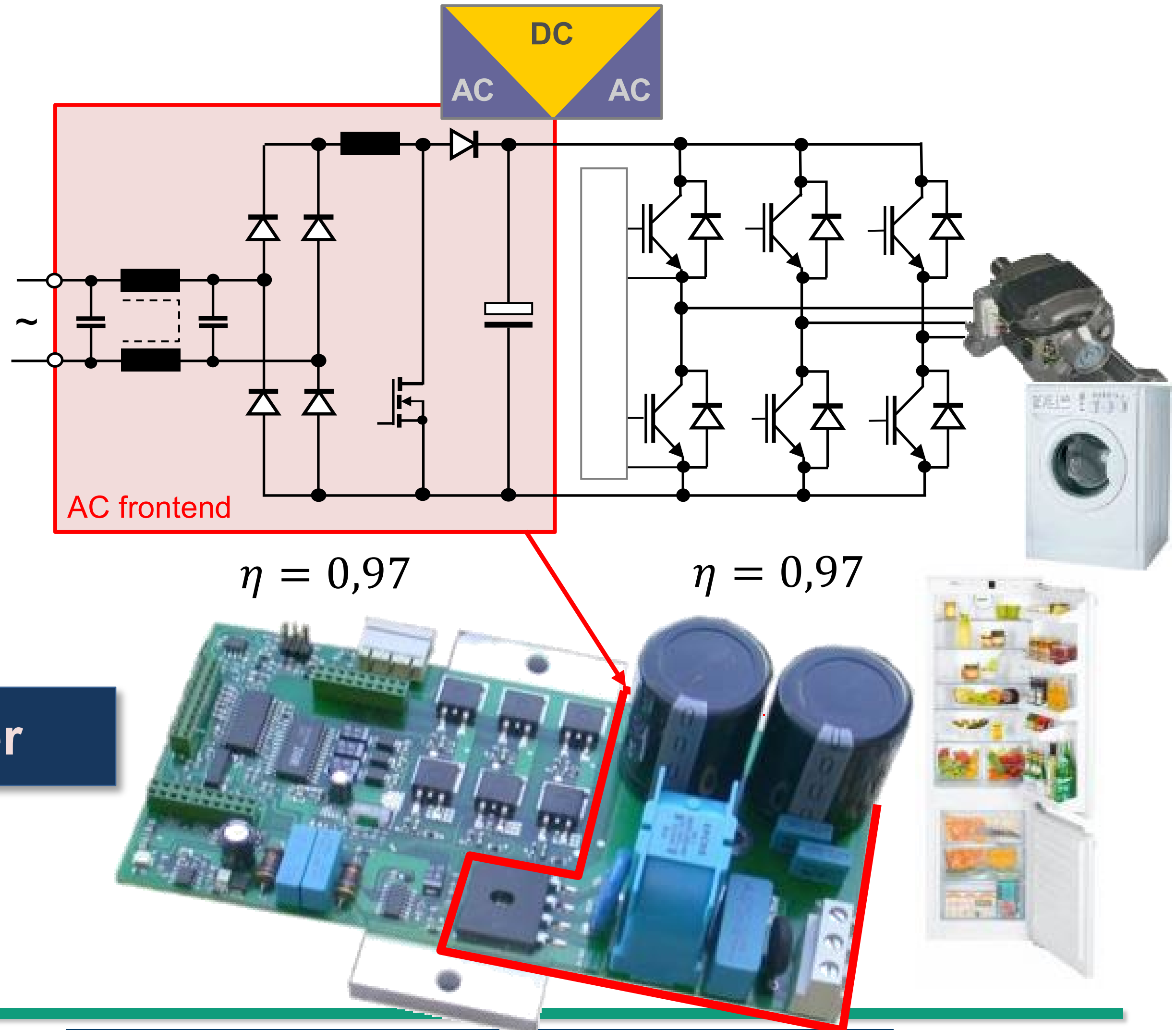


Variable Speed Drives

The **AC Frontend** causes about

- **50% of cost**
- **50% of losses**
- $>$ **65% of construction volume**

of the whole inverter!



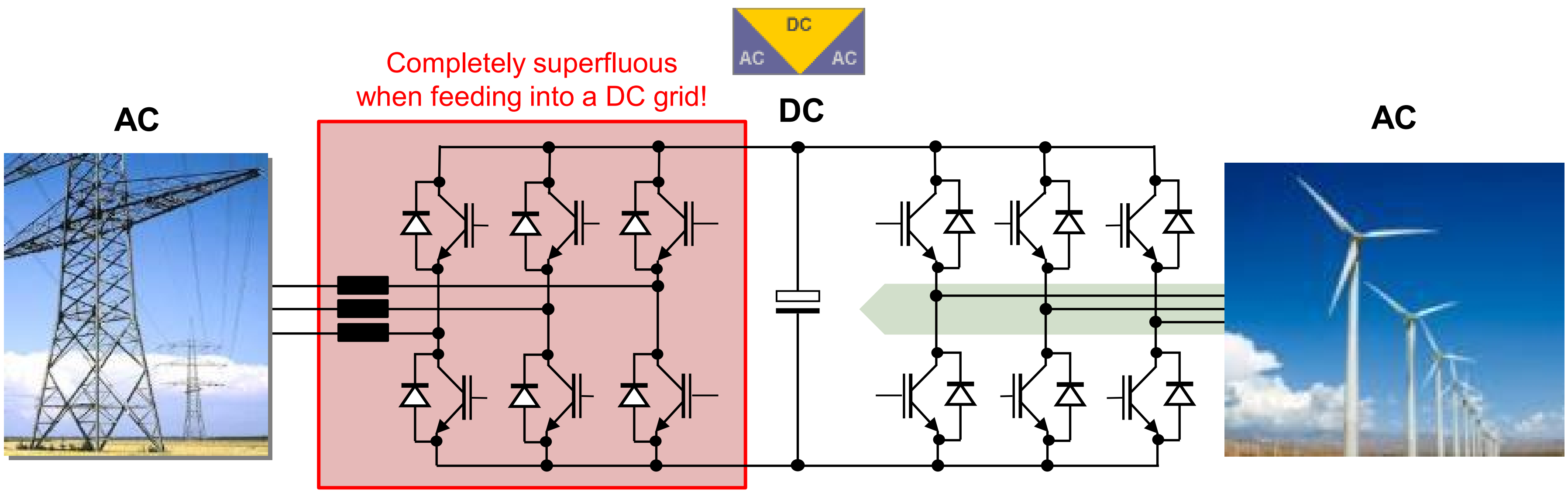
AC supply is often a

Cost Driver and **Efficiency Killer**

AC Grid Feed-in from Generators and Electrical Storages

AC Frontends

- are complex and expensive
  ⇨ and thus make many potential energy-saving applications uneconomical
- cause problems with disturbing mains feedback,
- make it more difficult to buffer peak loads using electrical energy storages.



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Aspects for a Reconsideration of Today's Power Supply Concepts

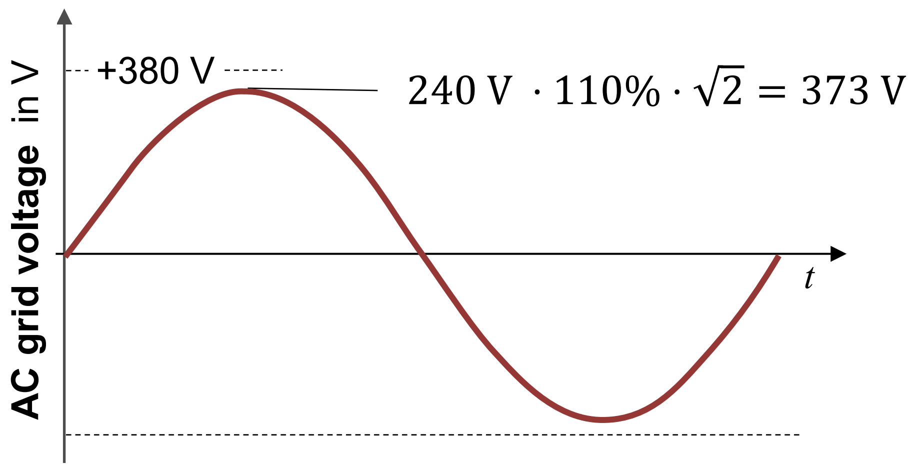
- **Reactive power increases losses and reduces transmission capacity in AC grids**
  ⇨ Problem does not exist in DC grids
- **The own use of renewable energy should be promoted**
  ⇨ PV, fuel cells, CHP or wind supply direct or cheaper direct current
- **Storage systems are becoming increasingly important as the share of PV and wind increases** ⇨ Batteries, electrolysers (H_2) work on a direct current basis
- **Energy efficiency in electric drives through energy recovery must be increased**
  ⇨ Significantly easier and more economical to implement in DC grids
- **Design and comfort aspects require ever more compact power supplies**
  ⇨ DC/DC converters are becoming smaller as the switching frequency increases, while the size reduction of AC/DC adapters is limited by the fixed mains frequency
- **The amount of electronic waste must be considerably reduced**
  ⇨ DC/DC converters of the same power can be implemented with significantly less material expenditure than AC/DC converters

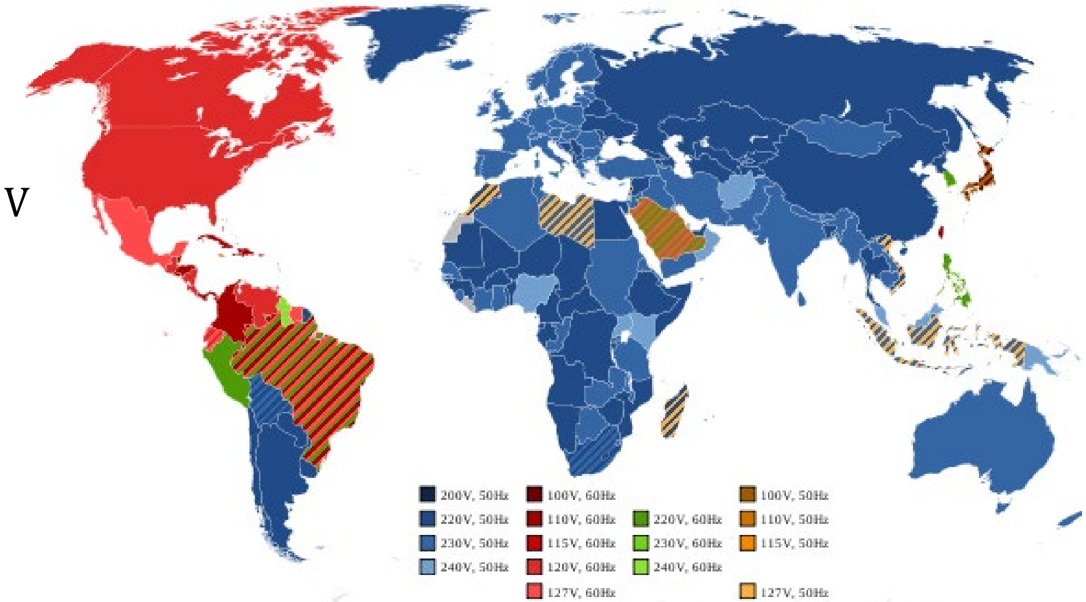
Alternating Current: **Historically a success story, today it is becoming more and more of a burden!**

Established DC Application Fields and Their Nominal Voltage

Nominal voltage	Application	
100 kV – 1 MV	High voltage DC transmission	HV
11 kV – 50 kV	Large drives, static frequency converters, reactive power compensators	MV
3.000 V	Full trains (catenary)	
1.500 V	Subway/tram (catenary)	LVDC
850 V	High voltage drivetrain in electric vehicles (premium class, sports car, SUV)	
760 V	Planned as DC grid nominal voltage for commercial (industrial) infrastructure (bipolar +/- 380 V)	
600/750 V	Underground/tram (3rd rail and catenary)	
400 V	High voltage drivetrain in hybrid and electric vehicles (mid range cars)	
380 V	DC grids in data centers; planned DC grid nominal voltage for building infrastructure	
270 V	Aircraft electrical systems (+/- 270 V)	
110 V	On-board power grid in local trains	
48/60 V	Telecom infrastructure (UPS)	SELV
48 V	Powertrain in hybrid vehicles	
24 V	On-board power grid in commercial vehicles	
12 V	On-board power grid in passenger cars	
5 V	USB bus	

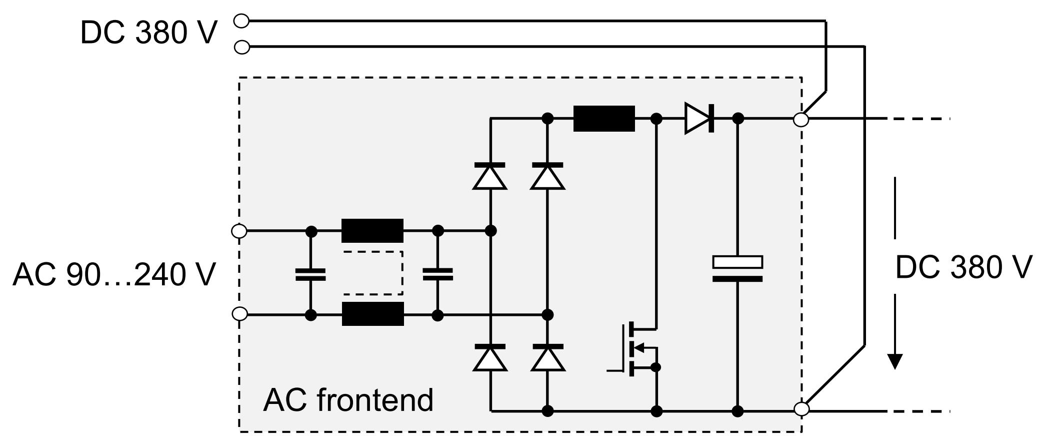
Why 380 Volts DC?





Source: www.wikipedia.org, Author: SomnusDe

Practically every power supply today has a PFC stage at the AC input[1)], which generates a DC voltage in the range from 380 to 400 volts as an internal DC link voltage. This means that, in principle, these devices can also be operated directly with DC voltage.



Although the universal voltage capability brings hardly any gain in efficiency and no advantages in terms of weight and construction volume, it simplifies conversion scenarios from AC to DC technology.

1) instead of a 50/60 Hz transformer, which would make DC operation impossible.

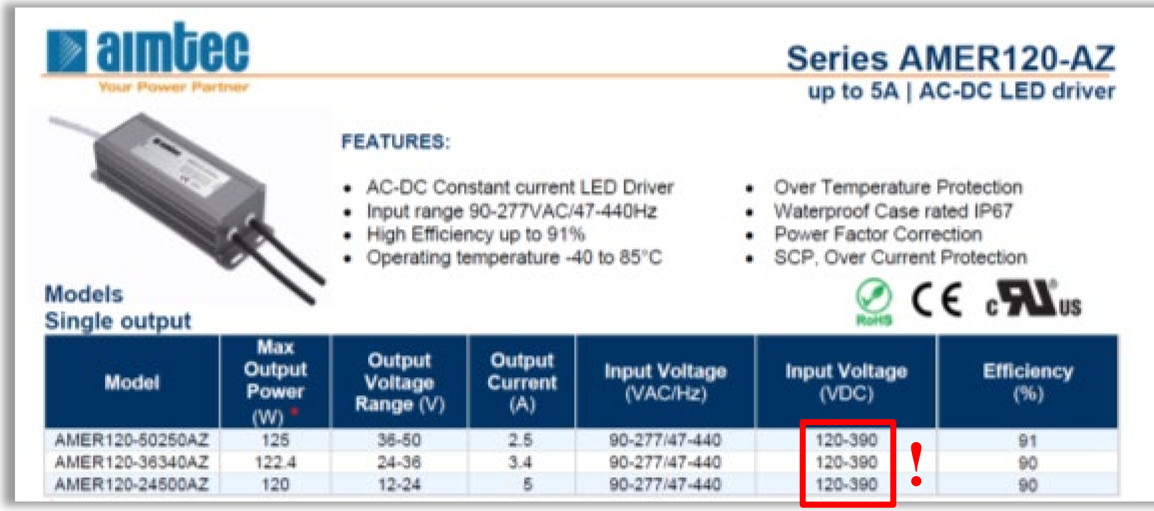
Universal Voltage Capability

more and more devices already allow an operation on both AC **and** DC grids

Example: LED Adapters

!

INPUT	VOLTAGE RANGE Note.5	90 ~ 295VAC	127 ~ 417VDC		
	FREQUENCY RANGE	47 ~ 63Hz			
	POWER FACTOR	PF ≥ 0.95/230VAC	PF ≥ 0.98/115VAC at full load a		
	EFFICIENCY (Typ.)	88%	88%	90%	
	AC CURRENT	2A / 115VAC	1A / 230VAC		
	INRUSH CURRENT(max.)	COLD START 65A/230VAC			
	LEAKAGE CURRENT	<1mA / 240VAC			


aimtec
Your Power Partner

Series AMER120-AZ
up to 5A | AC-DC LED driver

FEATURES:

- AC-DC Constant current LED Driver
- Input range 90-277VAC/47-440Hz
- High Efficiency up to 91%
- Operating temperature -40 to 85°C
- Over Temperature Protection
- Waterproof Case rated IP67
- Power Factor Correction
- SCP, Over Current Protection

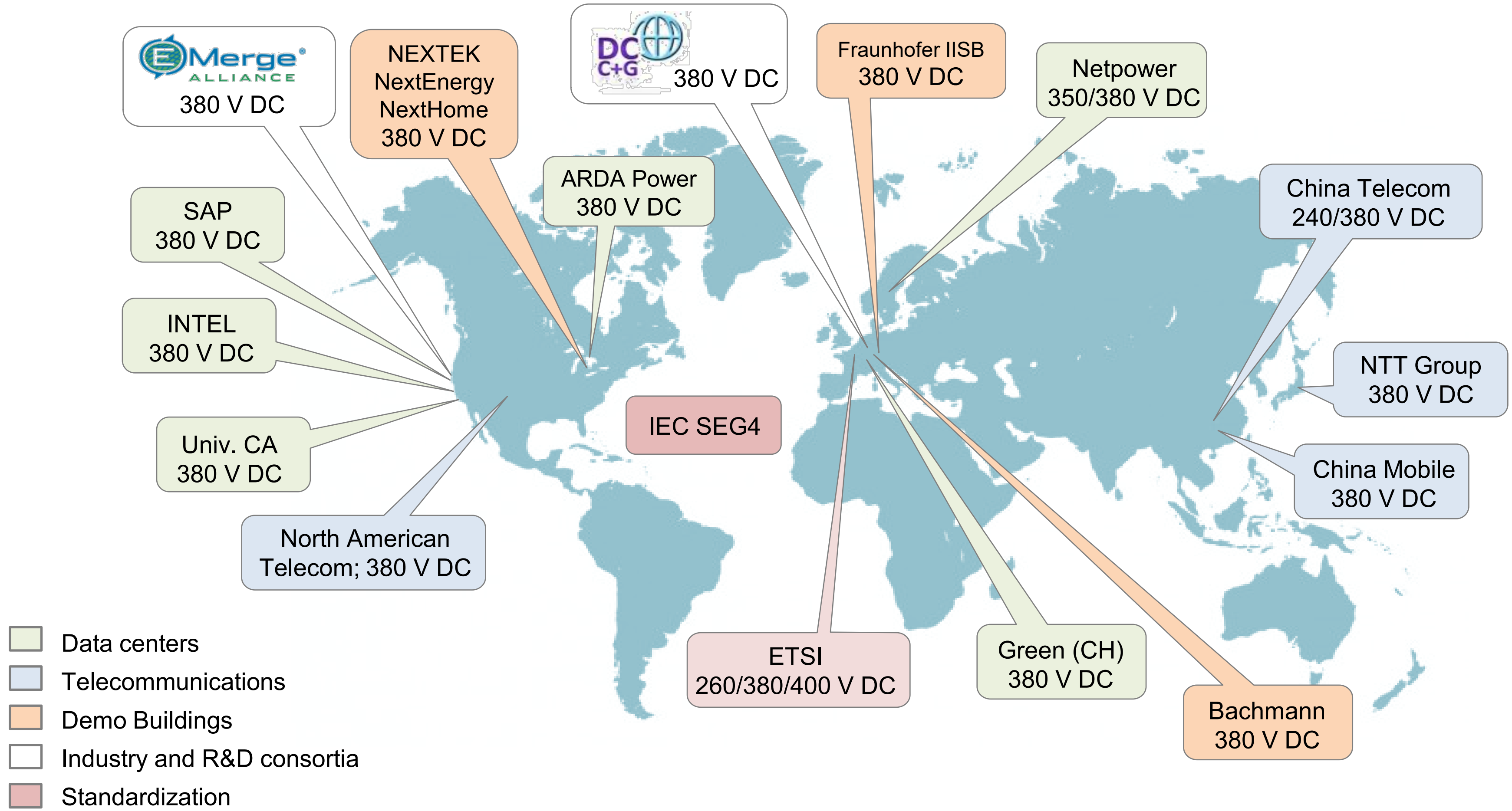
RoHS

Models
Single output

Model	Max Output Power (W) *	Output Voltage Range (V)	Output Current (A)	Input Voltage (VAC/Hz)	Input Voltage (VDC)	Efficiency (%)
AMER120-50250AZ	125	36-50	2.5	90-277/47-440	120-390	91
AMER120-36340AZ	122.4	24-36	3.4	90-277/47-440	120-390	90
AMER120-24500AZ	120	12-24	5	90-277/47-440	120-390	90

!

380 Volts are Developing into a Global Standard



Application Example Data Centers

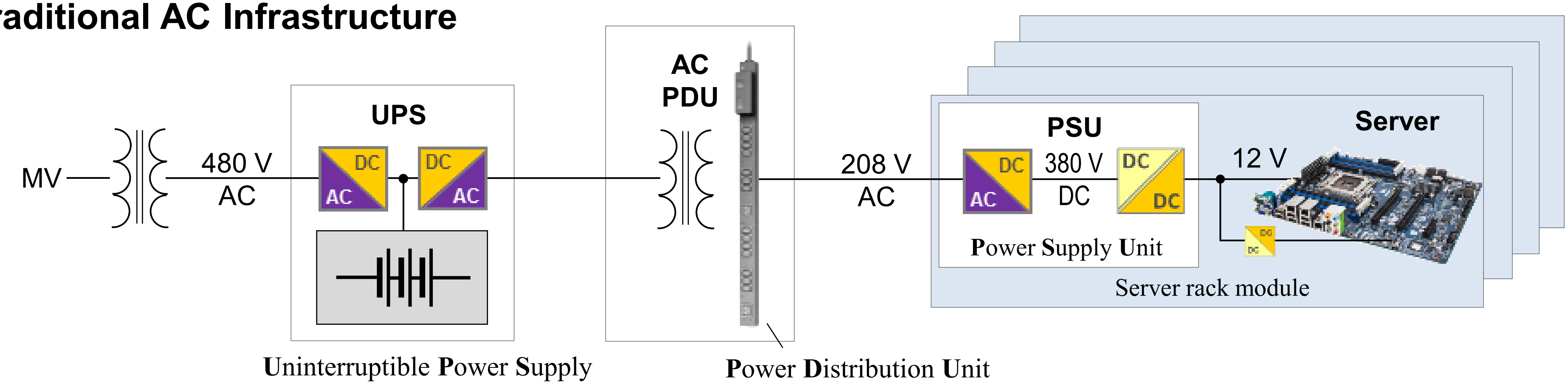
Data Center with **DC Power Infrastructure**
in Zurich/Lupfing, Swiss

- **Energy Efficiency: + 10%**
  compared to a comparable AC system,
  measured „from grid to chip“ at 40 to 60% server load.
- **Capital cost: - 15%**
  compared to a comparable AC system
- **Space requirement: - 25%**
  compared to a comparable AC system

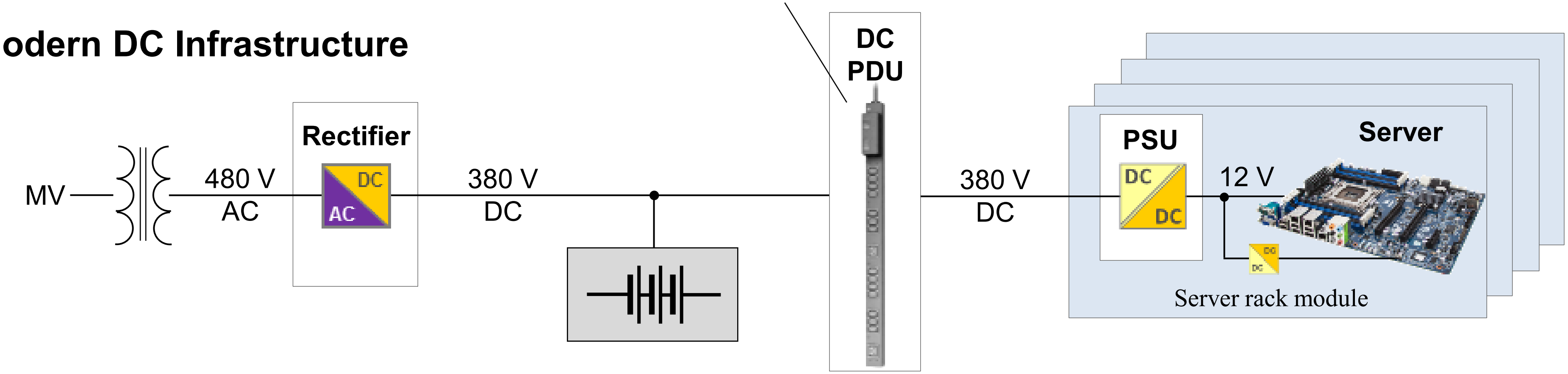
Source: ABB Presentation (K. Bittinger)

Application Example Data Centers (USA)

Traditional AC Infrastructure

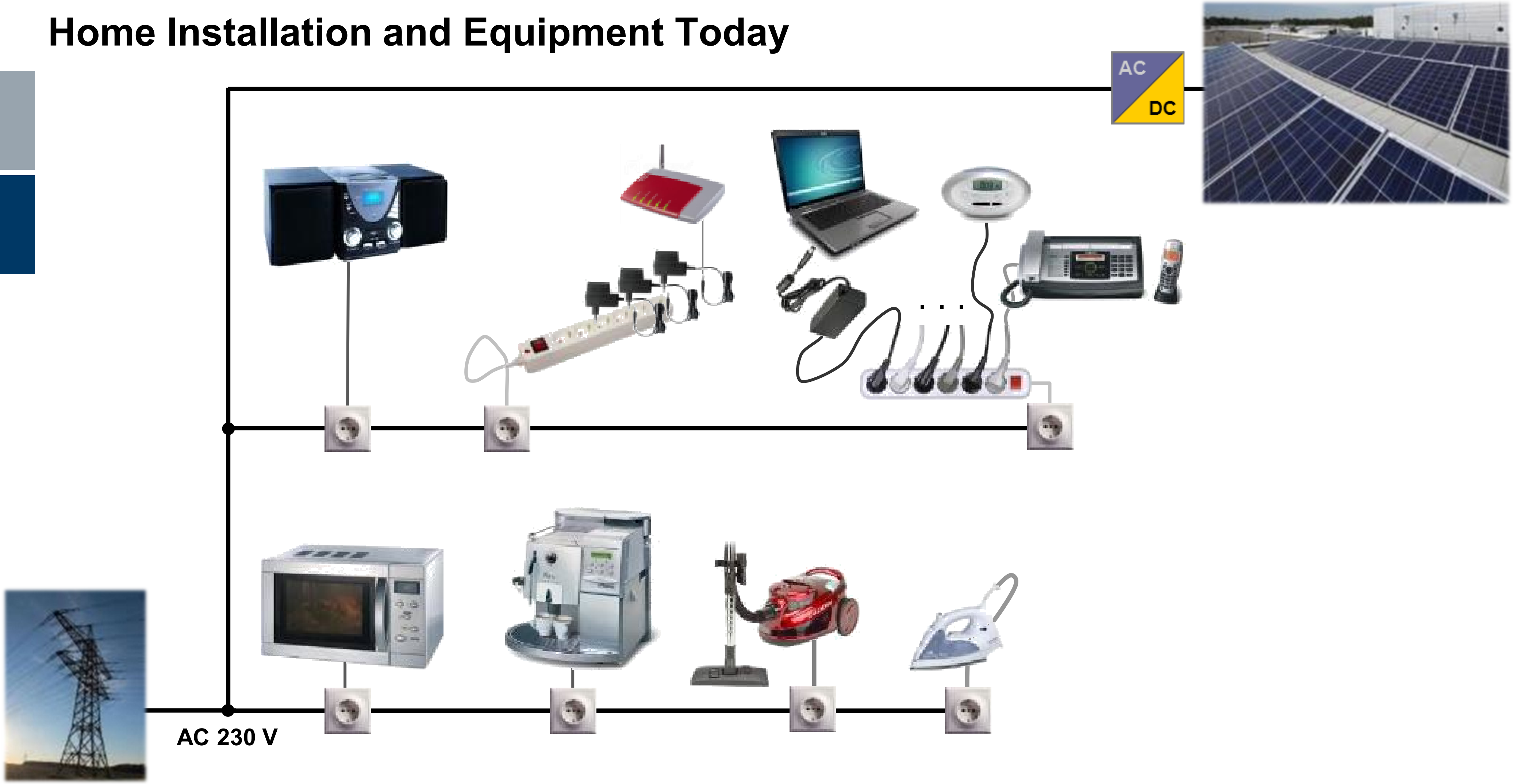


Modern DC Infrastructure



↳ Less investment costs, higher energy efficiency, lower space requirements, significantly higher security of supply

Home Installation and Equipment Today



DC Grids for Decentral Energy Systems

… an admittedly not entirely fair comparison:

AC Line Adapter	vs.	DC/DC Converter
75 W AC 230 V ⇨ DC 19 V		**75 W** DC 24 V ⇨ DC 19 V

Efficiency: **87 %**

Efficiency: **95 %**

Small and efficient enough to be integrated in a connector strip

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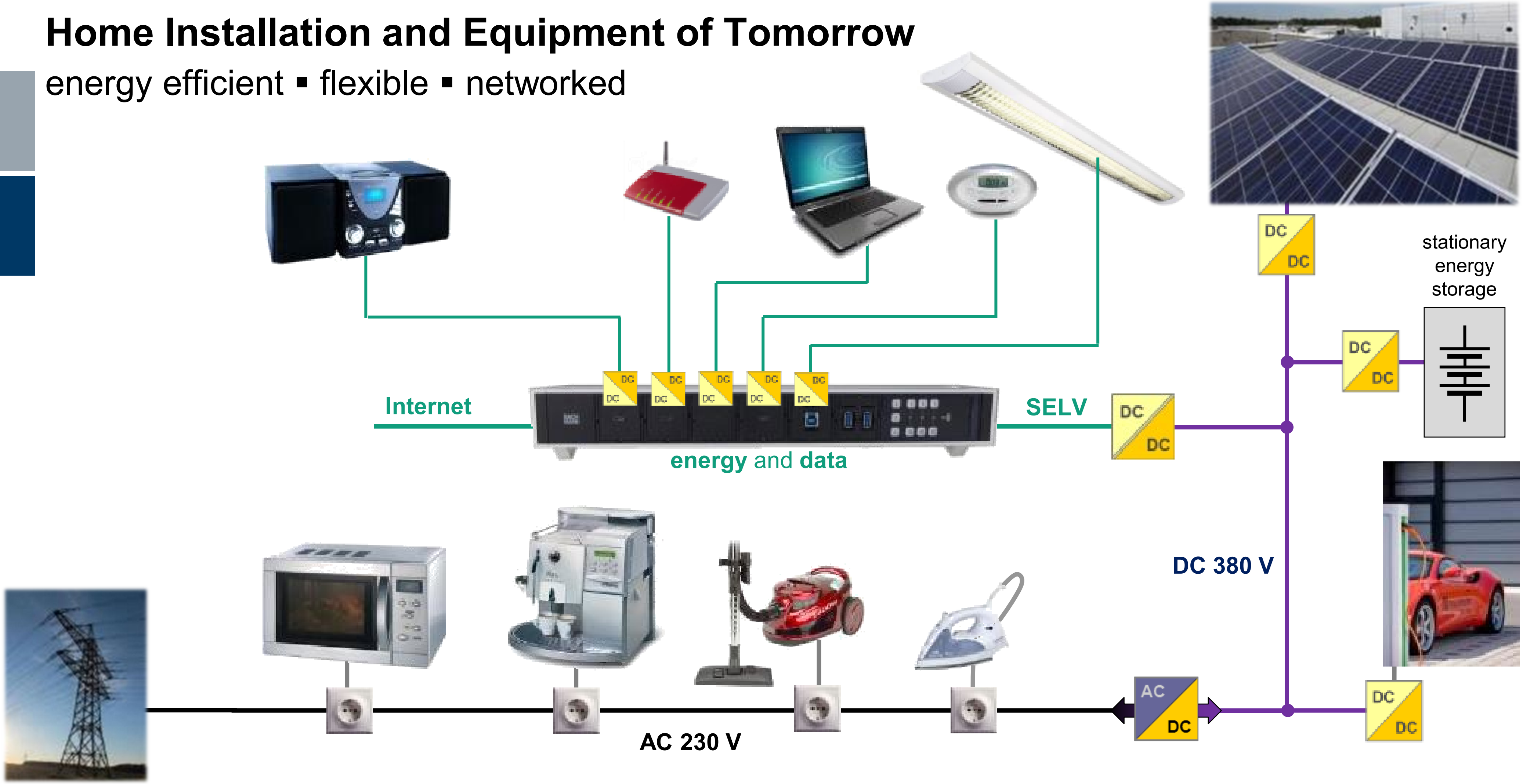
DC Grids for Decentral Energy Systems

Home Installation and Equipment of Tomorrow

energy efficient ▪ flexible ▪ networked



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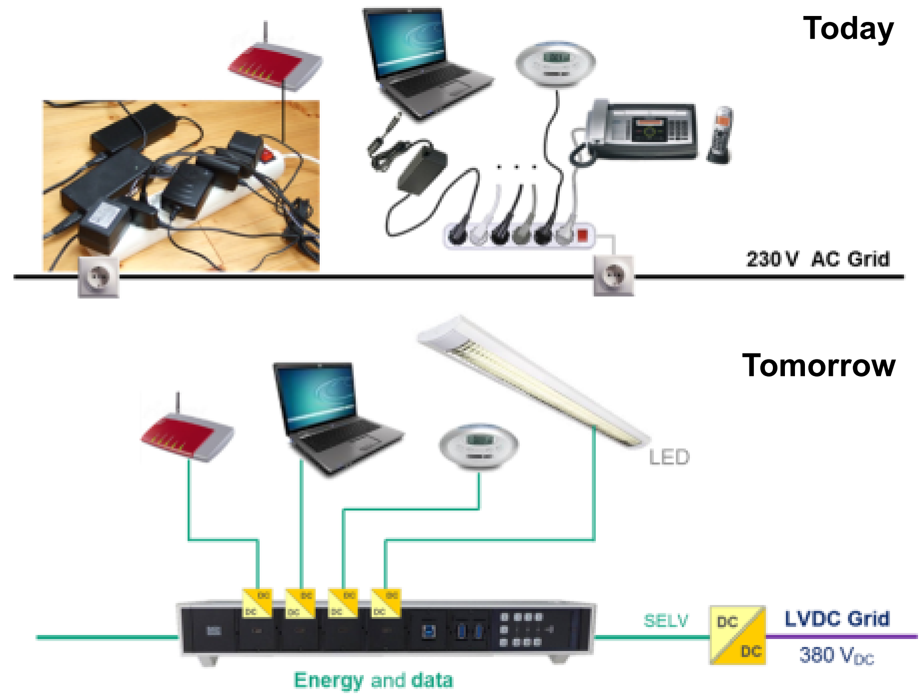
A Customized Power Supply - only feasible with DC

Market requirements

Appliances have to become
- less expensive,
- more compact,
- more energy efficient,
- more comfortable and
- more sophisticated in terms of design.



How to achieve that?

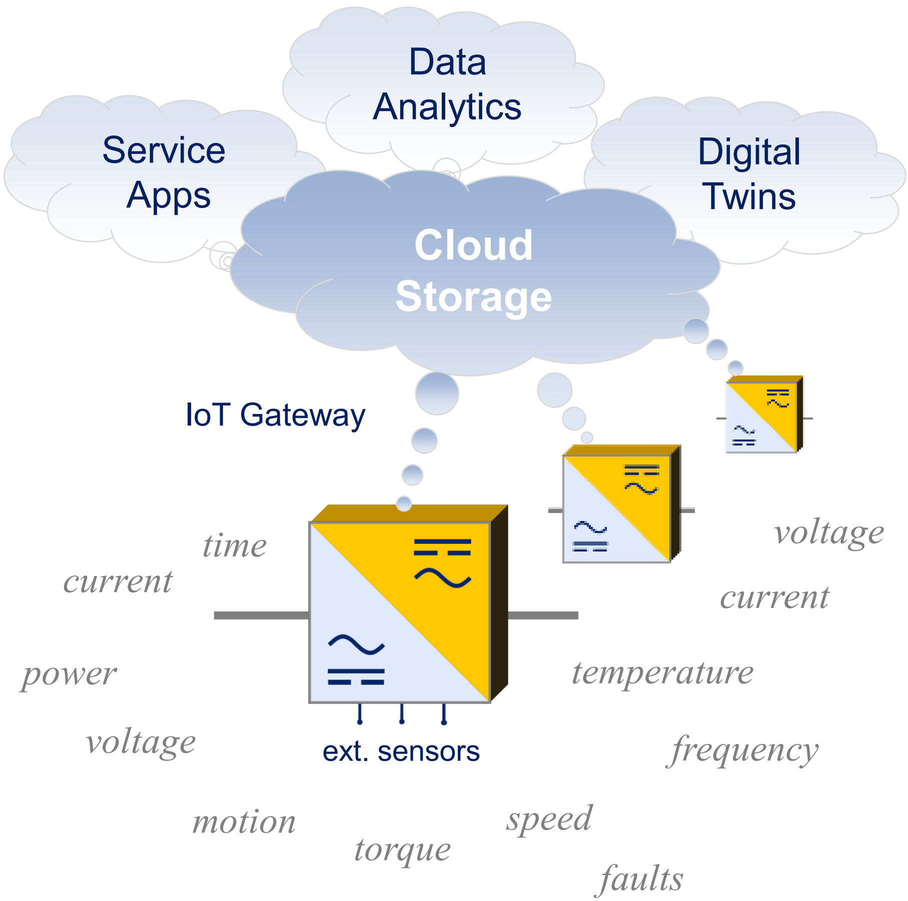
The power supply becomes part of the infrastructure and intelligent sockets supply the voltage required by the respective application.

Not a vision but already reality in some areas!

- Power-over-Ethernet (PoE), USB PD (USB 3.1 with Type C connector)
- DC fast charging stations for electric vehicles (up to 950 volts, 350 kW)

DC Grids for Decentral Energy Systems

… and an intelligent power supply can provide much more!



Cognitive Power Electronics

- **Power-as-a-Sensor**
- **Power-as-a-Monitor**
  - Process monitoring
  - Grid and equipment monitoring
  - Predictive maintenance
- **Software defined Power**
  - Power conversion modules with freely definable functionality
- **Power-as-a-Service**
  - Energy management
  - Application specific grid behaviour

A Large Number of Research Projects Deal with this Important Topic

DCC+G

DC Components and Grids

Partners: E-T-A, Emerson, Infineon, Fraunhofer IISB, TU Eindhoven, heliox, MTT, Siemens, SRB, Philips,
Funding: EU (eniac), Run-time: 2012 - 2015

DC-Schutzorgane + DC-Schutzsysteme

Development of new protection concepts, components and systems solutions for future DC grids

Partners: ABL Sursum, Bender, Bachmann BSG, Dehn + Söhne, E-T-A, Fraunhofer IISB, Phoenix Contact
Funding: BMWi, Run-time: 2016 - 2019 (DC-Schutzorgane); 2019 – 2023 (DC-Schutzsysteme)

DC-Industrie + DC-Industrie2

Intelligent open DC grid in industry for highly efficient system solutions in production environments with electric drives

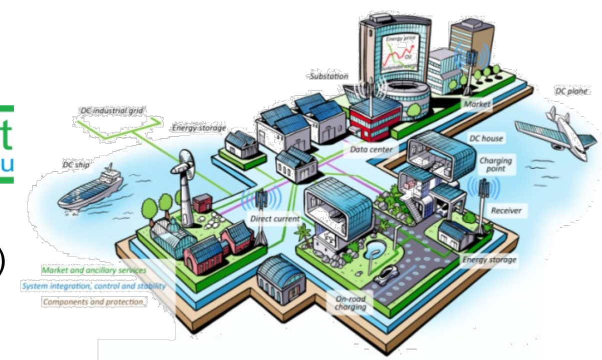
Partners: Baumüller, Bauer Gear Motors, Danfoss, Daimler, Lenze, Bosch Rexroth, Fraunhofer IISB, LTI Motion, Siemens, KHS, Hochschule Ostwestfalen-Lippe, Universität Stuttgart, Fraunhofer IPA, Weidmüller, ZVEI
Funding: BMWi, Run-time: 2016 – 2019 (DC-Industrie)

DC-Smart

DC Smart
www.dcsmart.eu

Enable a straightforward integration of smart grid system technologies, development and implementation of direct current distribution smart grids.

Partners: TU Delft, TU Eindhoven, Netherlands Direct Current BV, Fraunhofer IISB, CESM (Swiss)
Funding: EU (Horizon 2020), Run-time: 2016 - 2019



… and a lot of others!

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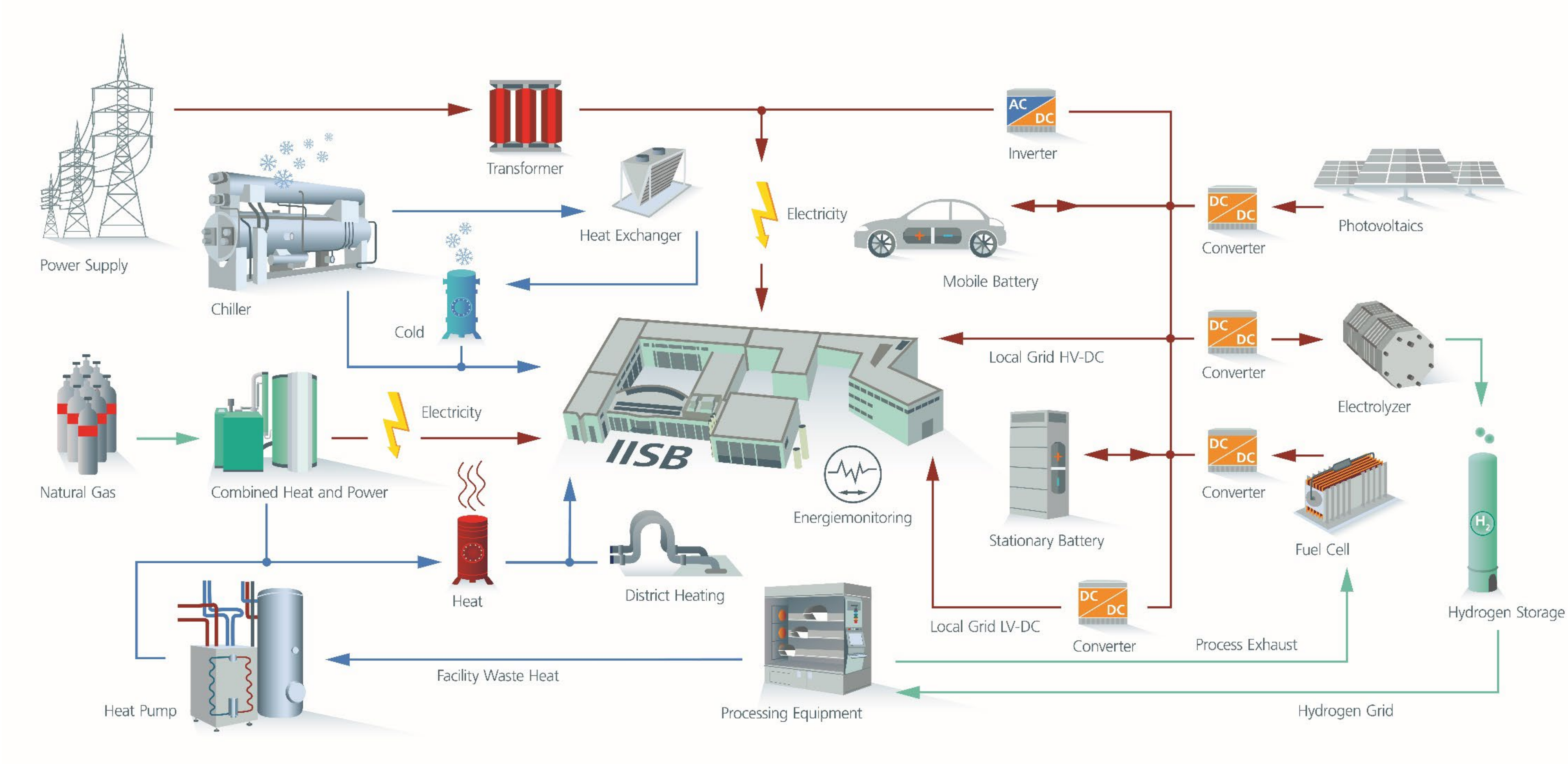
DC Grids as an Integral Part of Modern Cross-sector Energy Systems



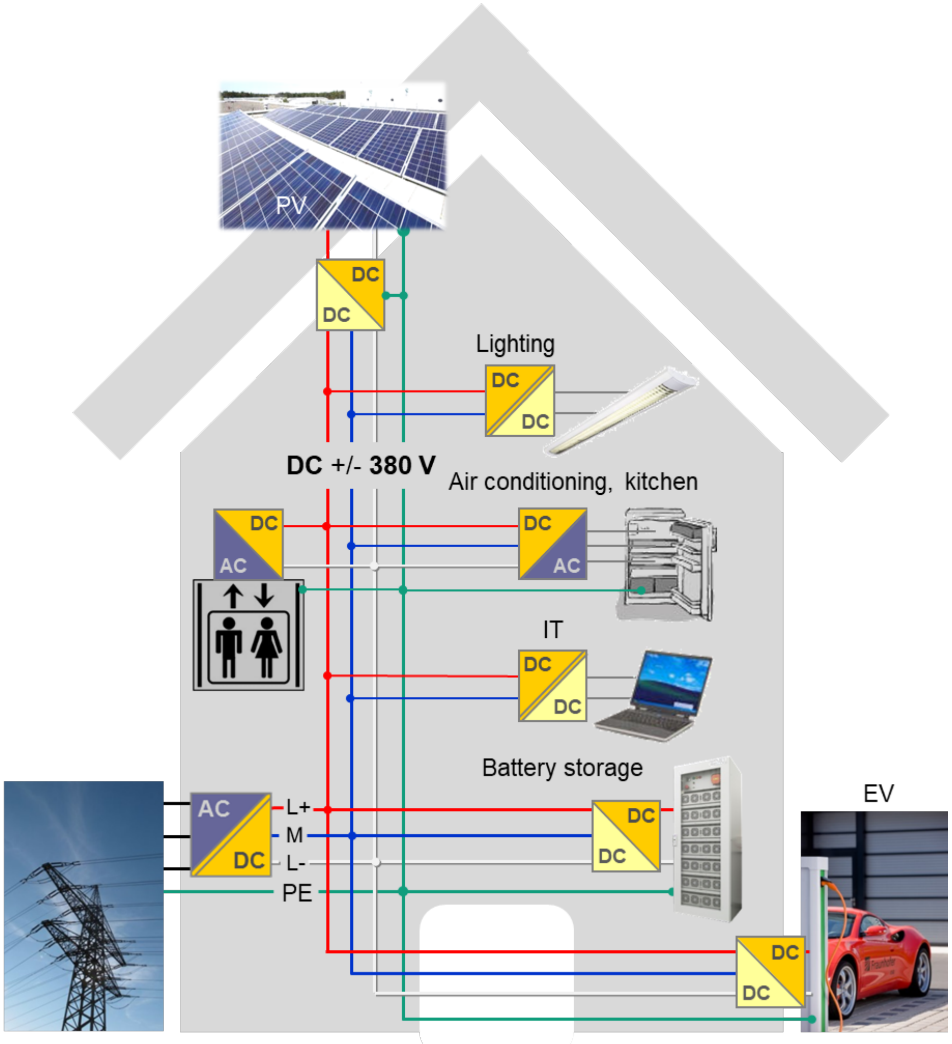
A Broad Technology Kit for Sustainable Energy Systems Already Exists

- Photovoltaic
- H_2 electrolyser
- Fuel cell
- LOHC technology
- Pressure storage
- Biogas
- Battery storage
- CHP plant
- Heat pump
- Electric vehicles
- Redox-Flow battery
- Cold/ heat storage
- Local heat/ cold grid
- Wind power
- Geothermal energy

The Challenge

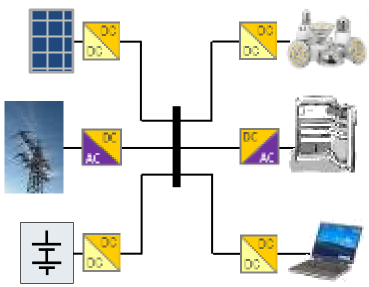
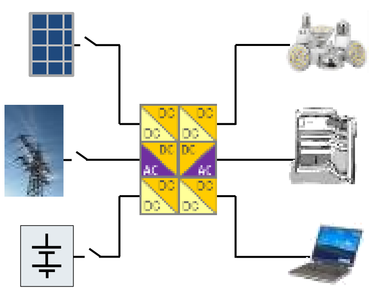
Combine the right technologies and design the individual components application-specifically so that the overall system is as economical and sustainable as possible!

DC Grids for Decentral Energy Systems



DC Grid Topologies

DC Grids

d-Star  decentral	**Advantages** ■ low planning effort ■ easy troubleshooting ■ relatively simple line protection **Disadvantages** ■ relatively long cable runs ■ stability analysis necessary for spatially extended networks (to avoid control instabilities, oscillations)	typical home installation
c-Star  central control	**Advantages** ■ very low planning effort ■ very easy troubleshooting ■ very simple line protection ■ easy control, no stability problems **Disadvantages** ■ relatively long cable runs ■ low impedance battery line (high short-circuit currents)	small island grids

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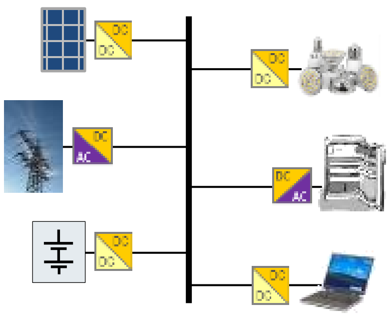
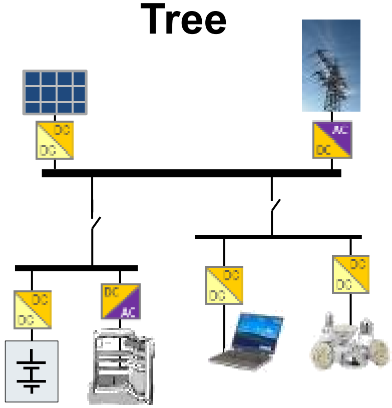
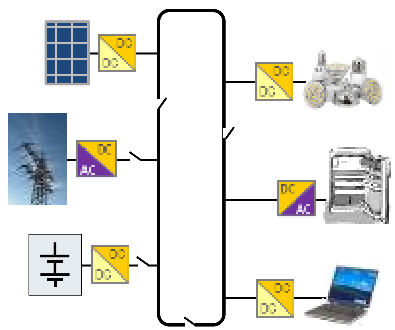
DC Grids

Bus 	**Advantages** ■ simple and very flexible installation of branch lines with minimal cabling effort **Disadvantages** ■ expensive central busbar (with quite a lot of copper) ■ stability analysis necessary for spatially extended networks (to avoid control instabilities, oscillations, etc.)	small industrial production plants
Tree 	**Advantages** ■ hierarchical structure in feed-in and load groups possible ■ selectivity in grid protection easier to implement ■ more easy troubleshooting in extended networks **Disadvantages** ■ increased installation effort	classic hierarchical electrical installation

Ring



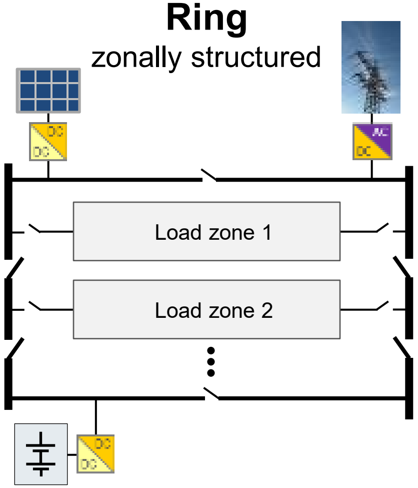
Advantages

- increased supply reliability
- reduced line losses

Disadvantages

- Isolation of a faulty grid section requires the coordinated operation of several switching points
- high planning effort for grid protection engineering

Ring
zonally structured



Advantages

- maximum availability
- minimal cross-influencing of the load zones in the event of a fault
- reduced line losses

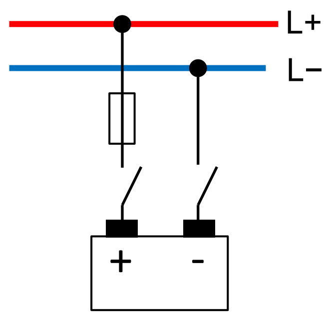
Disadvantages

- Isolation of a faulty grid section requires the coordinated operation of several switching points
- high effort for grid protection engineering
- very high infrastructural expenditure

DC grids in industrial production plants and data centers

The Grid Characteristic Changes Fundamentally with the Kind of Battery Connection!

Battery directly connected



Short circuit current of a midsize LiIon cell (50…100 Ah) typically
5 to 10 kA

Advantages

- **Many traditional grid protection concepts can be transferred** (melting fuses, etc.)
- Grid voltage hardly influenced by high inrush currents
- Low component count ⇨ supposedly more cost efficient
- Less electronic components ⇨ higher lifetime and availability (?)

Disadvantages

- Potentially very high short-circuit currents, resulting in high demands on the grid components
- Grid voltage fluctuates strongly with the state of charge (SoC)
- No individual charge / discharge control for distributed batteries
- Danger of very high equalizing currents when coupling different batteries
- It´s not possible to use the grid voltage as an independent grid control parameter and thus to define more complex grid functions via voltage windows.

Example

- 12/24 V automotive powernet
- Telecom power supply infra-structure

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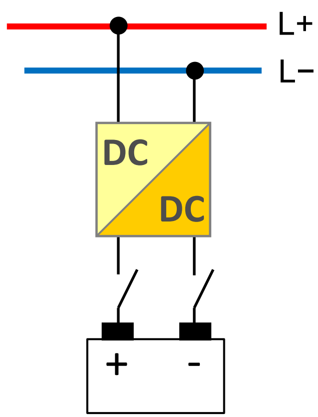
The Grid Characteristic Changes Fundamentally with the Kind of Battery Connection!

Battery connected via a converter



Short circuit current of DC/DC converters: typically less than 150% of nominal current

Advantages

- **Comparatively low short-circuit and fault currents**
- Grid voltage is independent of the state of charge and battery technology
- Individual charging / discharging management can be implemented
- Unproblematic handling of multi-battery configurations
- Grid voltage can be used as an independent control parameter
- A narrower grid voltage window offers cost-cutting potential for all grid components and end devices

Disadvantages

- Lower short-circuit power and therefore more sensitive to, e.g., high inrush currents
- A higher grid impedance increases the risk of grid instabilities (control oscillations)
- More expensive, increased failure rate (?)

Example

- almost all stationary storage systems in Li-Ion technology

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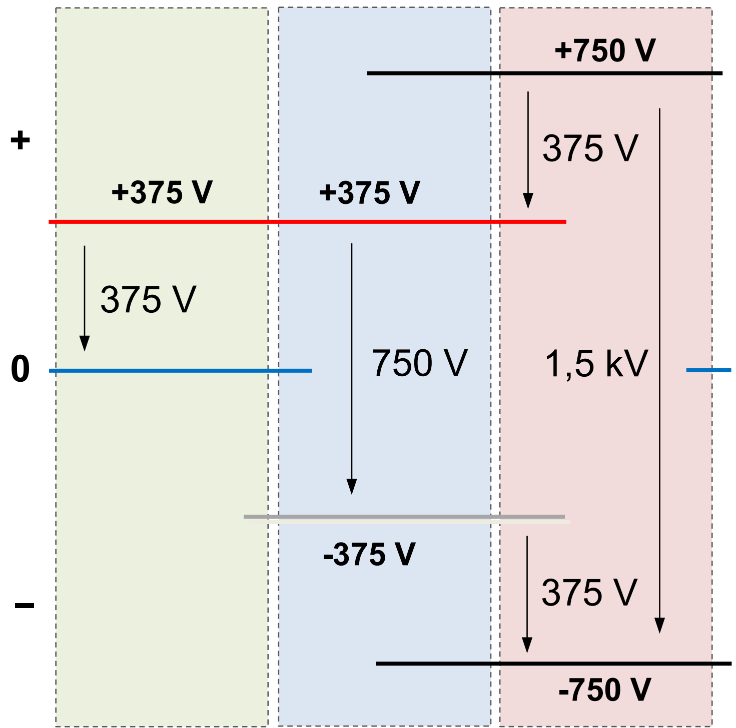
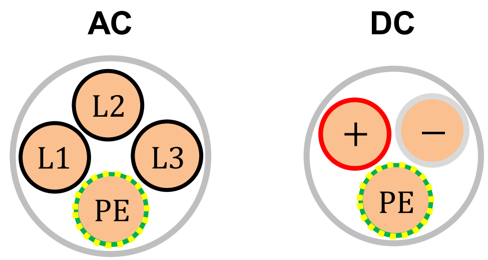
DC and AC Installations in Performance Comparison



1,500 volts form the low voltage limit according to Directive 2014/35/EU (Low Voltage Directive)

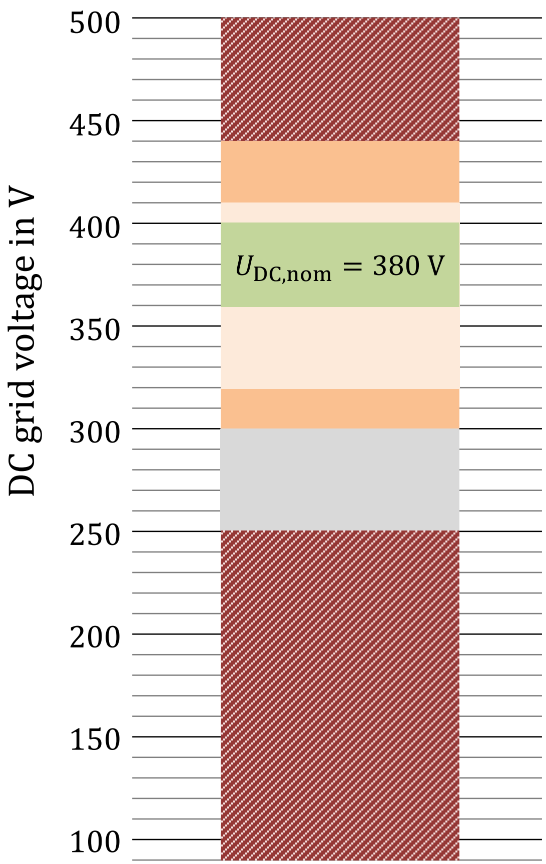
Grid form	Maximum power at 16 A single wire load capacity	Cable cores[1)]
DC 380 V	375 V · 16 A = **6,0 kW**	3
AC single phase, 230 V	230 V · 16 A = **3,7 kW**	3
DC +/-380 V	750 V · 16 A = **12 kW**	**3** (4)
AC three phase, 400 V	√3 · 400 V · 16 A = **11 kW**	**4** (5)
DC +/-750 V	1.500 V · 16 A = **24 kW**	3 (4)
AC three phase, 690 V	√3 · 690 V · 16 A = **19 kW**	4 (5)

1) including PE, in brackets with neutral conductor



Less copper or more transmittable power with DC technology

Grid Voltage Specification ■ The 380 V DC Grid at Fraunhofer IISB as an example



Nominal operation
- fully specified functionality

Stationary over-/undervoltage
- fully functional, but power derating permitted
- continuous operation permitted
- lower boundary of the voltage window extended for compatibility with 350 V systems (NL)

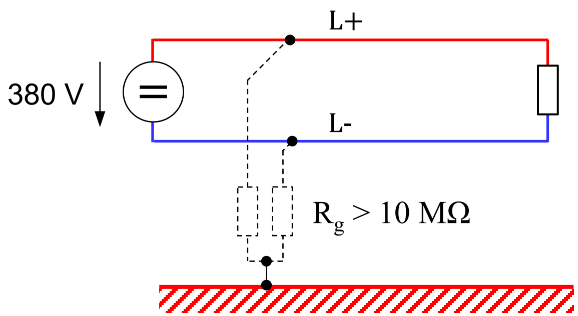
Transient over-/undervoltage
- voltage may be in this range only for a limited time
- functional restrictions are permissible, but must disappear when the voltage returns into the "stationary" window

Special function area
- reserved for various protection and security functions (e.g. emergency operation: only selected loads, such as emergency lighting or IT servers, may/must continue to run; all other loads must shutdown itself)

Shutdown area
- loss of function, devices switch off permanently

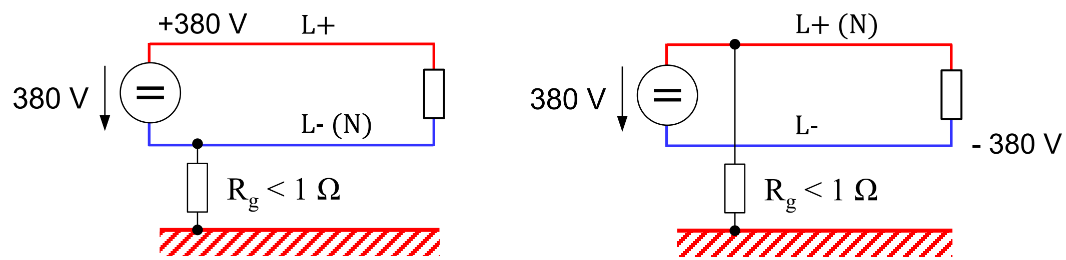
Earthing Concepts – an overview

Galvanically isolated (IT[1] system)

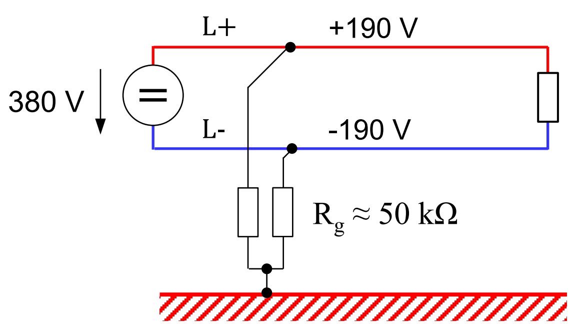


1) IT from French "Isolé Terre" (has nothing to do with "Information Technology")

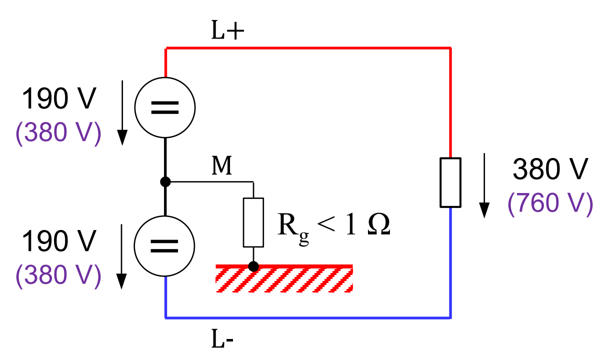
Unbalanced hard grounded



Symmetrically high-resistive grounded

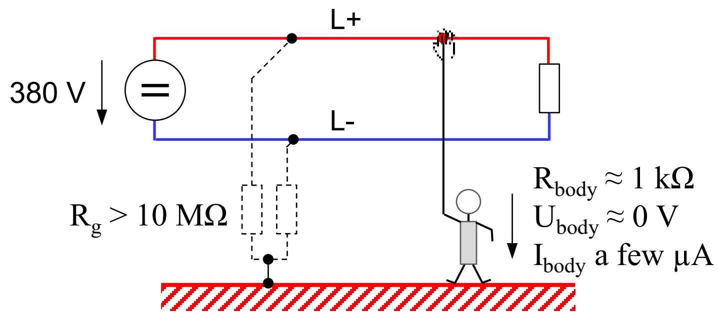


Symmetrically hard grounded

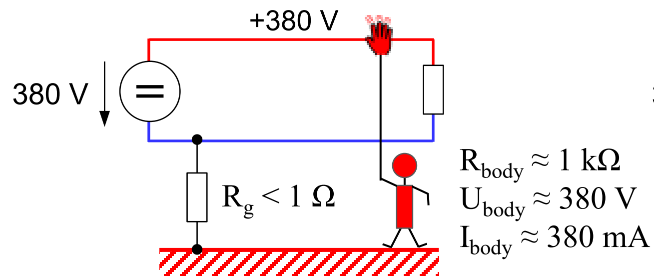


Earthing Concepts - static touch currents in the event of a fault

Galvanically isolated (IT system)

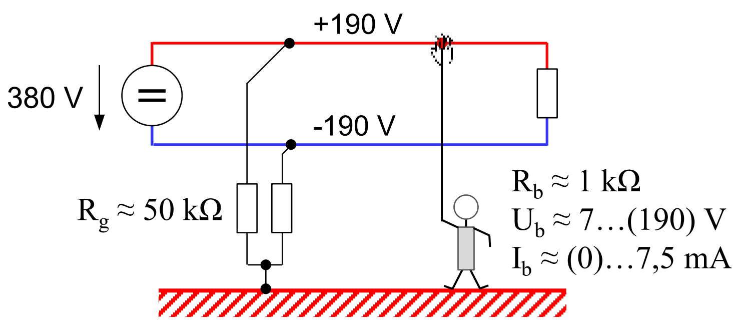


Unbalanced hard grounded

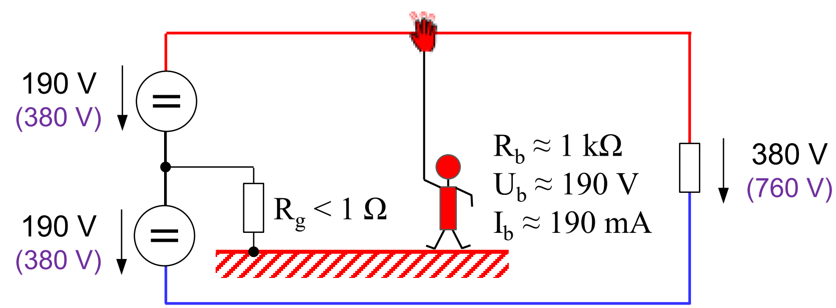


⇨ A residual current circuit breaker (RCD type B) is essential!

Symmetrically high-resistive grounded

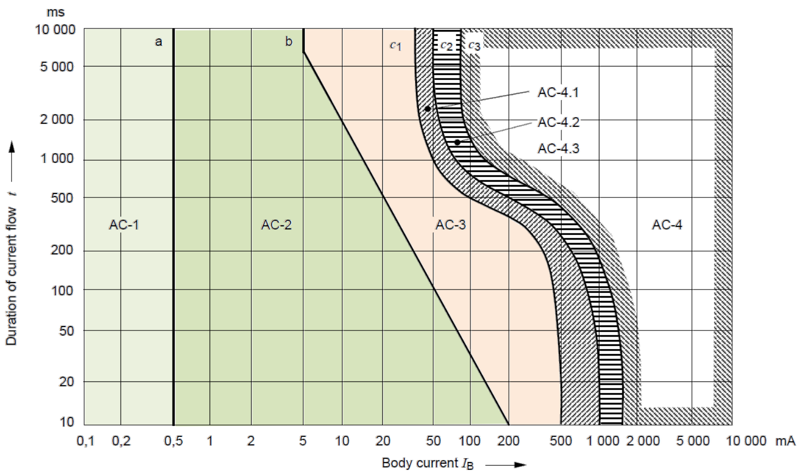


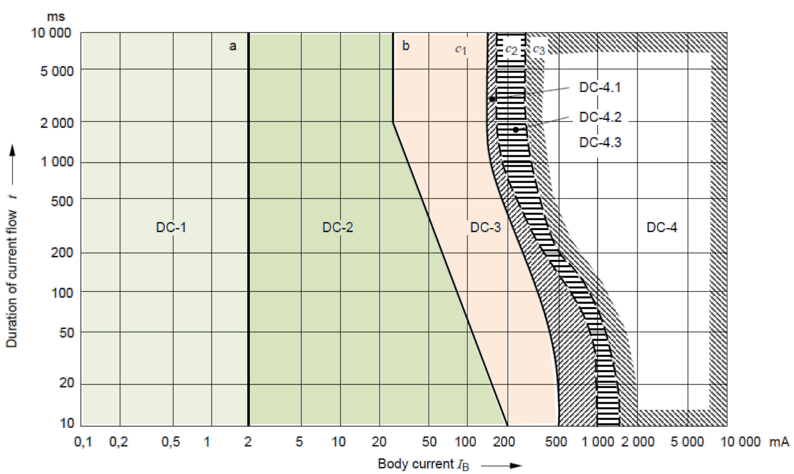
Symmetrically hard grounded



⇨ A residual current circuit breaker (RCD type B) is essential!

Impact of Body Currents





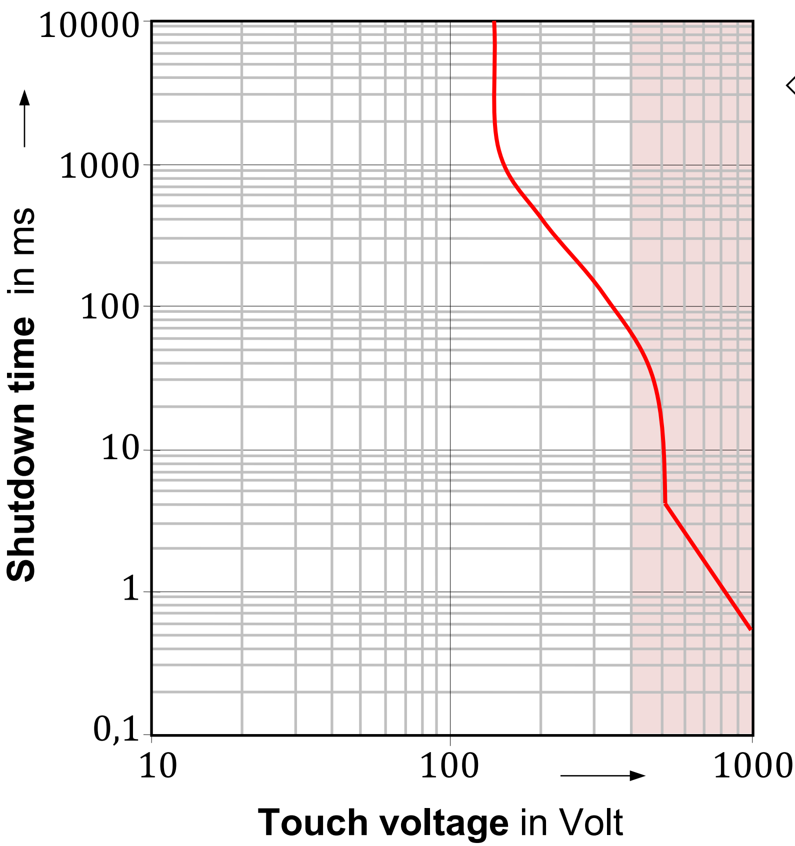
- Usually no noticeable effects
- Usually no harmful physiological effects
- The risk of ventricular fibrillation is still very low

Direct Current (DC) vs. Alternating Current (AC)

- For longer exposure times, the limits in the case of DC are significantly higher than for AC, but this does not mean that direct current is a priori safer!
- In addition to "ventricular fibrillation", other effects must be taken into account with longer exposure times:
  - Hemolysis (dissociation of red blood cells)
    ↳ Kidney failure, death after hours or days
  - Burn wounds, charring of tissue

Source: DIN IEC/TS 60479-1 (VDE V 0140-479-1)

Protection against Electric Shock



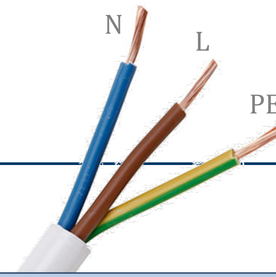
⇦ **Necessary shutdown time as a function of touch voltage**

(assuming a body resistance of 1 kΩ, resp. 500 Ω initial body resistance below 4 ms)

Achievable shutdown times

- Mechanical switches (RCD, ...): a few tens of **milliseconds**
- Mechanical high-speed switches: a few **milliseconds**
- Semiconductor switches: a few **microseconds**

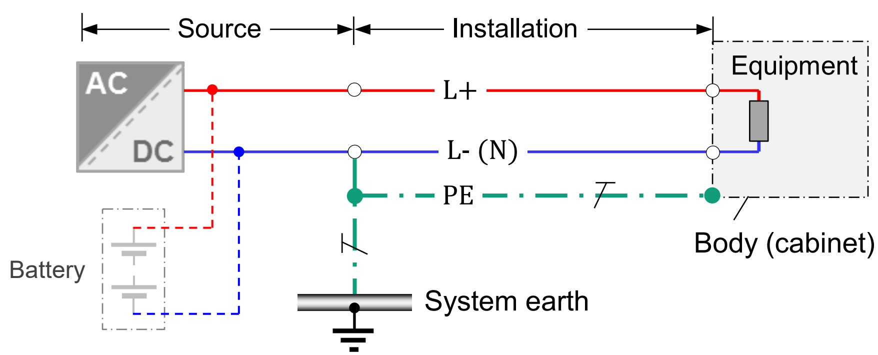
Values taken or derived from IEC/TS 60479-1 and IEC/TS 60479-2



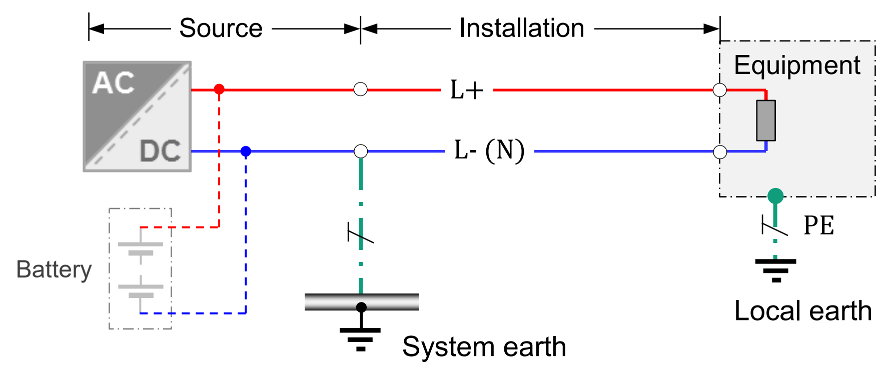
Nomenclature of Grid Earthing Arrangements

1. Letter Earth connection of the source	**2. Letter** Earth connection of equipment body	**Further letter** Arrangement of neutral and protective conductors
T Directly grounded (frz. Terre)	**T** Body directly grounded	**S** Neutral and protective conductors separated
I Isolation from earth	**N** Body connected to system earth	**C** Neutral and protective conductors combined (PEN)

TN-S Network

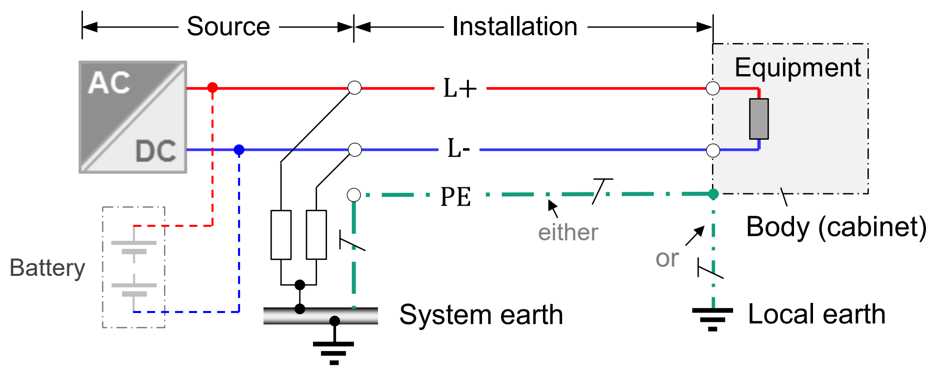
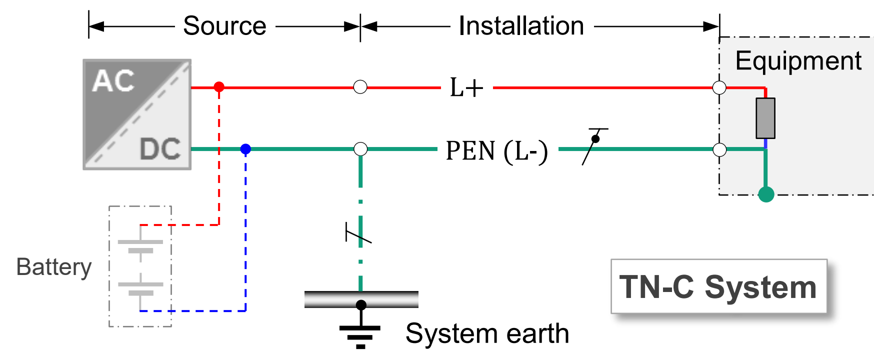


TT Network



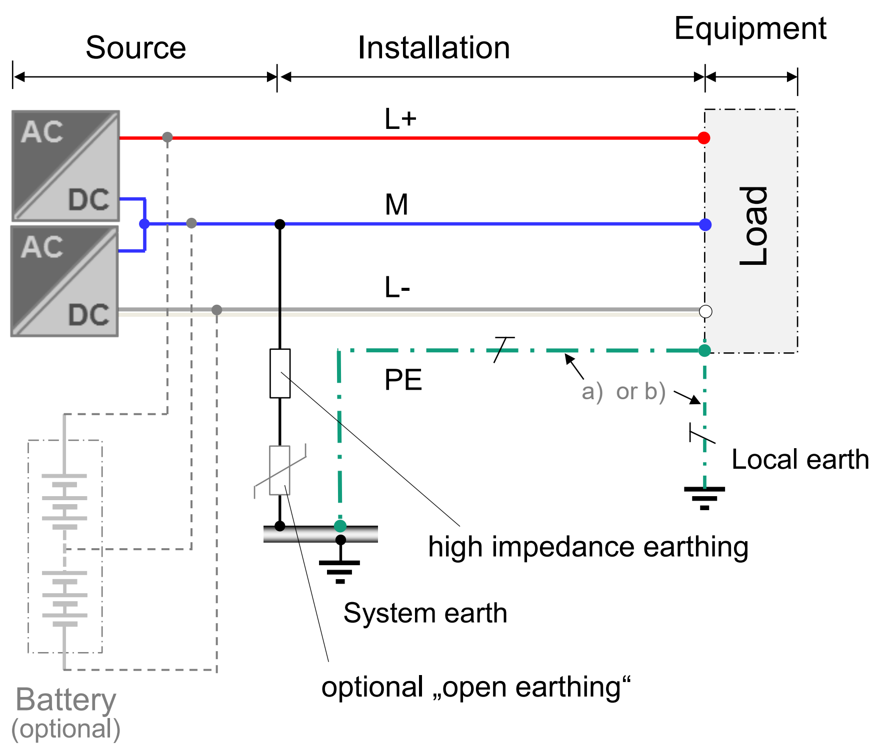
Symbols	Neutral conductor (N)	Protective conductor (PE)	Combined PE and N conductor

Earthing Systems

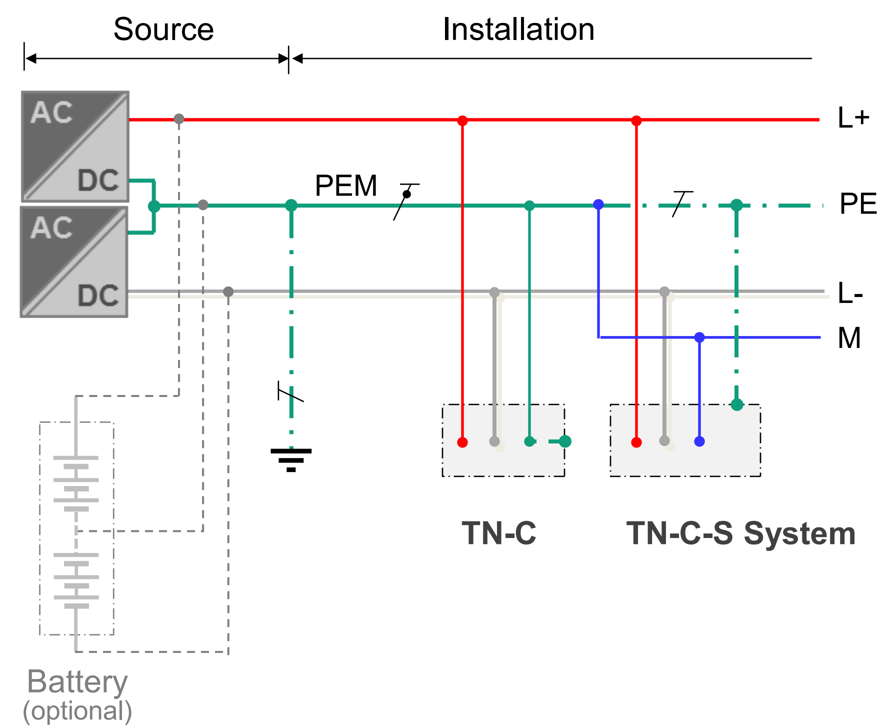
IT System	Hard Grounded Systems (TT, TN-S, TN-C, TN-C-S)
	
■ A single fault (e.g. earth fault, IT ⇨ TT) results in a fault message but not yet in an inevitable shutdown ⇨ high availability ■ Earthing must be so high resistive that no dangerous body currents can flow (typ. $> 50\ \mathrm{k\Omega}$ @ $400\ \mathrm{V}$) ■ Low fault earth currents reduce the risk of fire ■ Symmetrical grounding facilitates fault detection and avoids problems with CM filter chokes	■ The dangerous high touch currents make it necessary to switch off even in the event of a single fault ■ Higher compatibility with the grounding systems established in the AC world ■ Fault identification and isolation easier to perform ■ Higher robustness

Earthing in Bipolar DC Grids

IT System



TN-C-S System



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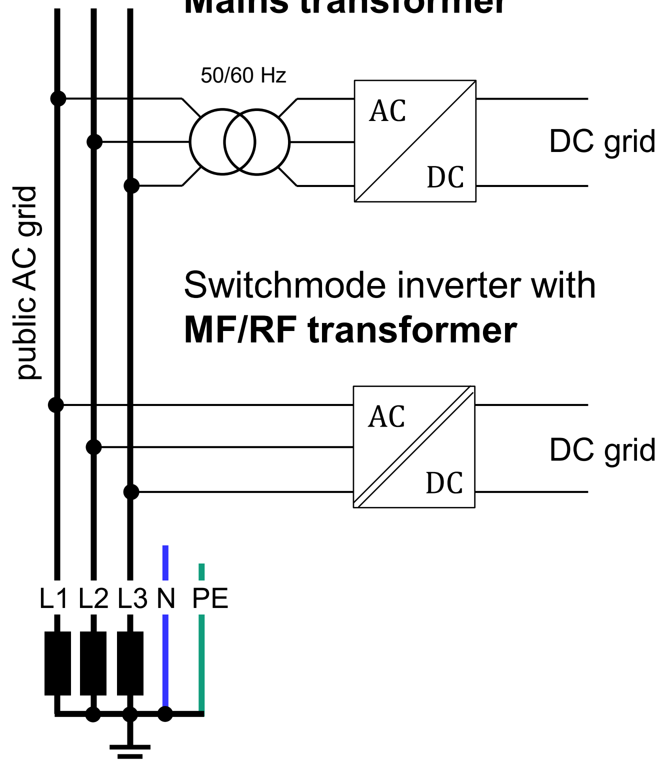
Direct and Indirect Grounding

DC Grid as an IT System

Isolation from AC grid via

Mains transformer

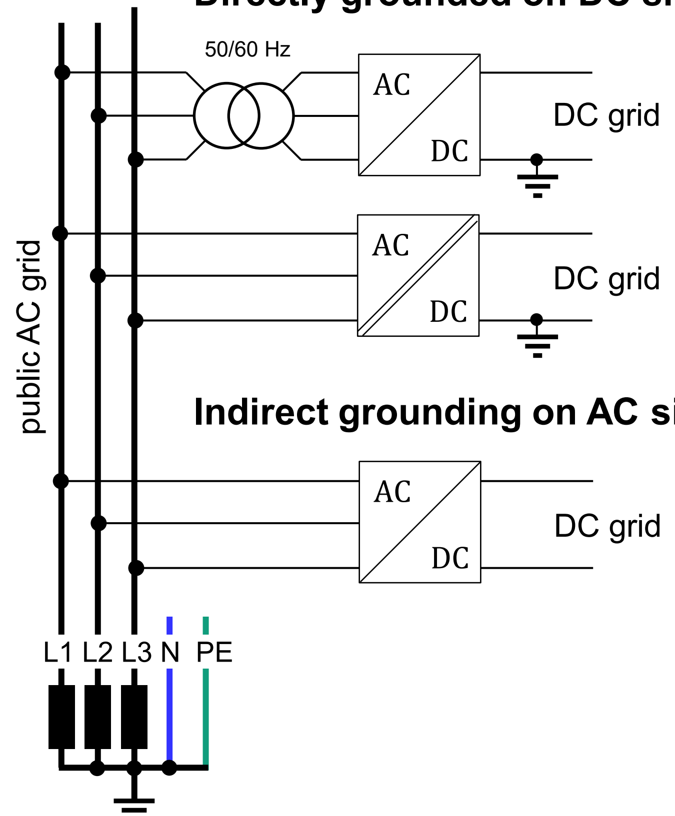
Switchmode inverter with MF/RF transformer



Hard Grounded DC Grid

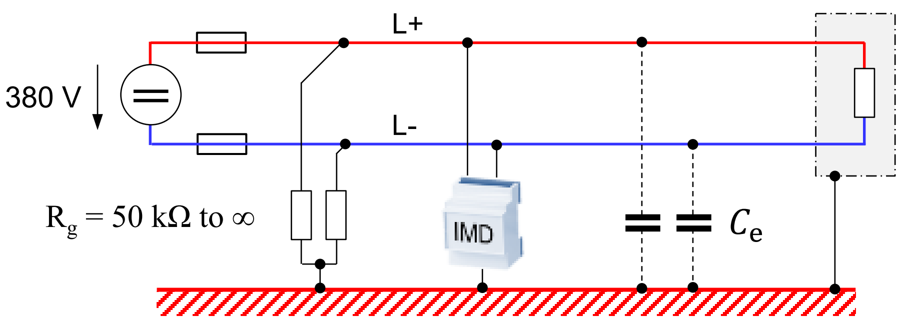
Directly grounded on DC side

Indirect grounding on AC side



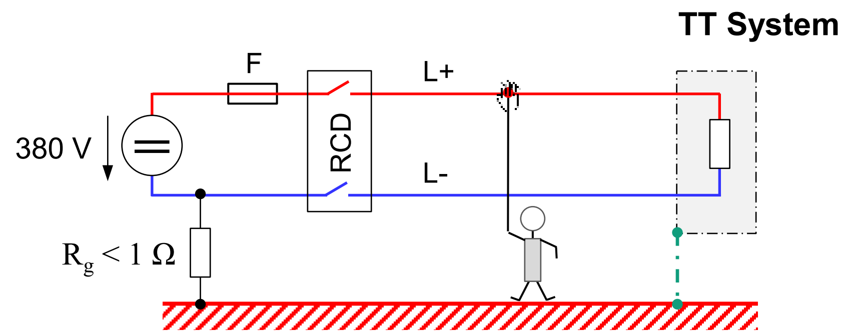
Personal Protection Measures

IT System



- An Insulation Monitoring Device (IMD) must be installed that detects and reports insulation faults
- Large earth capacitances (C_e = sum of all parasitic earth capacitances and all built-in EMI filter Y-capacitors) make insulation monitoring more difficult and can lead to a high touch current (discharge current pulse) in the event of contact.

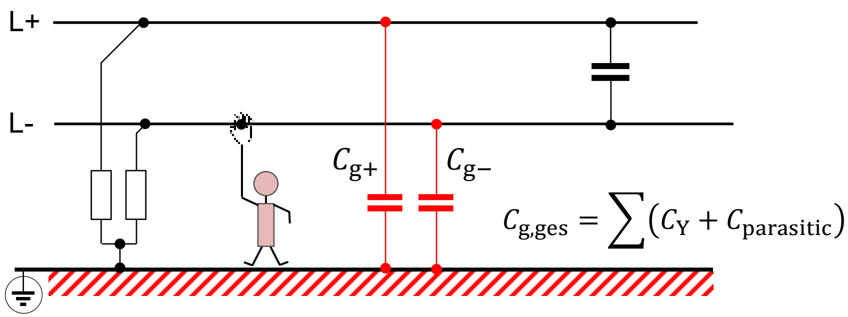
TT and TN-S System



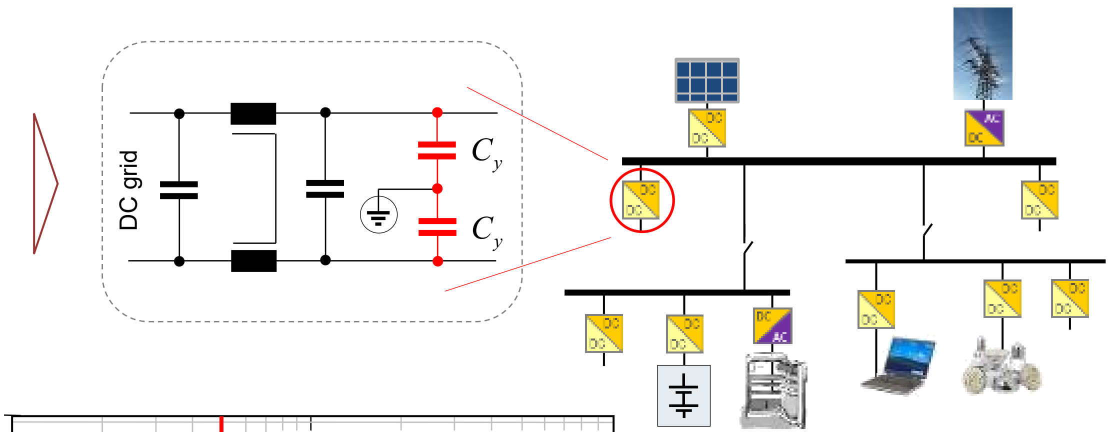
- A DC-compatible residual current circuit breaker (RCD type B) with a low differential trip current (30 mA) must be installed, which switches off immediately in the event of contact (personal protection)
- Fuse (F) is only used for line protection

Touch Currents in a Real IT Grid

Dangerous contact currents can also occur in IT grids as a result of high ground capacitances!

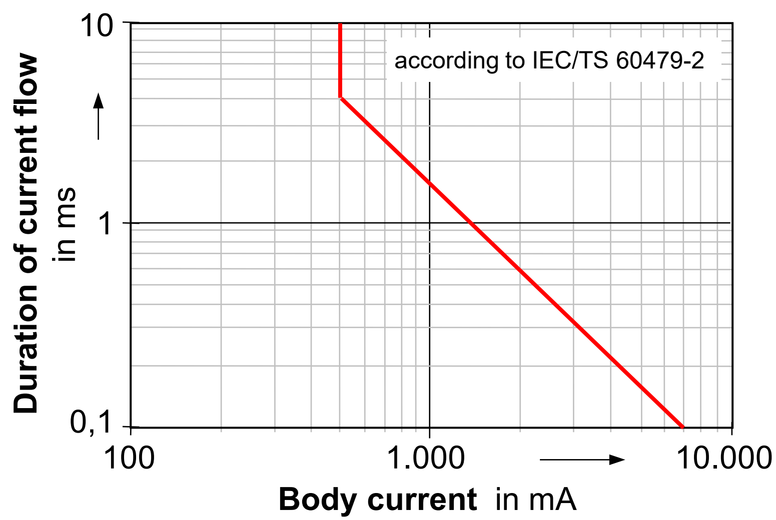


Typ. EMI filter structure at the input of each converter in the grid:



The **maximum permissible earth capacitance** can be derived from contact protection requirements, e.g. in accordance with IEC 60479

see exercise



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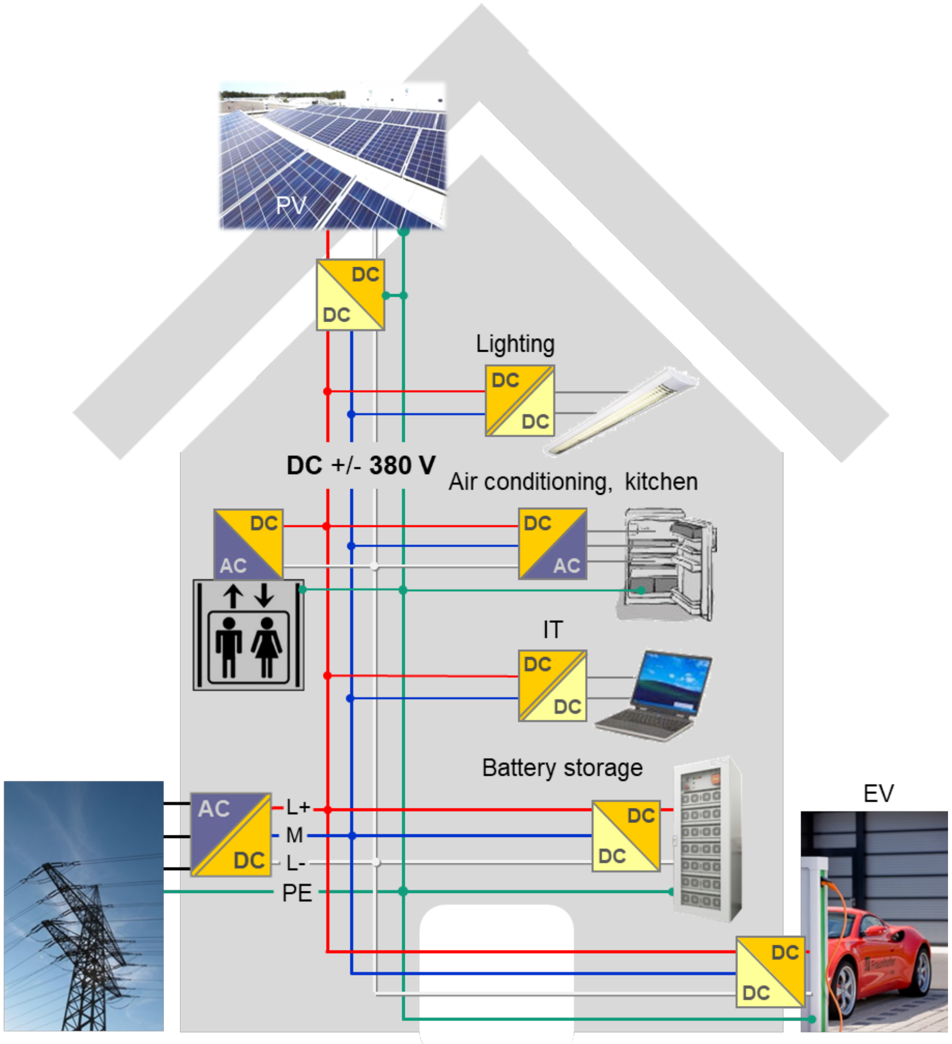
Room for Notes



Electrical Energy

Storages and Regenerative Sources

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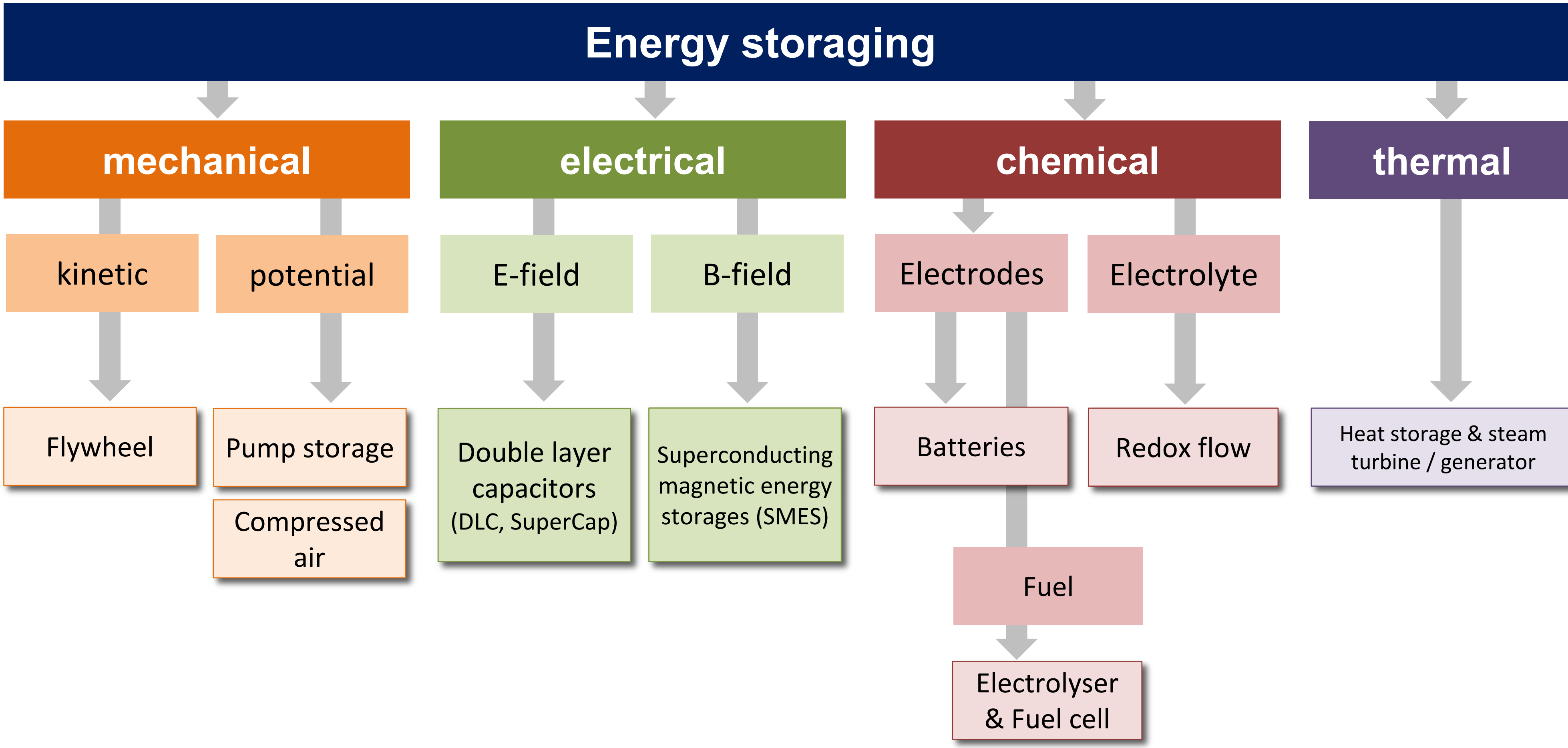
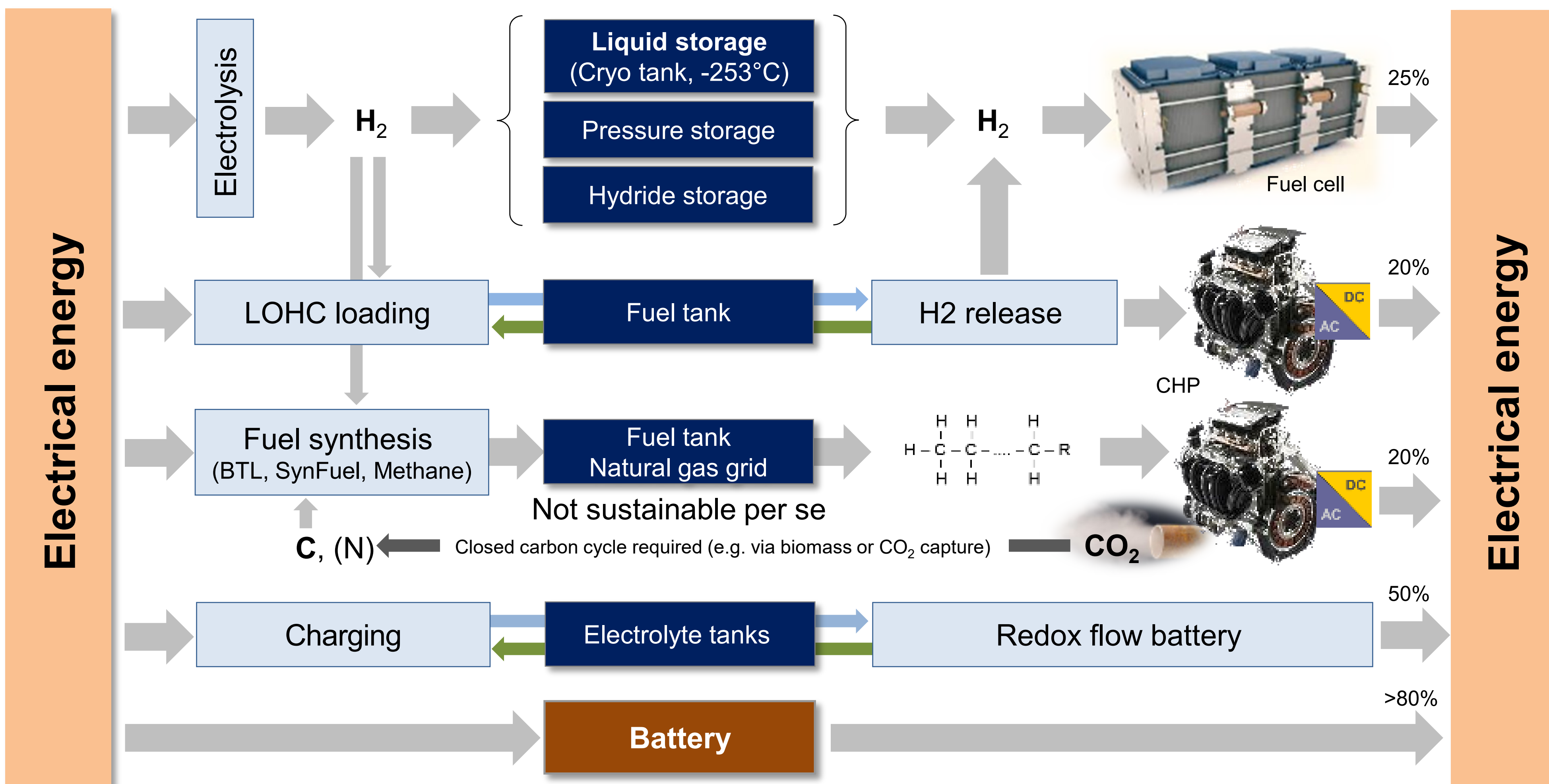
Electrical Energy Storage Technologies

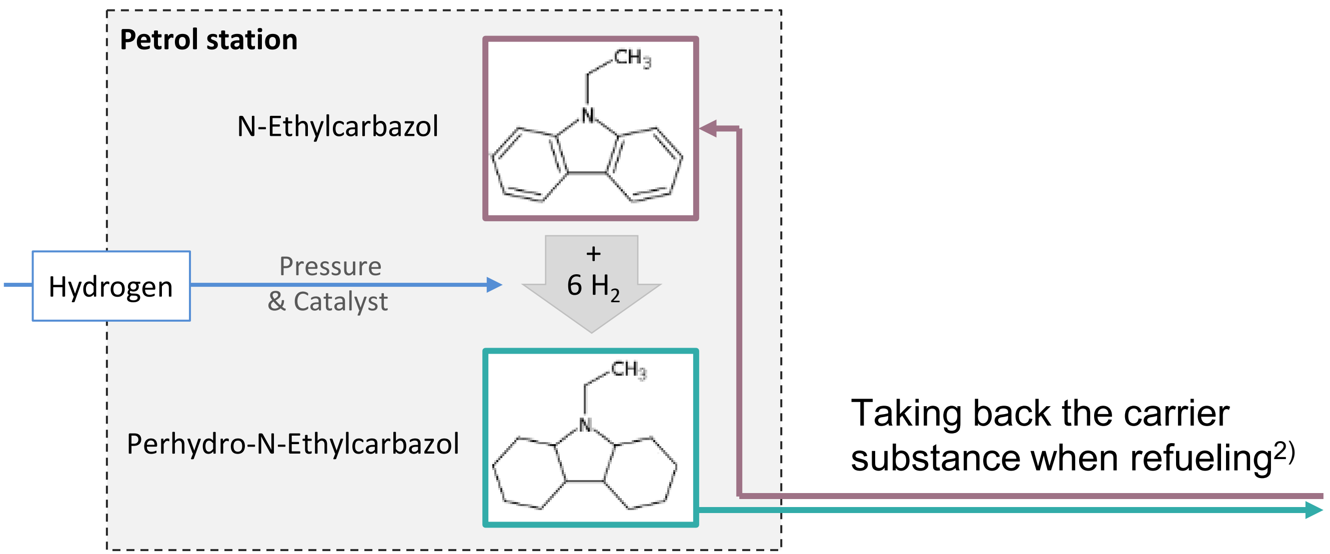


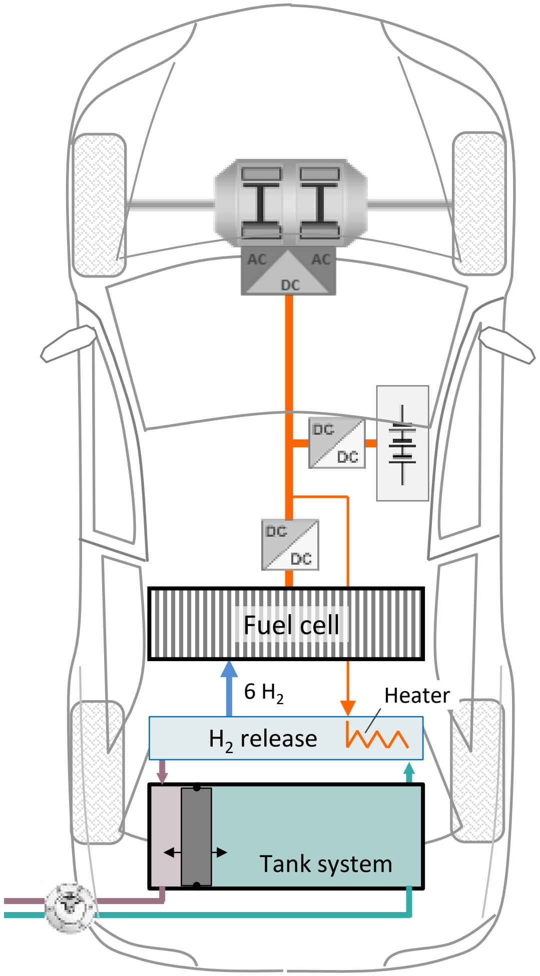
Electro-chemical Energy Storage Technologies



LOHC (Liquid Organic Hydrogen Carrier)

- Organic hydrocarbons that can be loaded with hydrogen relatively easily in terms of process technology and can release this H2 again by returning it to the starting carrier substance
- Typically, hydrogen with an energy content of about 2 kWh can be stored in one liter of these substances[1)]

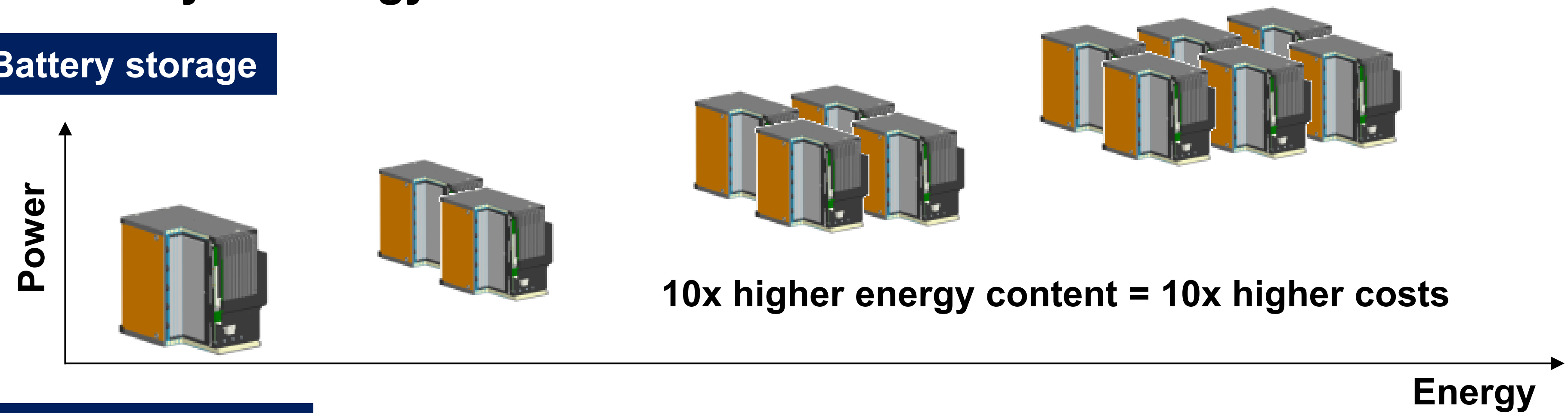




1) corresponding to about one sixth of the energy content of diesel 2) avoids an open carbon cycle

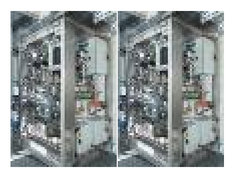
Scalability of Energy and Power

Battery storage

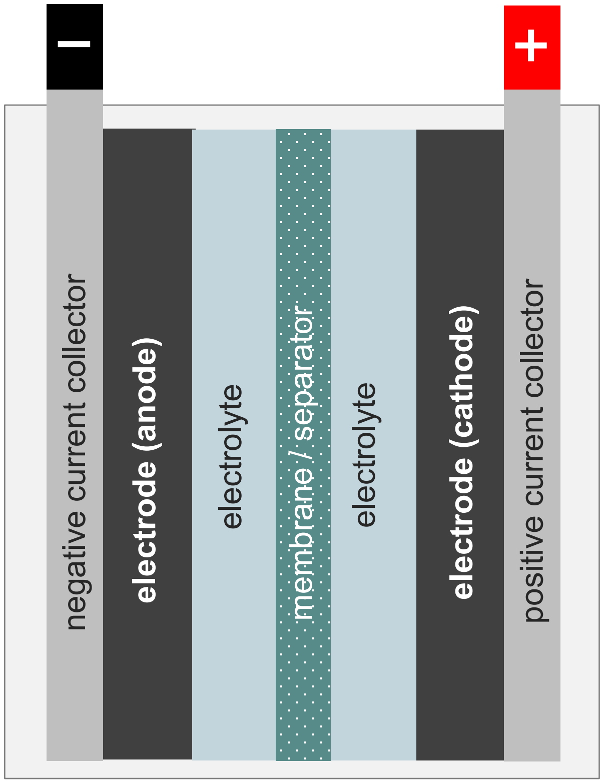


Chemical storage

The great advantage of chemical storages
The independent scalability of energy and power with usually very cost-effective scalability of the amount of energy that can be stored



Electrochemical Storages and Converters



Systematization

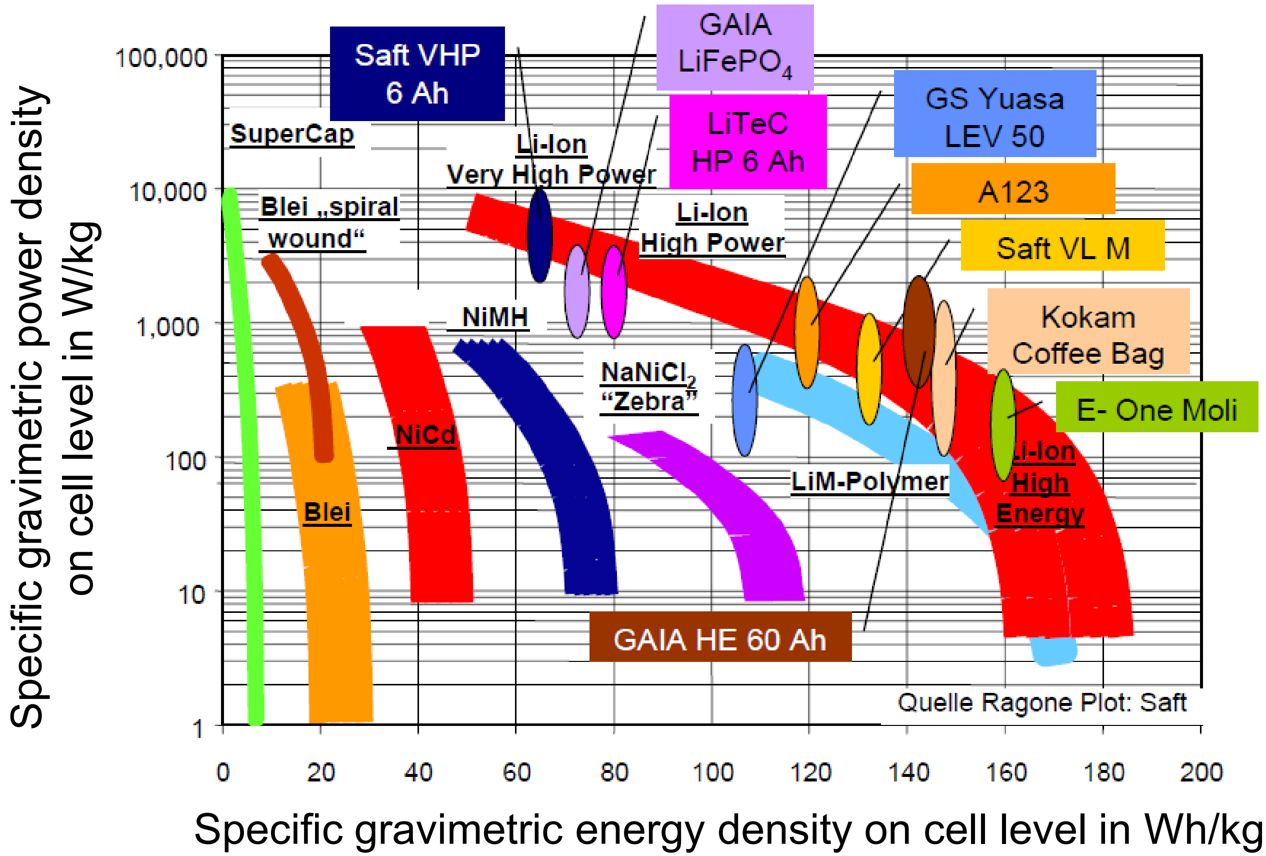
Electrode	Electrode	Electrolyte	Energy source	Application	
solid	solid	solid/liquid (stationary)	Electrode material	Primary/ secondary batteries	e.g. lead acid
liquid	solid /liquid	solid (stationary)	Electrode material		e.g. Na-$NiCl_2$
gaseous	solid	solid/liquid (stationary)	Electrode material		e.g. Zn-air
solid	solid	liquid (flow)	Electrolyte	Redox flow battery	
solid + gas	solid + gas	solid/liquid (stationary)	Gas	Fuel cell	

Battery Technologies

	Lead acid	NiCd	NiMH	Li-Ion	$NaNiCl_2$	NaS
Energy density [Wh/kg]	20 - 30	40 - 60	60 - 90	70 - 250	100 - 120	120 - 220
Full charge/discharge cycles	200 - 500	1000 - 1500	400 - 700	500 - 20000	2000 - 3000	2000 - 3000
Temperature range [°C]	-20 … +60	-40 … +60	-20 … +60	-20 … +60	+270 … +350	+270 … +350
Self-discharge [%/month]	5	20	30	2 - 5	0 (electrical)	0 (electrical)
Power density	high	high	high	very high	medium	high
Nominal voltage [V]	2,0	1,2	1,2	2,3 - 3,7	2,58	2,0 V
End-of-discharge voltage [V]	1,8	1,0	1,0	1,8 - 3,0		1,8
Charge/discharge efficiency[1] [%]	70 - 80	70	70	90 - 95	80 - 90	90
Remarks	Low manufacturing costs, not deep discharge capable, low cycle stability	Reliable, robust, long service life when unloaded, very good low-temperature behavior, memory effect (!)		High energy density, cycle stability typ. 1000-1500, LFP up to 4000, LTO over 10000	High calendar life, inexpensive materials, robust, reliable, relative high self-discharge due to thermal losses	Sensitive to deep discharge, relative high self-discharge due to thermal losses
EV application examples	City-El, REVA	Citroen AX electrique	Prius I-III	i-MieV, Tesla, Ampera, u.v.a.	MES-DEA	stationary battery storages

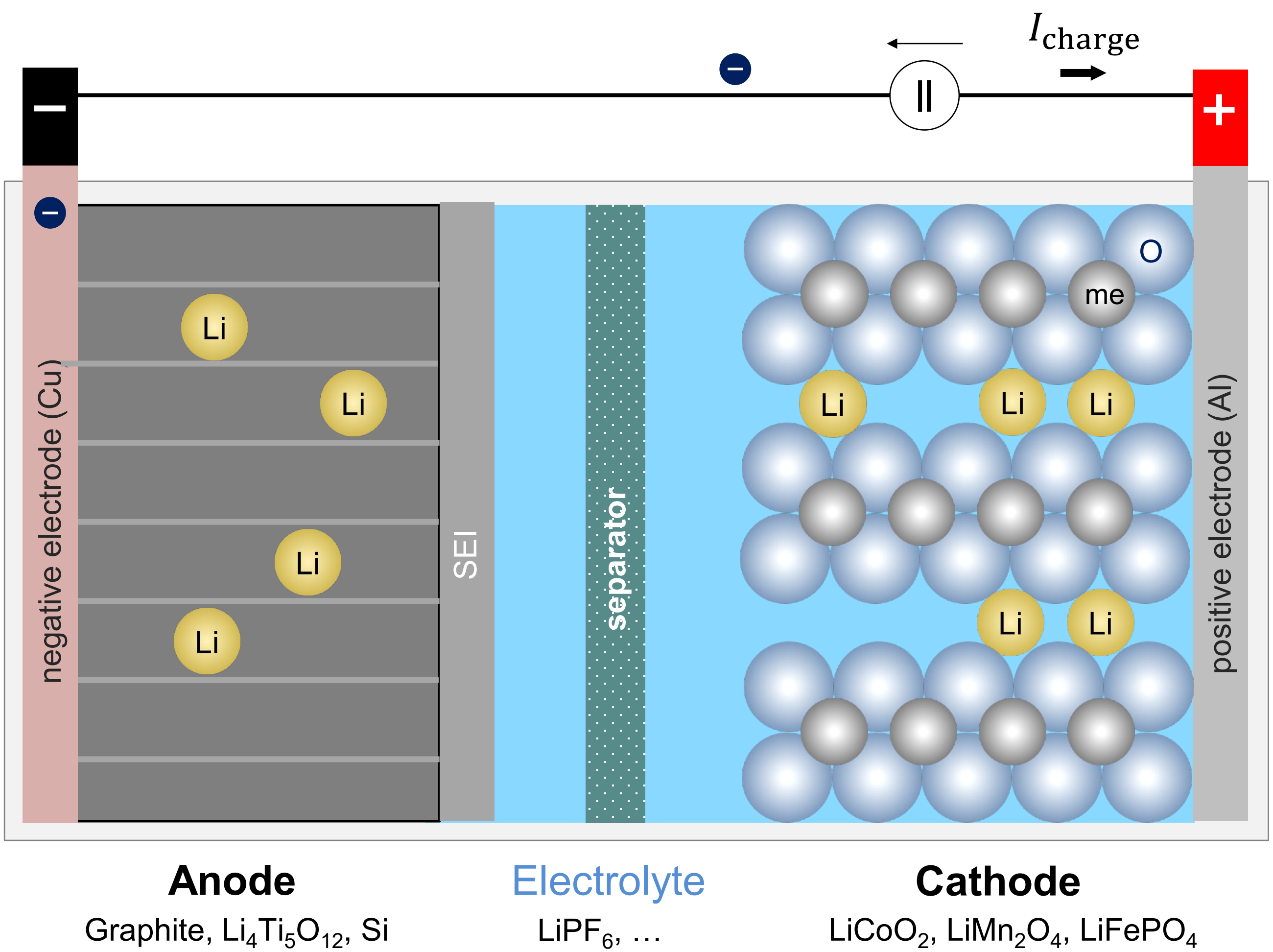
1) heavily dependent on cell temperature and the C-rate during charging/discharging

A Comparison of Electrical Storage Technologies



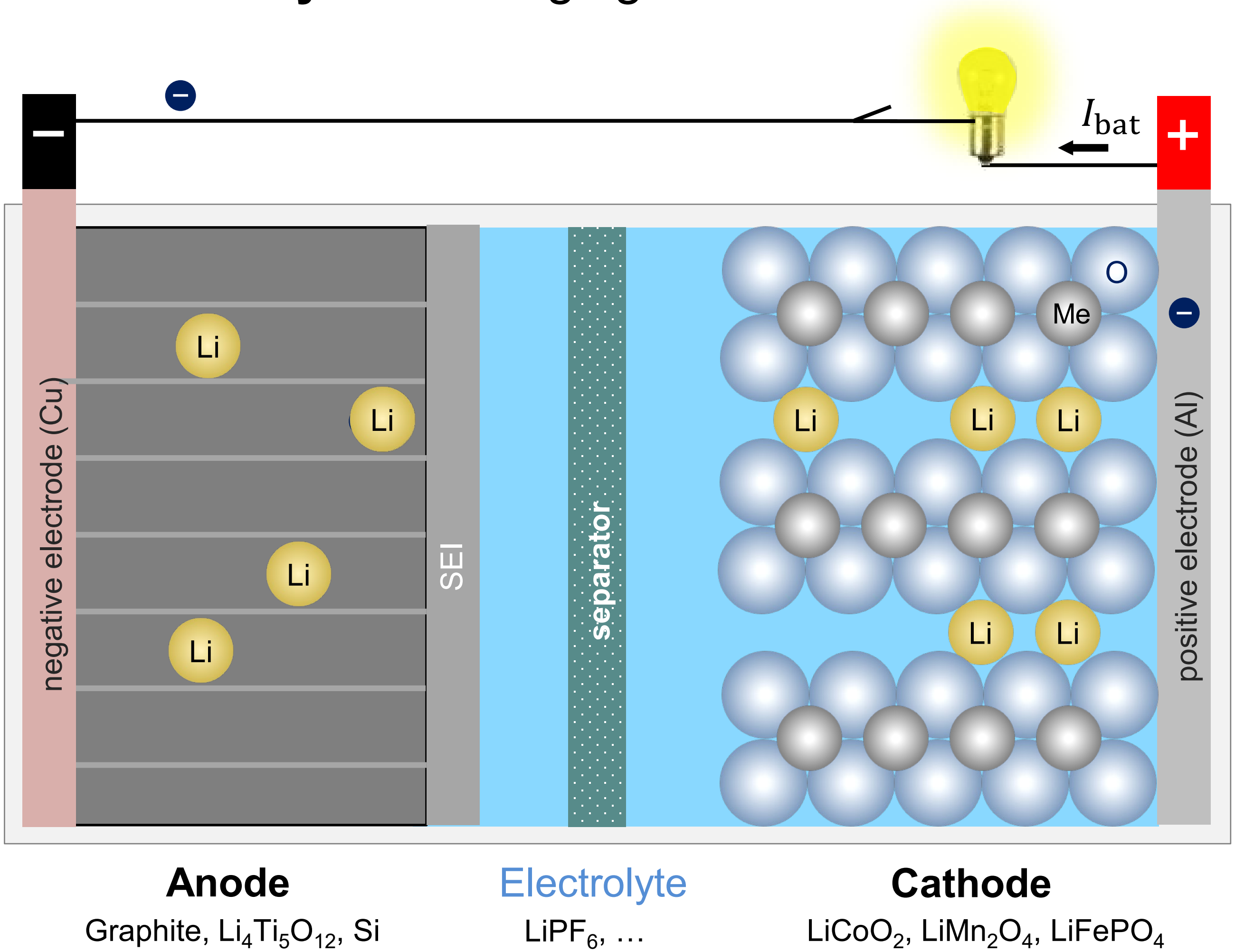
Picture: Dr. Dick, RWTH Aachen, ISEA

Li-Ion Battery ▪ Charging



Lithium is intercalated in the electrodes and is exchanged as Li-ion between the positive and negative electrode materials during charging/discharging.

Li-Ion Battery ▪ Discharging



Lithium is intercalated in the electrodes and is exchanged as Li-ion between the positive and negative electrode materials during charging/discharging.

Li-Ion Battery Technologies

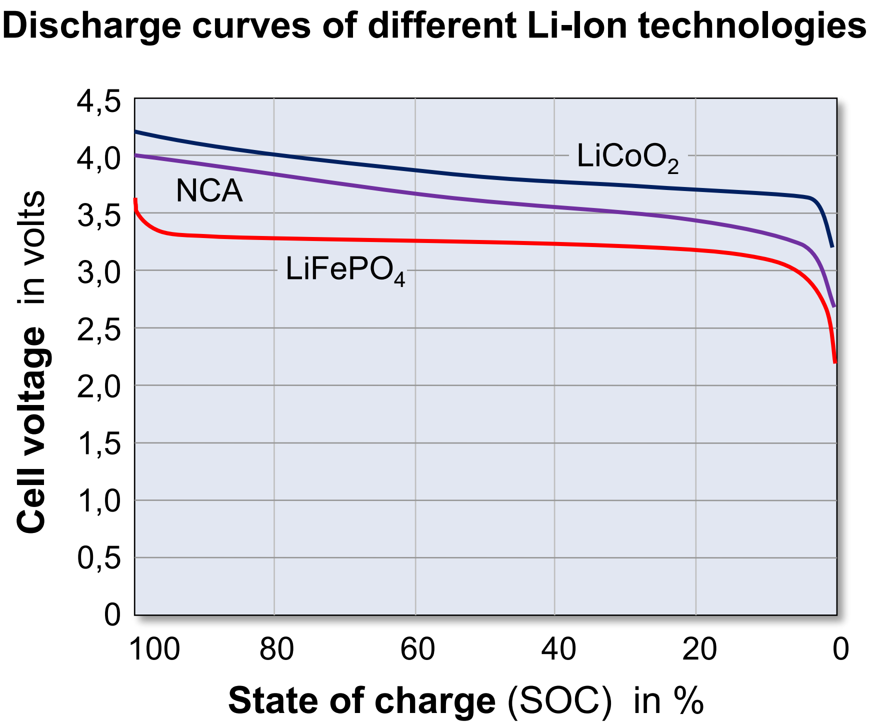
The option of combining different **anode materials**, **cathode materials**, **electrolytes** and **separator** technologies opens up a huge field of cell technologies with a wide variety of properties (in terms of energy density, safety, cycle stability, temperature range, etc.):

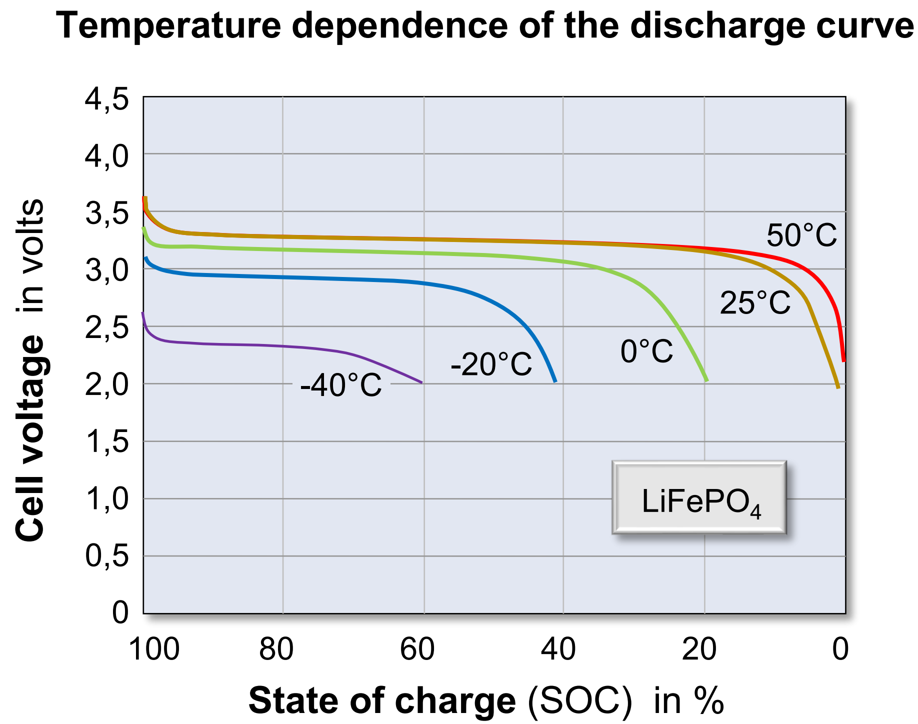
Cathode	Anode	Nominal voltage [V]	Energy density [Wh/kg]	Properties	Producer
LCO	Graphite	3,7	110 - 190	A compromise between energy density, cycle stability and safety. High content of the critical raw material cobalt	Sony
NMC	Graphite	3,6	120 - 200	Similar to LCO, but lower costs and less critical raw materials	Panasonic, Li-Tec, Kokam,..
NCA	Graphite	3,6	160 - 230	High energy density, but more safety critical	Saft, Samsung
LFP	Graphite	3,3	90 - 140	High safety, good cycle stability, high power density (high charging/discharging currents), but lower energy density	Sony, A123, ..
LMO	Graphite	3,7	100 - 120	Lower energy density and cost, good safety	LG Chem., ..
NMC/LCO/ LMO/LFP	LTO	2,3	70 - 90	Very high cycle stability, high safety, wide temperature range, safe against deep discharge - but a comparably low energy density	Toshiba, Altair-Nano, Leclanché
:	:			:	

LCO: $LiCoO_2$ (Lithium Cobalt Dioxide)
NMC: $LiNi_{0,33}Mn_{0,33}Co_{0,33}O_2$ (Lithium Nickel Manganese Cobalt Dioxide)
NCA: $LiNi_{0,8}Co_{0,15}Al_{0,05}O_2$ (Lithium Nickel Cobalt Aluminum Dioxide)

LMO: $LiMn_2O_4$ (Lithium manganese spinel)
LFP: $LiFePO_4$ (Lithium iron phosphate)
LTO: $Li_4Ti_5O_{12}$ (Lithium titanate)

Li-Ion Batteries





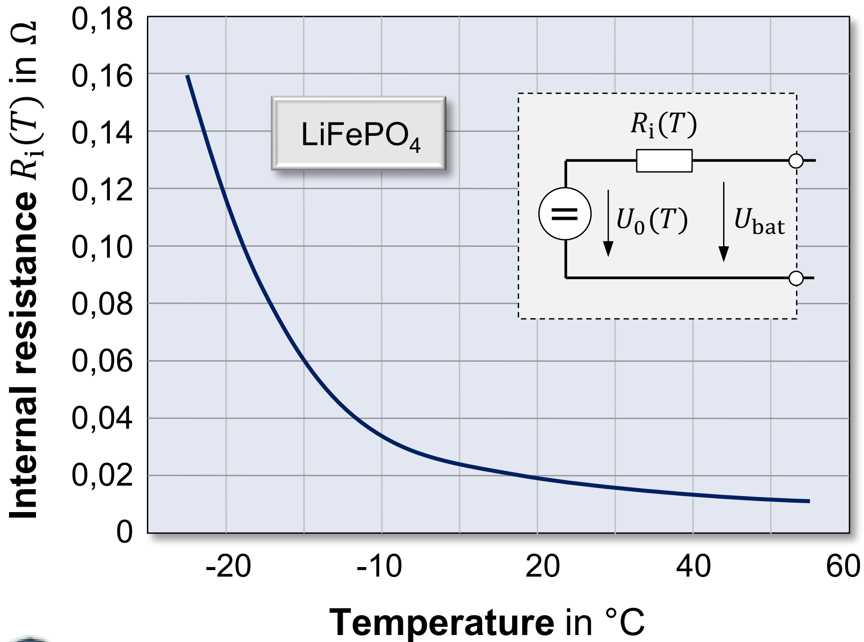
- A flat voltage curve is advantageous in many applications, but makes it almost impossible to determine the state of charge by measuring the cell voltage only!

- At low temperatures, the amount of energy that can be extracted decreases drastically
- The terminal voltage drops significantly at low tempera-tures due to the steep increase of the internal resistance

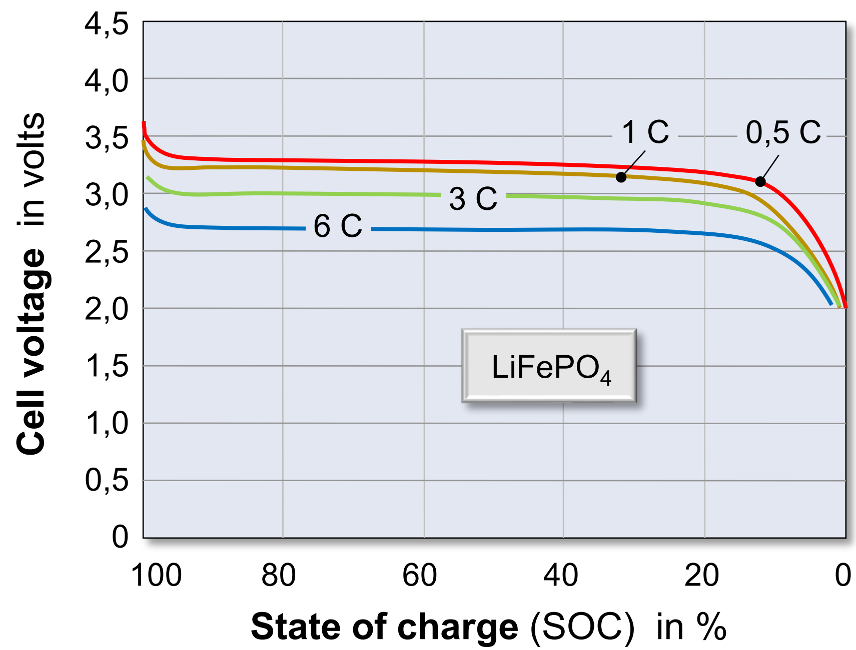
Typical curves, in addition there is a strong dependence on the discharge current (C rate)

Li-Ion Batteries

Temperature dependence of the internal resistance



Current dependence of the discharge curve



Internal resistance as a function of temperature, measured on a 2.3 Ah cell from A123-Systems (@3,2V)

What is a C Rate?

Charging/discharging currents respectively power values are always to be seen in relation to the capacity or the energy content of a battery!

$$\text{C Rate} = \frac{\text{Current}}{\text{Rated capacity [Ah]}} = \frac{\text{Power}}{\text{Nominal energy content [Wh]}} \qquad [\text{C Rate}] = \text{h}^{-1}$$

Example

Discharging a
100 kWh Battery with a power of 250 kW
(⇨ C Rate = 2,5 h^{-1})

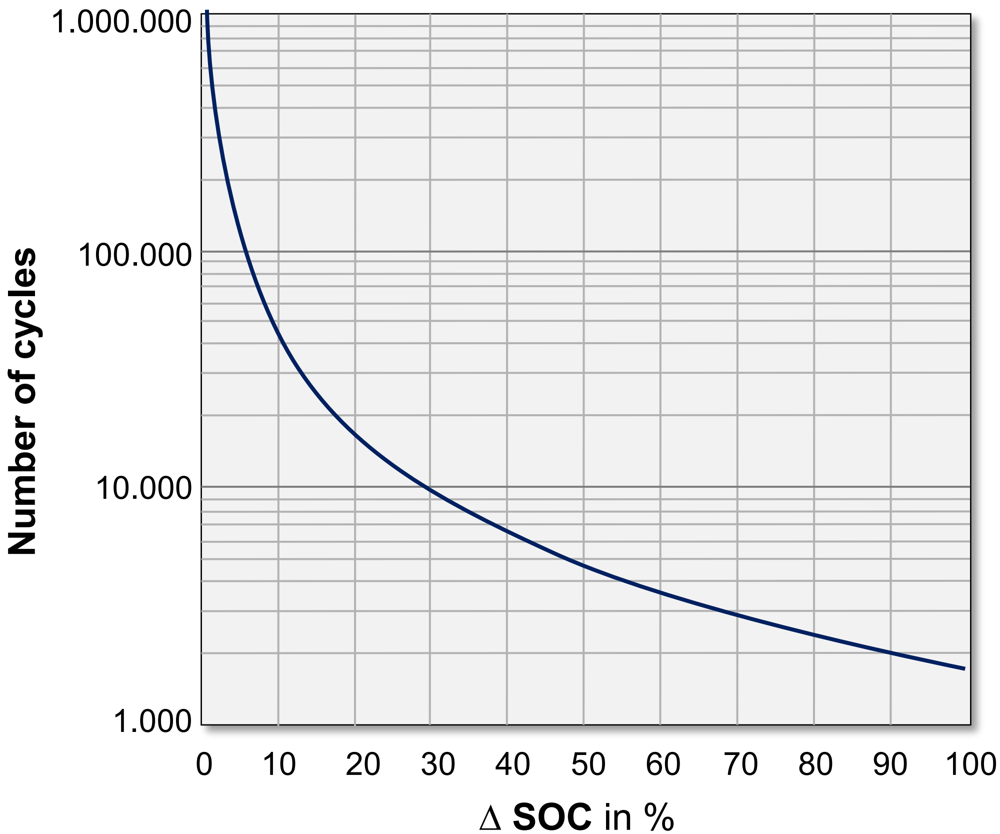
means far less stress on the cells than discharging a
5 kWh Battery with a power of 50 kW
(⇨ C Rate = 10 h^{-1})

For modern Li-Ion cells, guideline values when discharging are

C Rate [h^{-1}]	
< 1	uncritical load
1 - 3	incipient impact on lifetime
3 - 10	Cell technology must be specified for this stress, significant impact on lifetime
> 10	Only possible with certain cell technologies (LFP, LTO), thermal management and temperature monitoring are mandatory

The critical C rates during charging are generally significantly lower than when discharging, especially at low temperatures!

Cycle Life



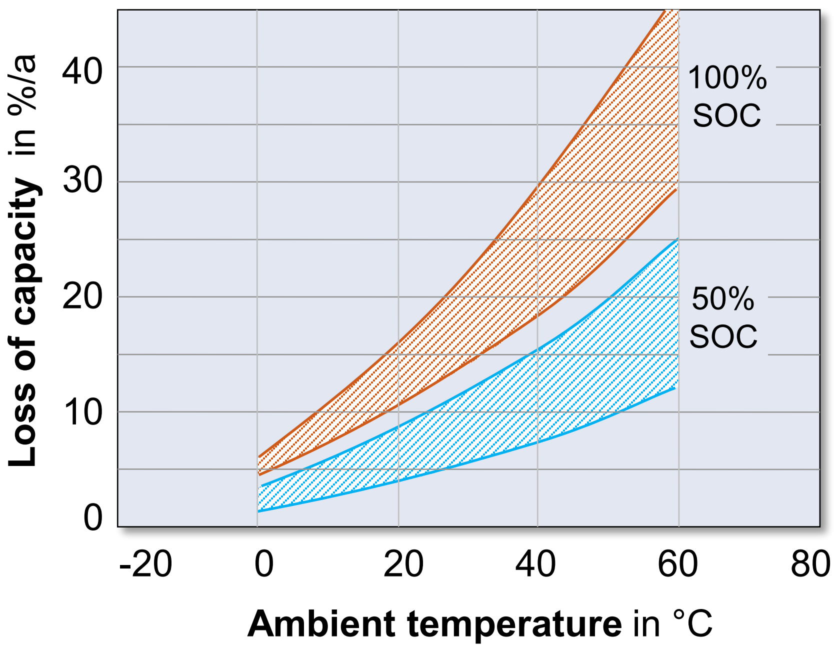
A high application specific number of cycles requires a drastic reduction of the charge/discharge depth!

For a given energy exchange, the percentage change in the state of charge (∆ SOC) decreases as the energy content of the battery increases.

Typical curve of modern Li-Ion technologies (except lithium titanate) @ battery temperature of about 25°C

Calendar Lifetime

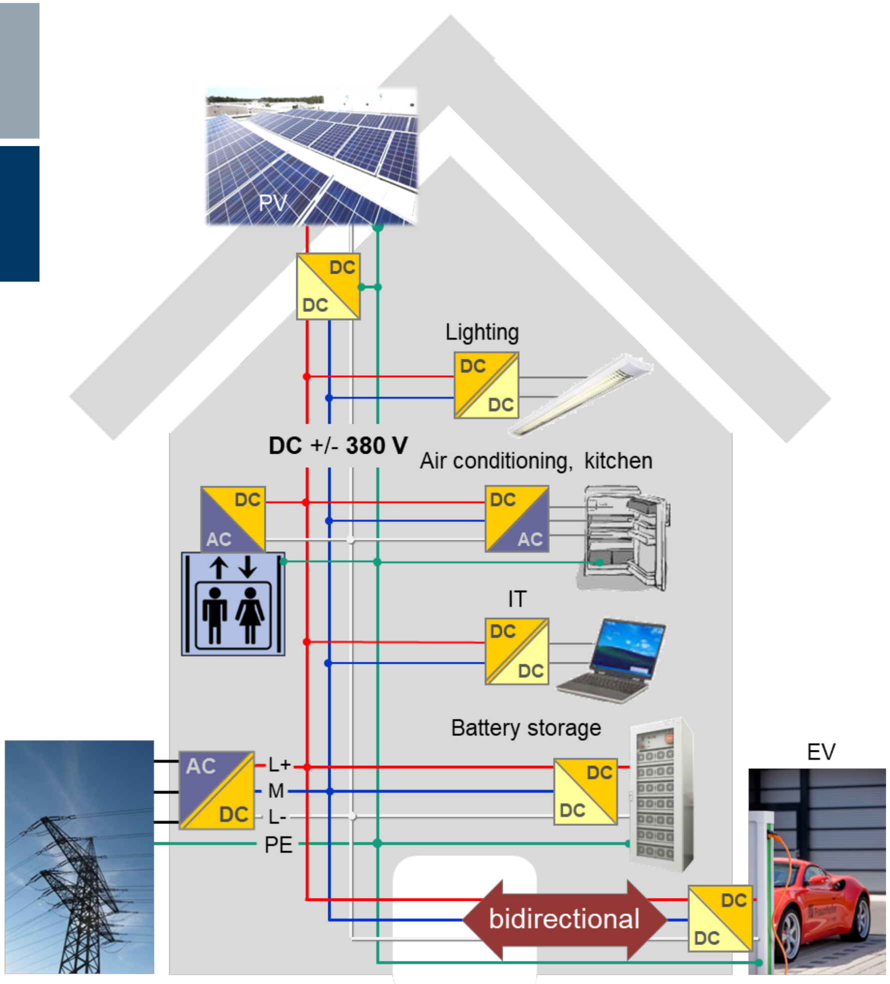
Even without cyclic loading Li-Ion batteries show a permanent loss of capacity depending on the ambient temperature and the state of charge during storage!



- Aging increases dramatically with the "storage temperature" and the state of charge
- The aging behavior is also dependent on the specific cell technology
  - **Do not store Li-Ion batteries in warm environment a/o fully charged** ($SOC_{storage\_optimum}$ = 30…50%)
  - A reduction in the state of charge during longer periods of non-use (e.g. vehicle idle times) increases battery life

Data source: Bulletin SEV/AES 3/2009; Prof. Sauer/RWTH

Electric Vehicles as an Energy Storage in the Grid



Does that make sense in terms of battery life?

A 60 kWh battery with 2,000 full charge cycles means a theoretical mileage of

$$\frac{60\ \text{kWh}}{20\ \text{kWh}/100\ \text{km}} \times 2.000 = 600.000\ \text{km}$$

- There is therefore enough service life for other usage scenarios than "just" driving! With a view to the calendaric lifetime this is even a must.
- Cost reduction by increasing the self-consumption of electricity
- Emergency power functionality; increase in home supply resilience
- Revenue from the provision of AC grid services

and in terms of sustainability:

- Regularly lowering the state of charge can even extend the service life of Li-Ion batteries!

Li-Ion Battery Cell Designs

button cell

0,01…0,2 Ah

cylindrical cell

2…40 Ah

- Long experience with high volume production
- Mechanically robust
- Reliable sealing

coffee bag (pouch) cell

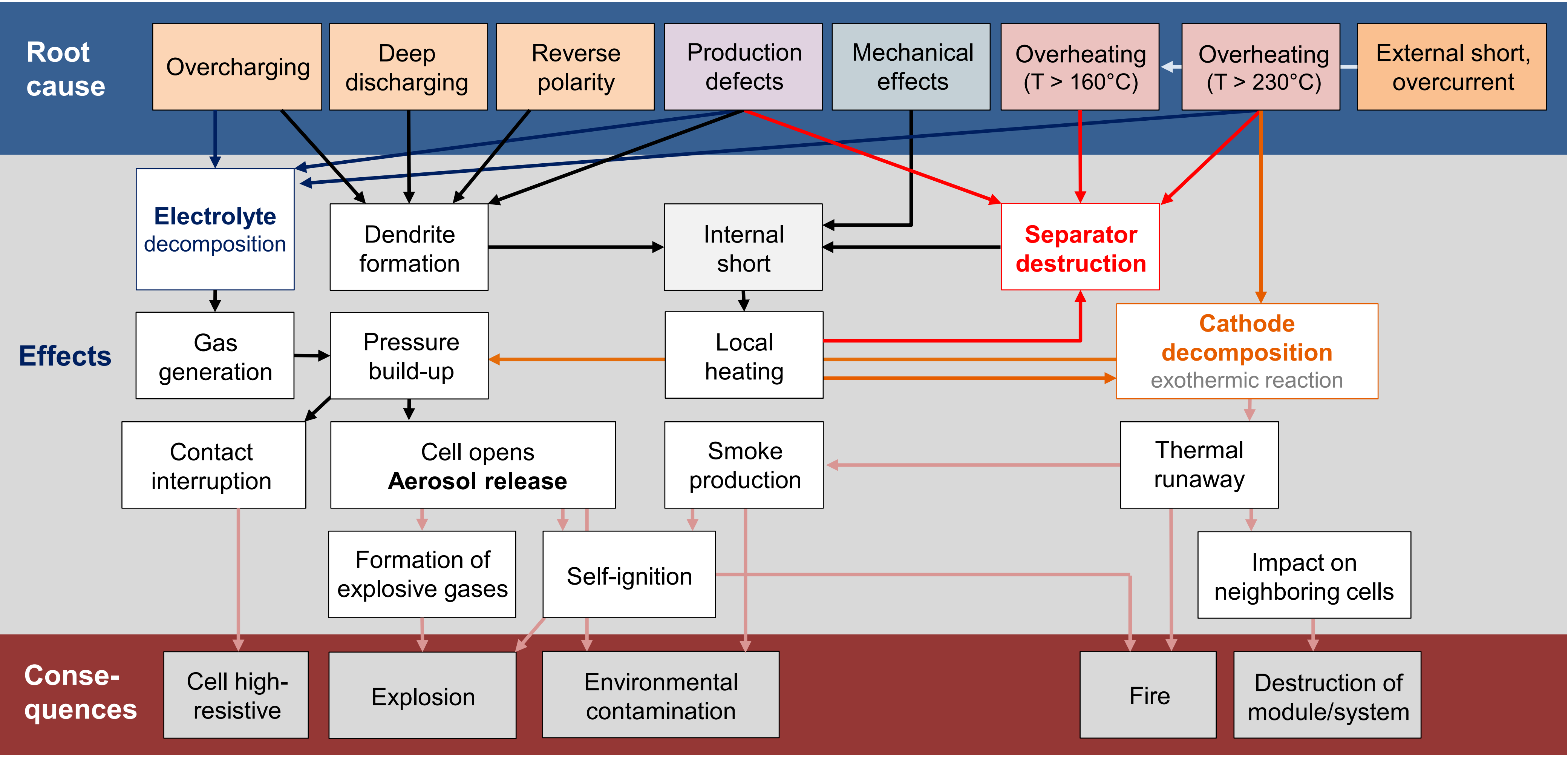
2...200 Ah

prismatic cell

0,5…200 Ah

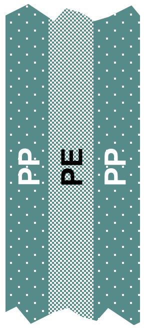
- High energy density due to minimal dead volume in the cell stack
- Easier cooling, more homogeneous temperature distribution

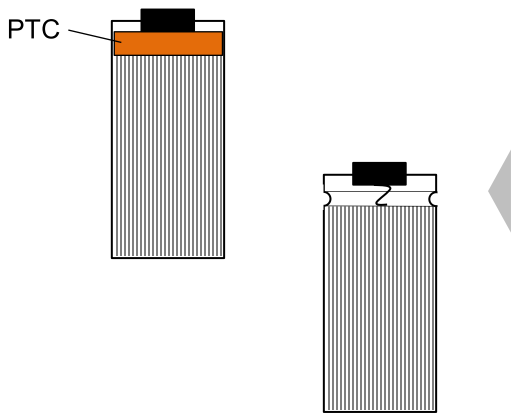
Potential Hazards with Li-Ion Batteries



Representation based on Prof. Dr. J. Tübke, Fraunhofer ICT

Safety Measures at Cell Level





Shut down separator

- Micropores close under the influence of temperature and interrupt the ion transport (i.e. the electric current flow)
- Often implemented as a three-layer film made of polypropylene (PP) and polyethylene (PE): PE melts a bit earlier (130°C) and closes the pores

Separator with a microporous ceramic coating

- SEPARION®: Al_2O_3 powder on carrier fleece; mechanically stable up to 240°C

PTC

- A thermistor (PTC) increases its resistance at a certain threshold temperature, reducing the current and thus the risk of a "thermal runaway"

Current Interrupt Device (CID)

- An increase in pressure leads to a defined deformation of the cell housing and thus to the tearing off of the internal contact (⇨ current interruption)
- Also as a classic internal melting “fuse”

Electrolyte additives

- Flame retardant additives

Safer electrode materials

- Use of less critical electrode materials such as lithium iron phosphate

Requirements for the Structure and Construction of a Battery System

Electrically

- Comprehensive touch protection
- Overcharge and deep discharge protection
- Short circuit protection
- Isolation of the storage connections in the event of a fault (via DC contactors)
- Self-monitoring with regard to limit parameters
- Very low internal power consumption of the cell electronics to avoid deep discharge during storage
- High immunity to interference
- Recording of all important system parameters (cell voltages, temperatures, battery current, ..)
- Data interface to the application

Mechanically

- Protection of the cells against environmental influences (humidity, ...)
- Crash protection (to avoid contamination, fire or explosion)
- Mechanical compliance to cell dimensional changes during charge/discharge
- An inexpensive and highly automatable assembly

For mobile applications

- Mounting frame and housing with lowest possible weight and volume overhead

Thermally

- Temperature control of the cells within a specified temperature window
- Temperature of all cells as homogeneous as possible (since temperature is a key aging factor)
- Thermal management with lowest possible weight and volume overhead

Basic Rules for Handling Battery Cells and Storages

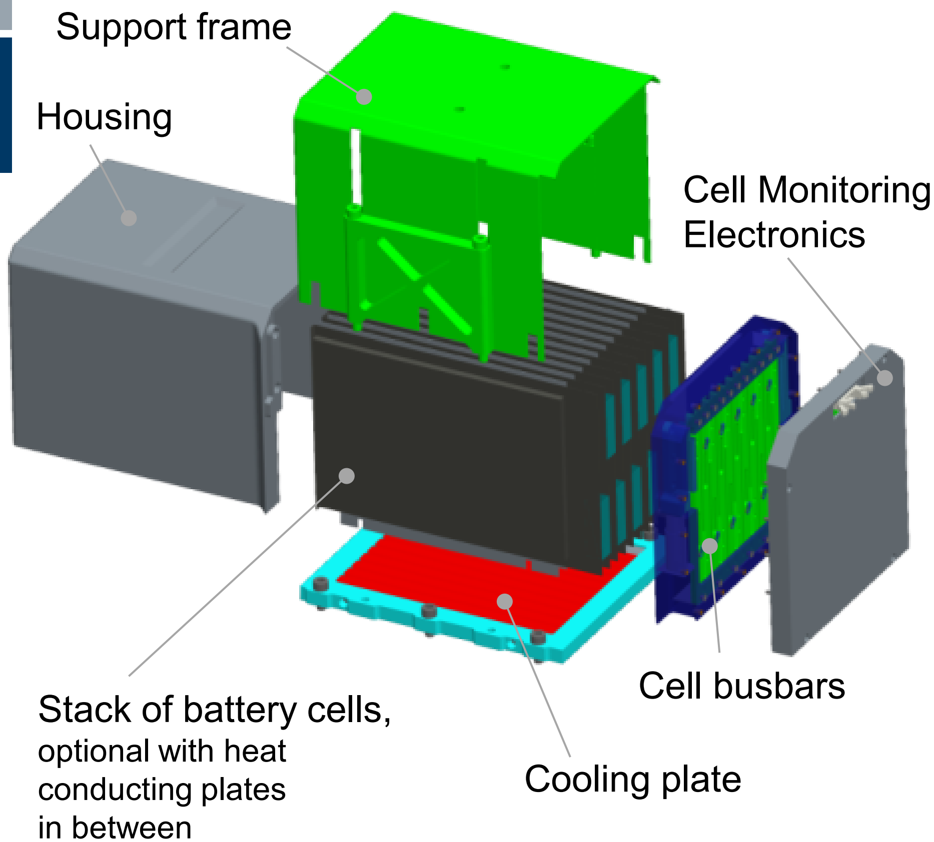
Commercial Li-Ion batteries

- Note the data sheet!
- Comply with the given limit values (current, voltage, temperature)
- Charger and battery storage must match
- Most Li-Ion technologies do not tolerate significant charging currents (C/100) at low temperatures (below zero °C).
- Store mechanically damaged or suspicious battery modules outdoors and fully discharge them
- Caution when connecting modules in parallel: extremely high currents are possible without prior voltage equalization

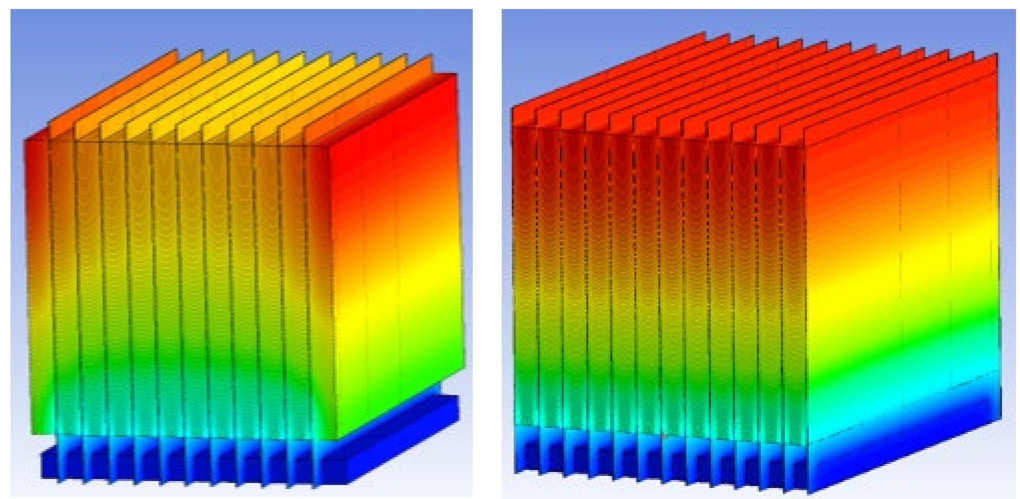
Open Li-Ion modules and single cells

- Use personal protective equipment (gloves, goggles, protective coat)!
- Use only insulated tools!
- Cover open battery connections with insulating material (e.g. rubber mats)!
- Place metal fire extinguisher and sandbox (water basin) within reach!
- In the case of modules with voltages greater than 60 V: Observe the regulations for "working under voltage“!
- Attention in the event of a leak (e.g. escape of liquid, perception of odours): the electrolyte ($LiPF_6$) forms highly dangerous hydrofluoric acid (HF) with atmospheric moisture
- Label any critical or suspect cells (dropped, mechanically damaged, thermally or electrically overloaded) and store them specifically (e.g. in a F90 cabinet)

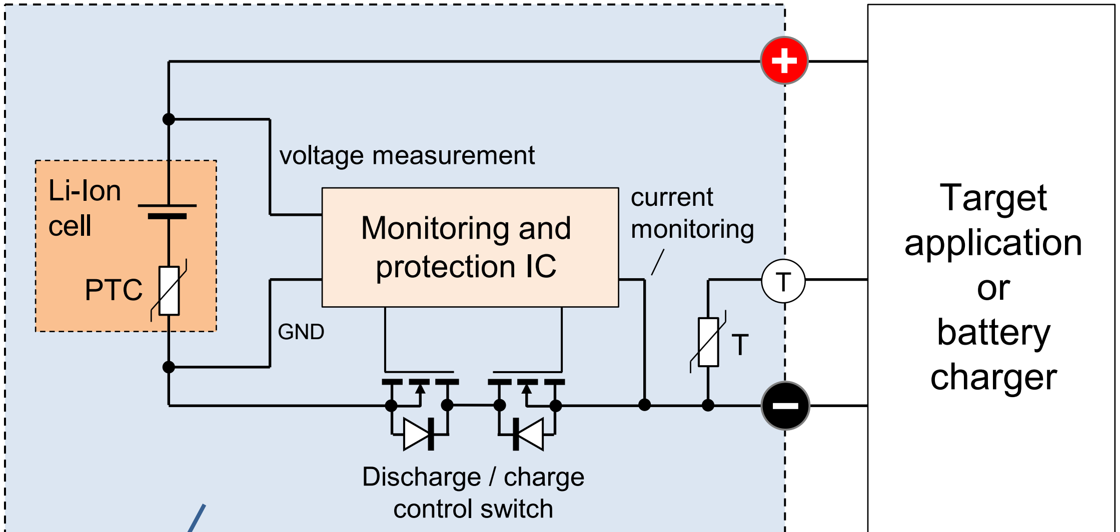
Design of a Battery Module - an example



- A temperature distribution that is as homogeneous as possible within a battery module is essential for an even aging of the cells!
- In the end, the weakest cell in a battery module determines the lifespan of the entire battery!



Single Cell Monitoring and Protection

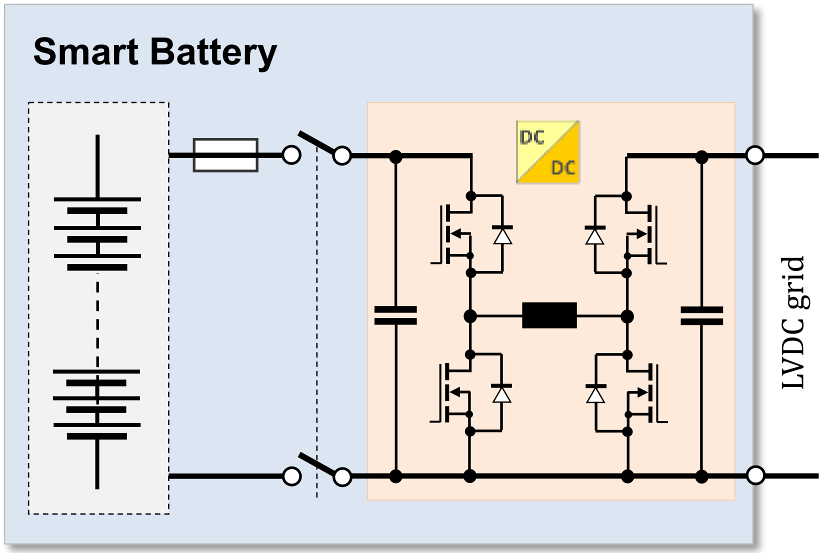


Protection against mishandling

- due to overcharging,
- deep discharging,
- polarity reversal,
- external short circuit,
- overheating as a result of overloading

Electronics cannot make a bad cell safer, but prevent good quality cells from being damaged by the user!

Smart Battery ■ the way to safe, modular and universal battery systems



Smart Battery

- Output voltage independent of battery voltage or state of charge
- Inherent inrush current limiting and precharge functionality
- Current and energy limitation in the event of a fault in the application
- Precise charge/discharge management
- Overcharge and deep discharge protection

An integration of the power electronics **into the battery system** is a prerequisite for maximum safety, modularity and functional flexibility.

vgl. Patent: WO 03/015237 A1

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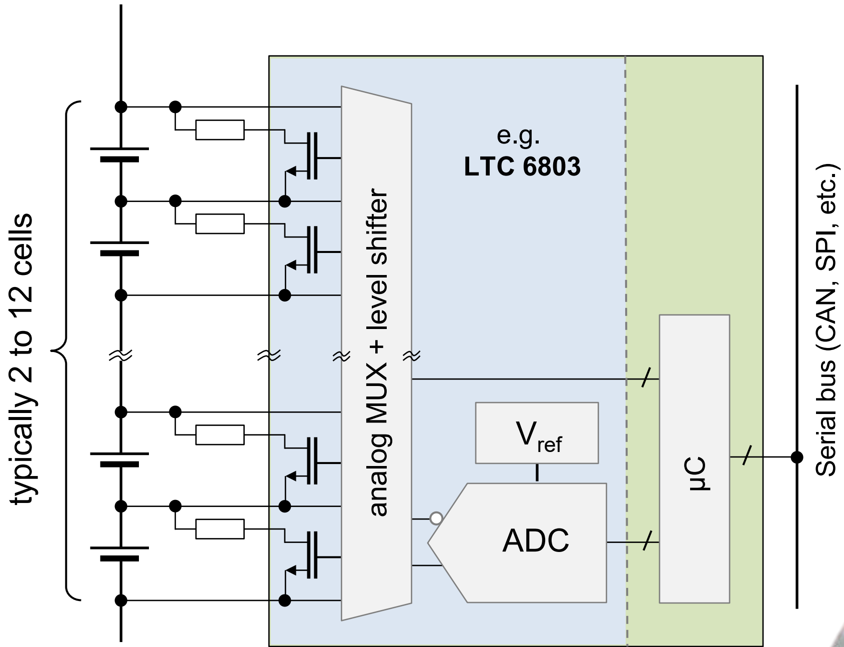
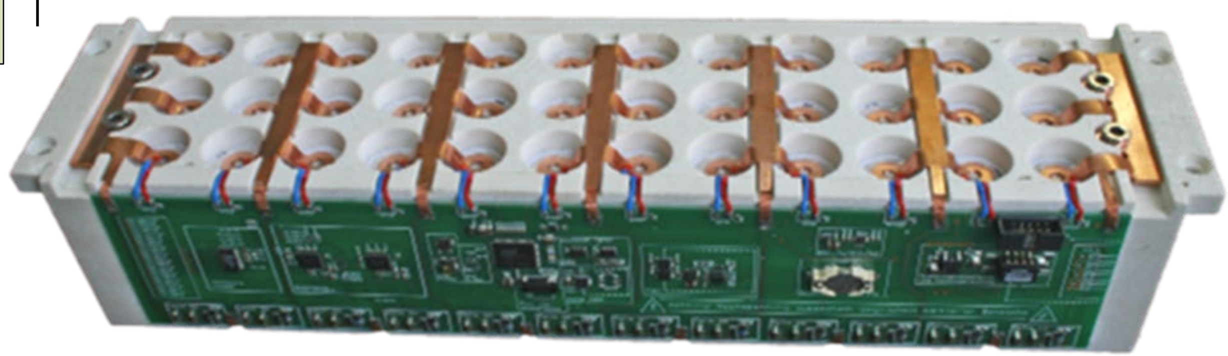
Li-Ion cells in series require individual cell monitoring and charge balancing



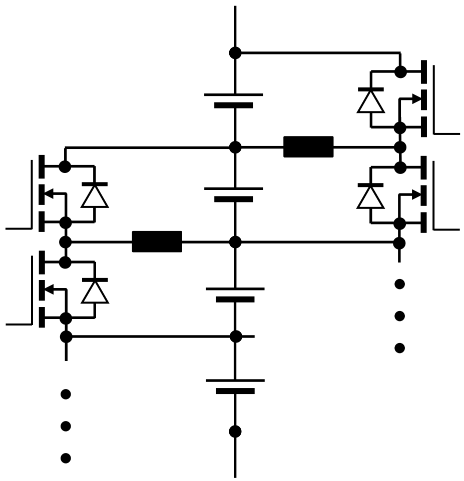
Cell electronics for battery modules

- Individual cell voltage measurement
- Individual cell temperature measurement (optional)
- Cell individual passive charge equalization
- Communication between different modules and with a central battery management system (BMS) via serial data bus



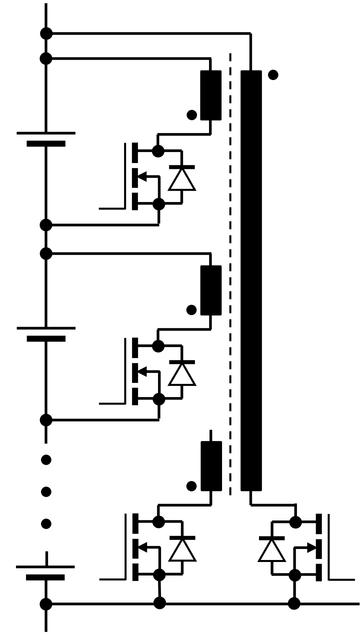
Active Charge Equalization ▪ two of numerous circuit examples

Buck/boost converter principle



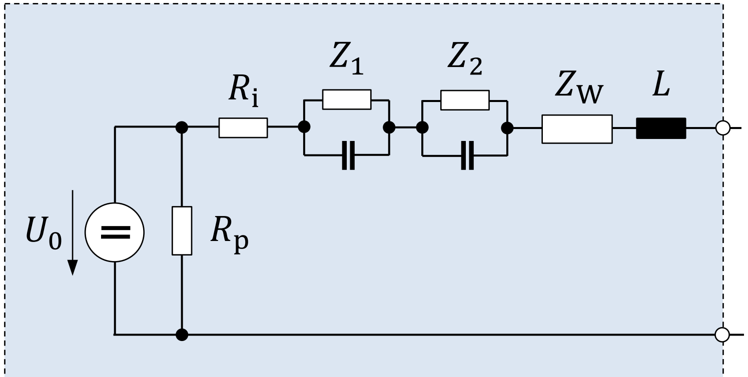
- Very high recharging currents possible
- Suitable for cell “preheating” at low temperatures using circulating currents
- Charge can only be "moved further" from cell to cell
- Significant effort

Flyback converter principle

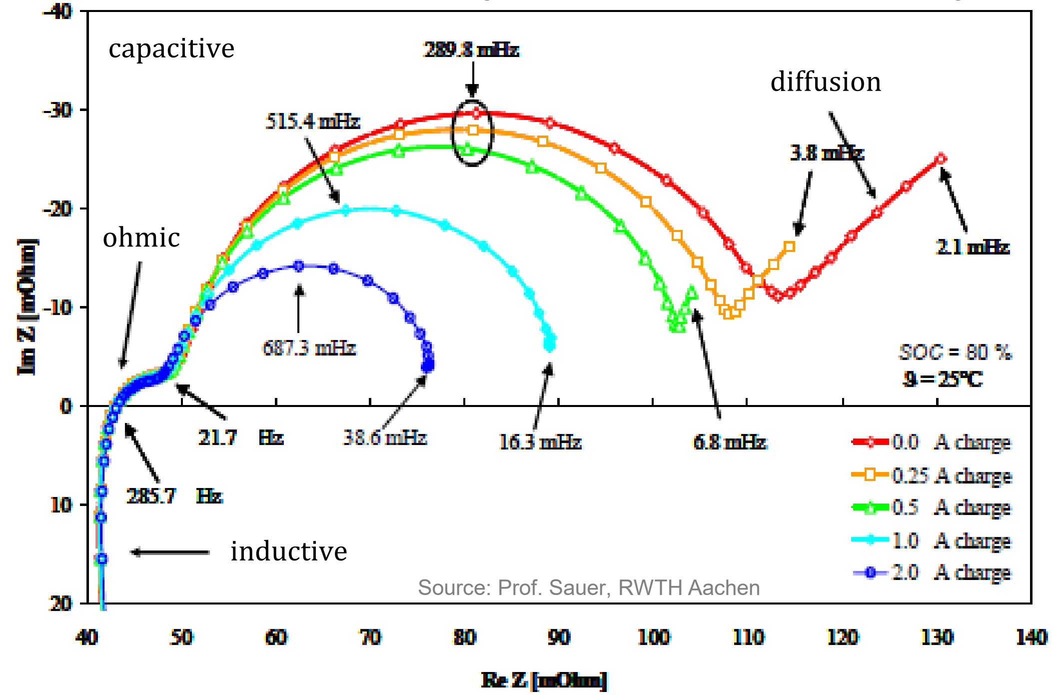


- High recharging currents possible
- Random charge redistribution
- Expensive transformer required
- Significant effort

Electrical Equivalent Circuit of a Li-Ion cell



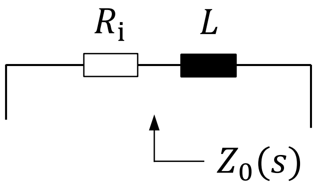
Parameter extraction e.g. from **impedance spectroscopy**

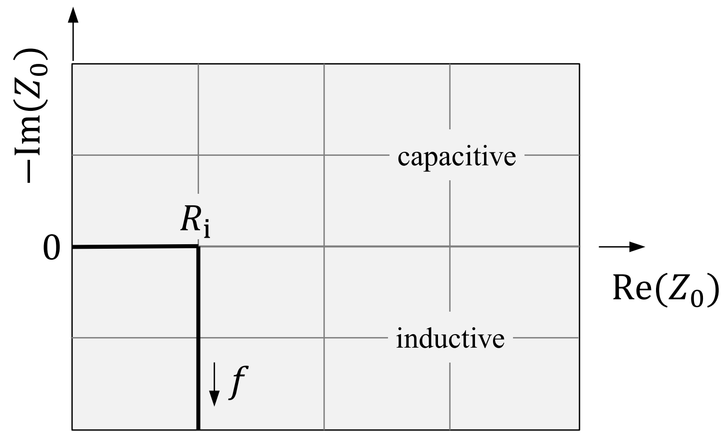


U_0 : open circuit voltage (= f(SOC, T, ..))
R_p : self-discharge
Z_1 : SEI layer
Z_2 : charge transfer and double layer capacitance
L : series inductance (cell bus bars, …)
Z_W : Warburg impedance (diffusion model)

- Almost all elements of the equivalent circuit are functions of the state of charge (SoC), temperature, state of health (SoH), etc.!
- Within the switching frequency range of power electronics, a single Li-Ion cell or a battery module can be described to a very good approximation as a voltage source with an internal ohmic resistance (R_i) and a series inductance (supply leads).
- The capacitive branch is only relevant for very low-frequency events (e.g. load steps)

The Basic Elements of the Equivalent Circuit in an impedance plane

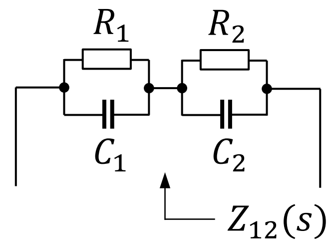


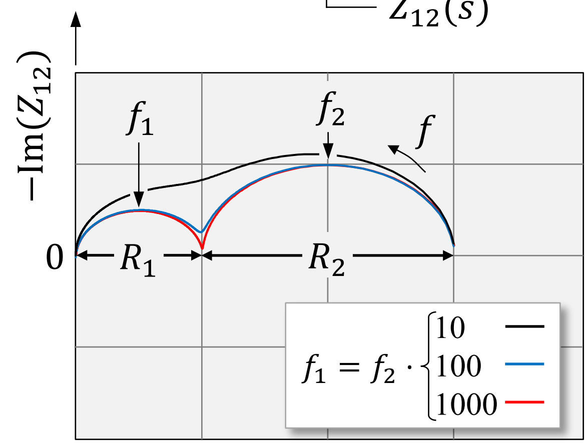


$$Z_0 = R_\mathrm{i} + sL = R_\mathrm{i} + j(2\pi f)L$$

Note

Electrochemists commonly plot the negative imaginary part upwards on the y-axis (for whatever reason ☺)





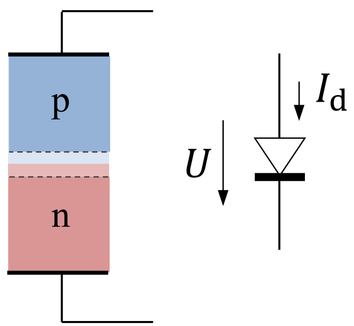
As the distance between the natural frequencies decreases, the individual semi-circles "blur".

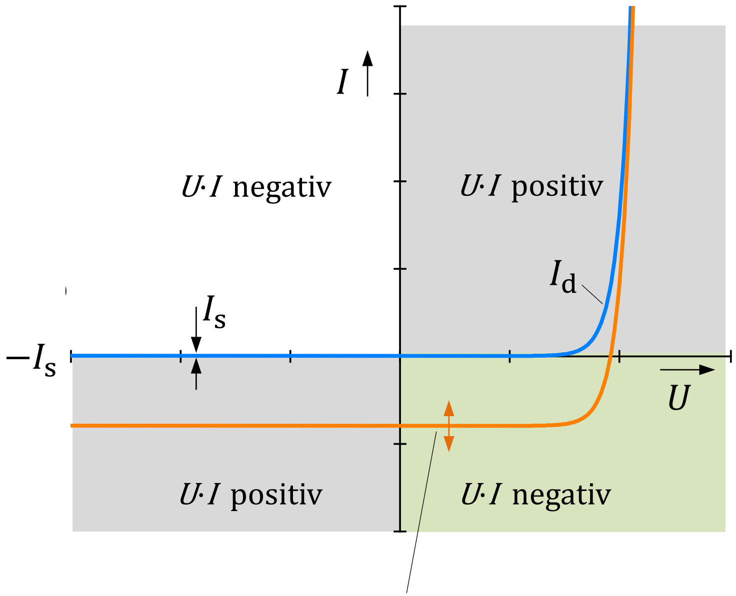
Each RC term provides an impedance characteristic according to:

$$Z_\mathrm{x} = \frac{1}{\frac{1}{R_\mathrm{x}} + sC_\mathrm{x}} = \frac{R_\mathrm{x}}{1 + j\,2\pi f R_\mathrm{x} C_\mathrm{x}} = \frac{R_\mathrm{x}}{1 + j\frac{f}{f_\mathrm{x}}}$$

with $f_1 = \dfrac{1}{2\pi R_1 C_1}$ and $f_2 = \dfrac{1}{2\pi R_2 C_2}$

Characteristic of a Semiconductor p/n Junction





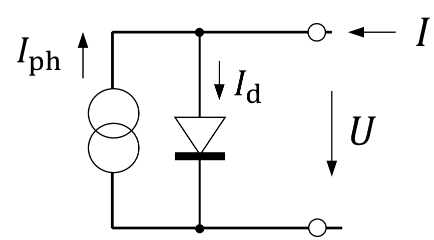
⇨ In the 1st and 3rd quadrant, $U{\cdot}I$ is positive, i.e. the diode consumes power (power loss) and heats up

⇨ In the 4th quadrant, $U{\cdot}I$ is negative, i.e. the diode delivers power: **generator operation** ⇨ photodiode

$$I_d = I_s \cdot \left(e^{\frac{U}{n\,U_T}} - 1\right)$$

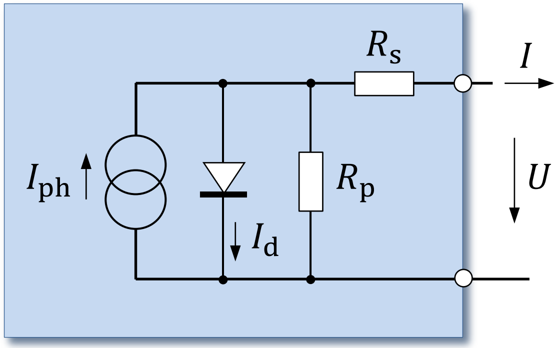
$U_T = kT/q$ (thermal voltage)
I_s : reverse bias saturation current
k : Boltzmann constant ($1.38 \cdot 10^{-23}$ Ws/K)
q : elementary charge ($1.602 \cdot 10^{-19}$ As)
n : ideality factor (≈ 1…2)

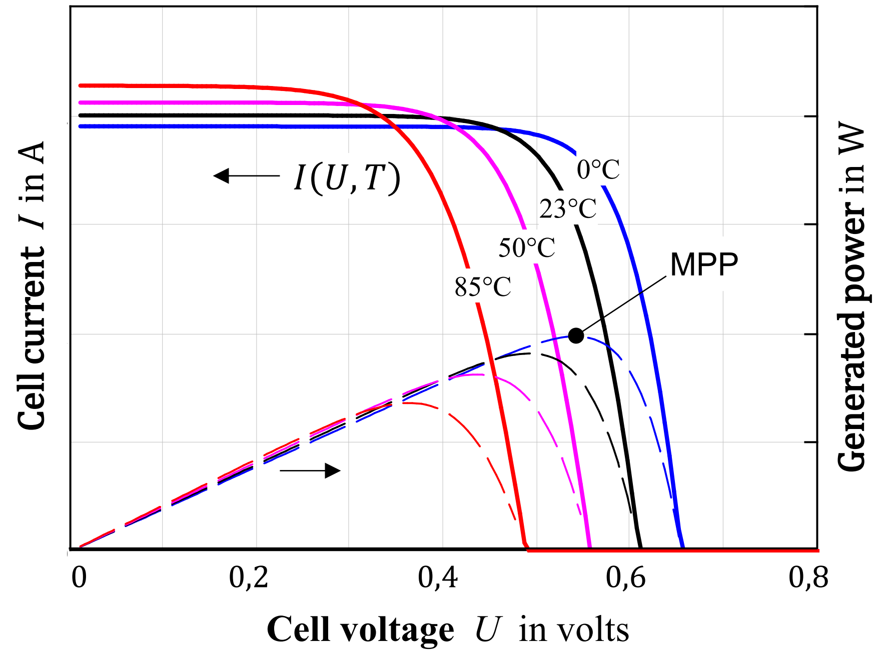
A photocurrent adds when a p/n junction is irradiated:



$$I = I_d - I_{ph}$$

Photovoltaic - electrical characteristics of a solar cell





Solar cell characteristic

$$I(U,T,S) = I_{ph}(T,S) - I_s\left(e^{\frac{U+R_S(T)\,I}{n\,U_T(T)}} - 1\right) - \frac{(U+R_S(T)\,I)}{R_p}$$

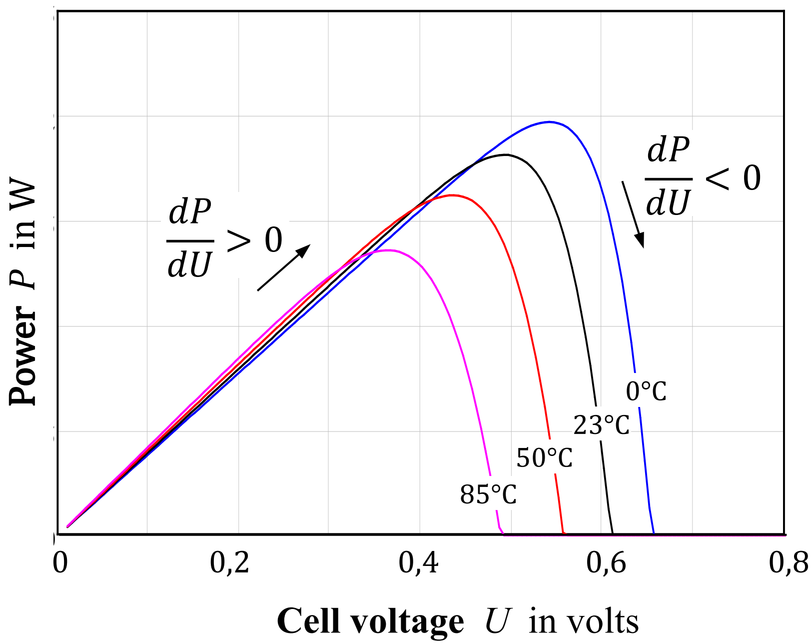
and if R_s and R_p are negligible:

$$I(U,T,S) = I_{ph}(T,S) - I_s\left(e^{\frac{U}{n\,U_T(T)}} - 1\right)$$

S : Solar irradiance in W/cm^2
I_{ph} : Photocurrent
R_s : Series resistance

- Changing from a consumer to a generator arrow system tilts the 4th quadrant of the diode characteristic to the 1st quadrant of the PV cell characteristic.
- The hotter the PV cell, the lower the output power at a given irradiance!

Maximum Power Point Tracking (MPPT)



MPP search methods

- Imposing a small disturbance and observing the change in power »perturb and observe«
- Observation of the change in conductance when the operating point changes (»Incremental conductance«). From

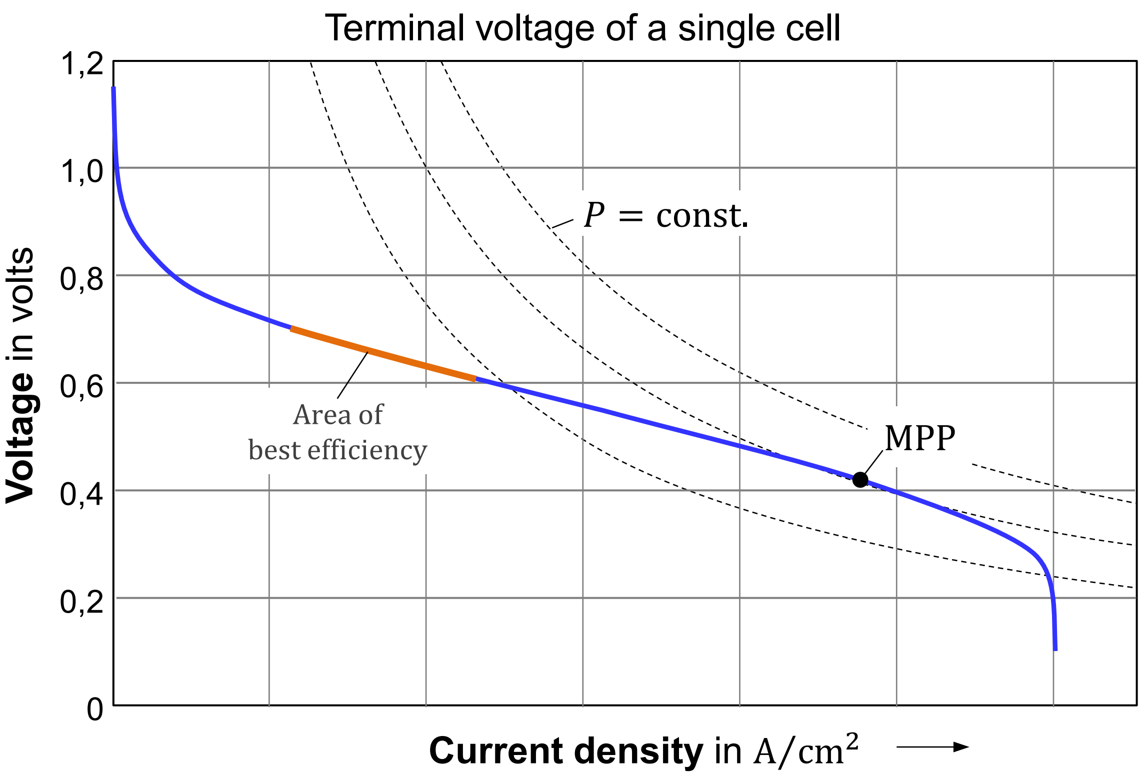
  $$\frac{dP}{dU} = \frac{d(UI)}{dU} = I\frac{\partial U}{\partial U} + U\frac{\partial I}{\partial U} = I + U\frac{\partial I}{\partial U}$$ it follows

  left of the maximum $\frac{dP}{dU} = I + U\frac{\partial I}{\partial U} > 0$ $\quad \frac{dI}{dU} > \frac{-I}{U}$

  and right of the maximum: $\frac{dI}{dU} < \frac{-I}{U}$

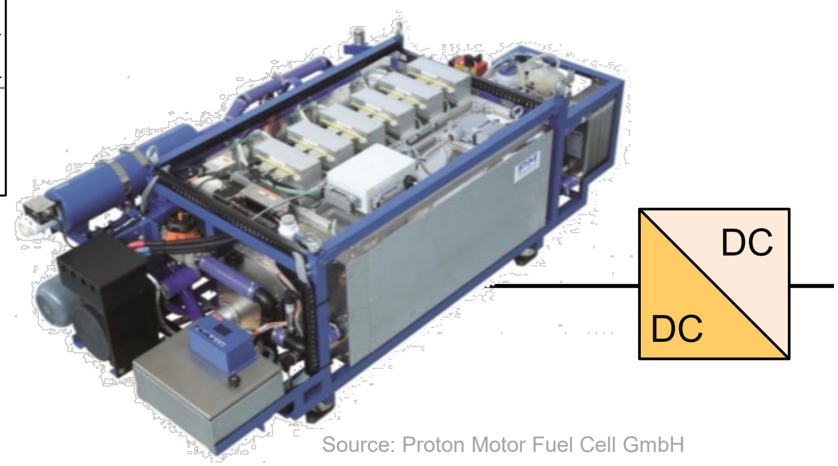
- To impose small changes in the operating point, the current/ voltage ripple caused by a connected switchmode converter or inverter can also be used.
- The MPP search for partially shaded solar modules poses a particular challenge, since the power curve can then have several local maxima.

PEM Fuel Cell - electrical characteristics



Voltage-current characteristic

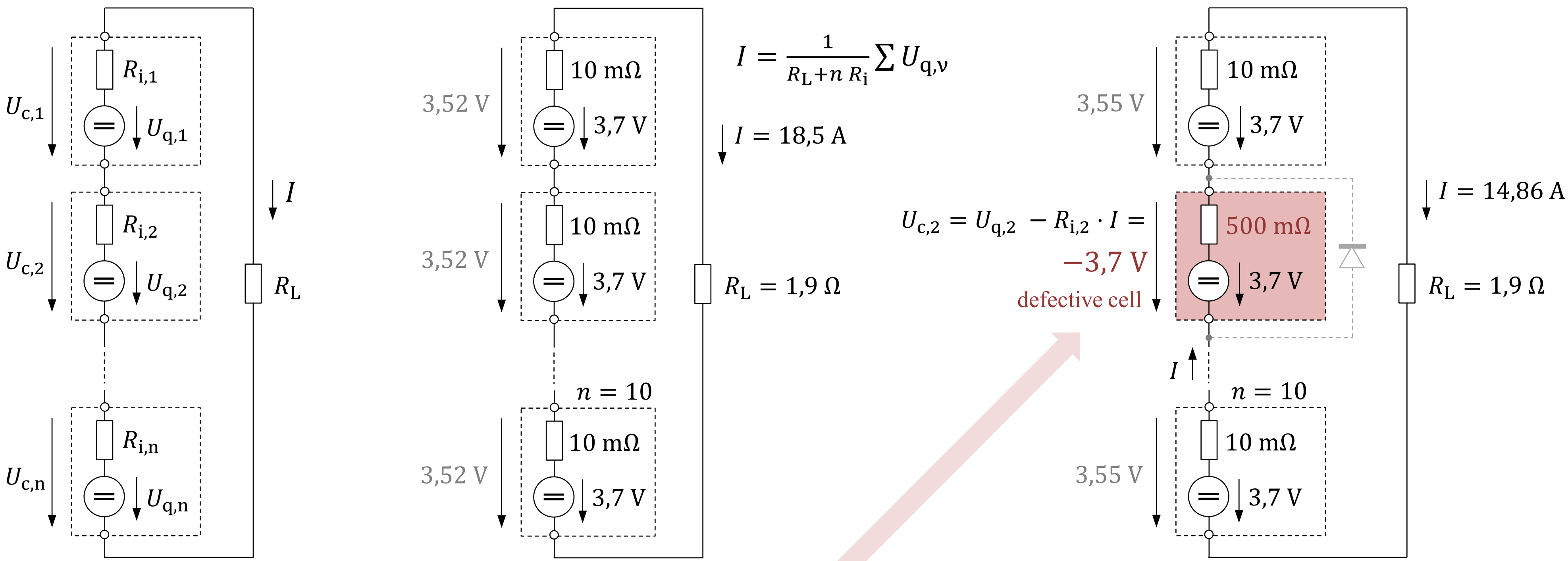
- The very "soft" output characteristic generally requires a DC/DC converter for coupling the fuel cell to an application like a DC grid
- A DC/DC converter allows the operating point of the fuel cell (FC) to be optimized between high efficiency and maximum power output (MPP) regardless of the DC grid voltage



Source: Proton Motor Fuel Cell GmbH

Series Connection of Voltage Sources (PV cells, fuel cells, battery cells, …)

Equivalent circuit | **Nominal operation** - number example | **Voltage reversal on a defective cell**



- When battery cells, PV or fuel cells are connected in series, a defect in one cell can lead to a voltage reversal across the affected cell!
- Methods to keep the whole stack functional are a bypass diode (only for sources since unidirectional) or an anti-fuse

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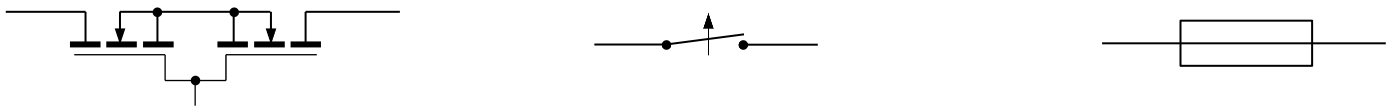
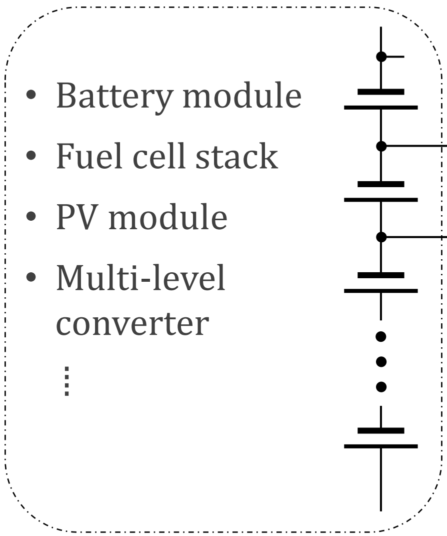
Fault Isolation - to ensure system functionality in case of a fault

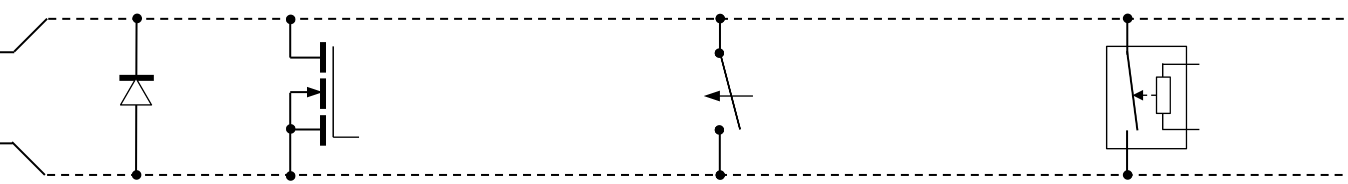
- **Overcurrent** or **short circuit protection** requires **interrupting** protection elements for fault isolation



Semiconductor Switch **Mechanical Switch** **Fuse**

- In contrast, fault isolation in case of **series connected cells or subsystems** requires **short-circuiting** protective elements to maintain the system function (current path must be maintained)





Power semiconductor
- Very high cost at higher currents and high cell counts
- Power dissipation requires cooling

Mechanical switch

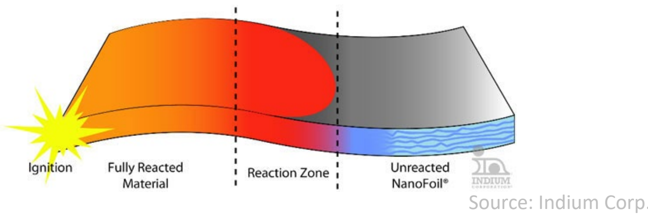
Triggerable antifuse

Challenge: How to realize a triggerable short-circuiting protective element with very high current carrying capability, low on-state losses and **minimum cost**?

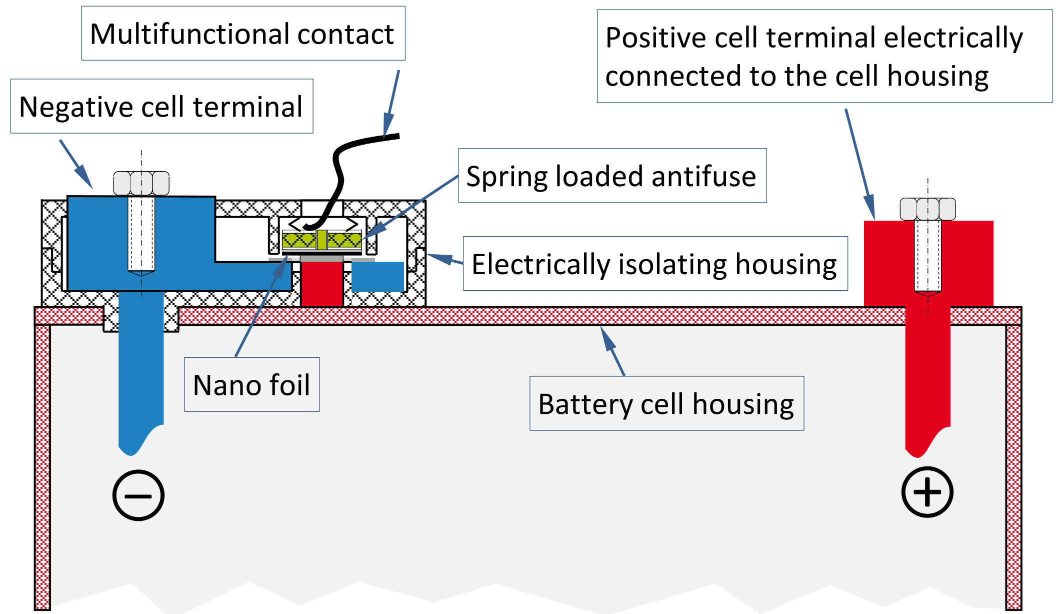
Triggerable Power Antifuse, e.g. for integration in prismatic battery cells

An innovative low-cost solution based on an exothermally reactive multi-layer foil

- Aluminum/Nickel bi-layers, each 50 nm thick (total foil thickness 40 to 100 µm)



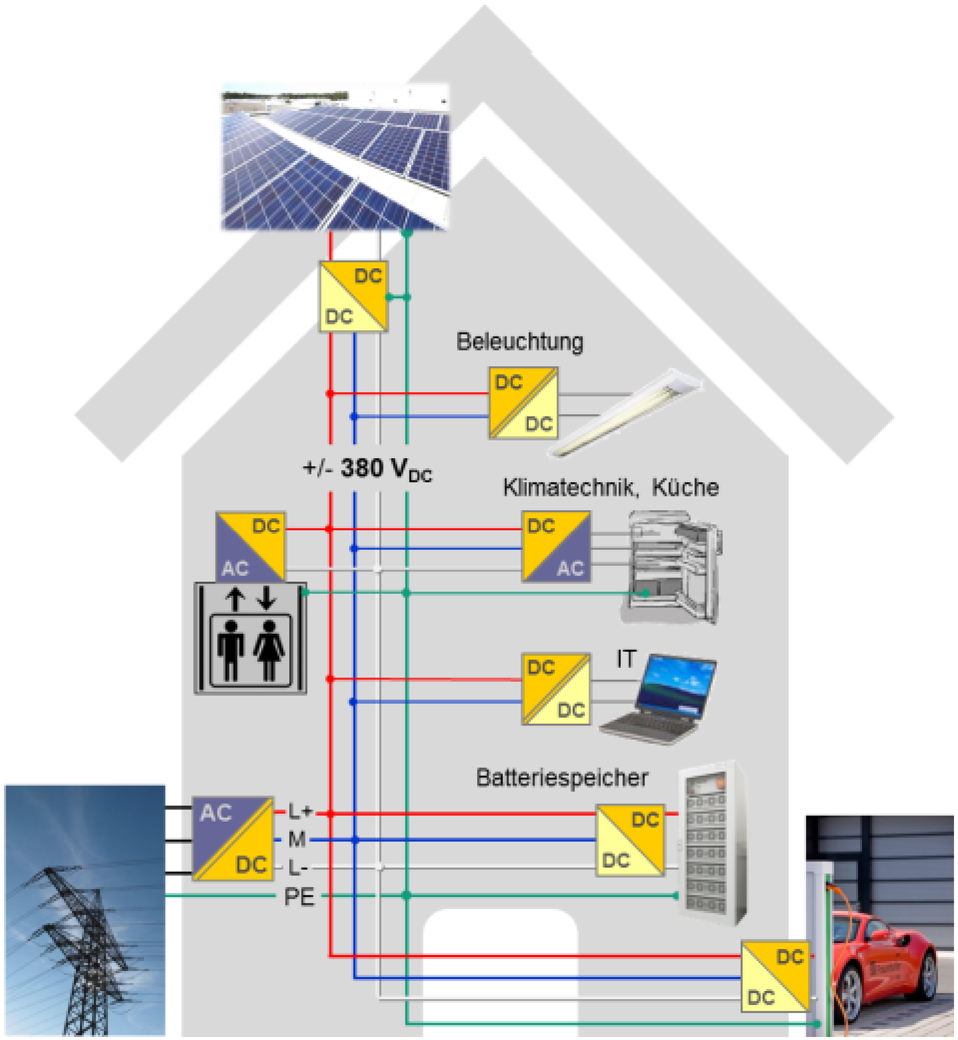
- Both metals enter into a self-sustaining exothermic reaction that releases approx. 1 kJ/g of heat
- Reaction can easily be triggered electrically
  - ↳ the heat released can be used to solder two electrical contacts
    - ↳ very high current carrying capability at low cost!



[1] R. Waller, V. Lorentz, and M. März, “Electrical bridging device for bridging electrical components, in particular an energy source or an energy consumer,” DE102015222939 / EP3378112 / WO2017085157 / KR1020187014257 / CN201680067611, Nov. 20, 2015

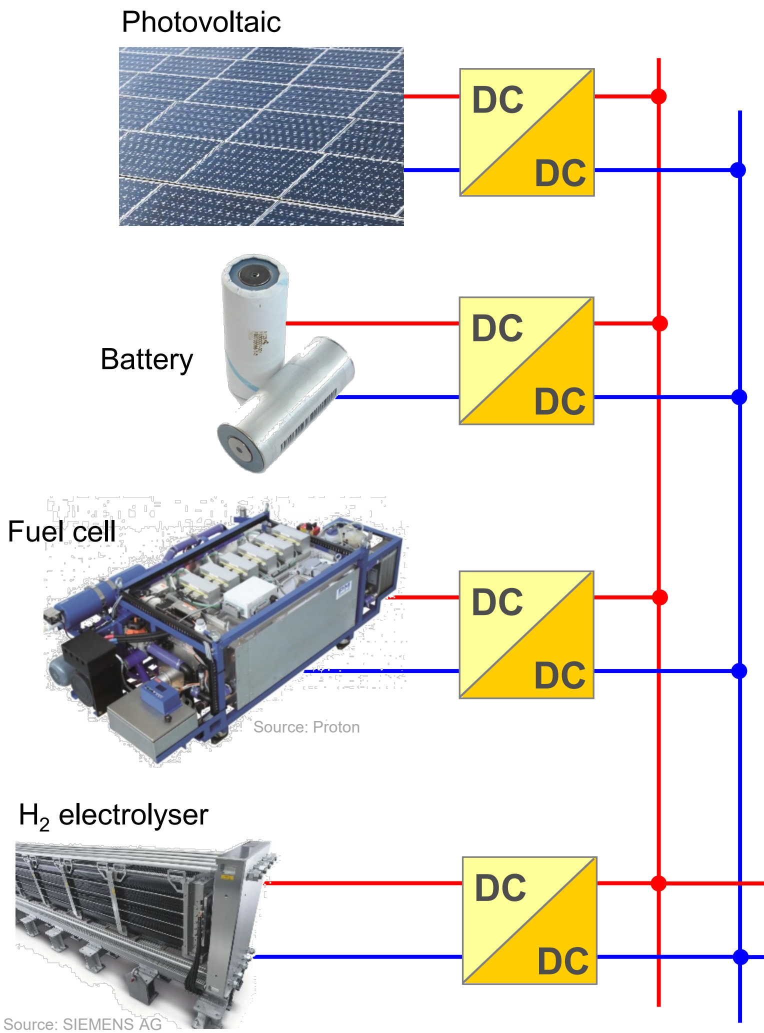
[2] R. Waller, V. Lorentz, and M. März, “Electrical bypass device for bypassing an electrical energy source or an energy consumer,” DE102016208419 / EP3465800 / WO2017198599 / US20190131612, May 17, 2016

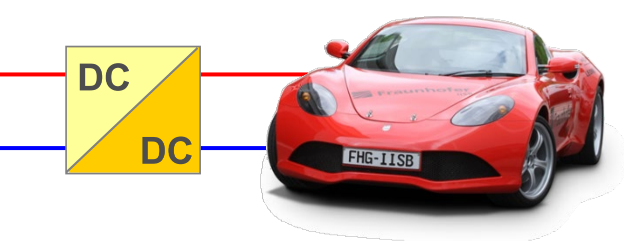
[3] R. Waller, V. Lorentz, and M. März, “Electrical energy storage cell with integrated bridging device”, DE102016208421 / EP3459133 / US20190131611, May 17, 2016



Non-isolating

DC/DC Converters

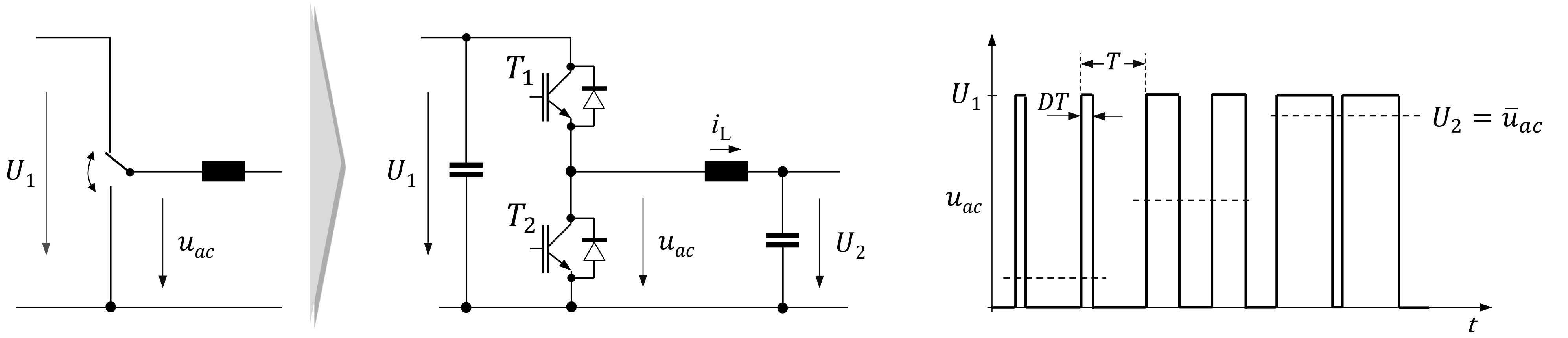




Functions

- A DC/DC converter allows **two** parameters (e.g. the input and the output voltage or input power and output current) to be regulated independently of one another
- Non-isolating converters provide no electrical (galvanic) isolation between the input and output terminals. They can thus only be used if this isolation is not required, e.g. for reasons of personal protection, to eliminate ground loops or electrical potential references.
- In contrast to isolating DC/DC converters, bidirectional operation (energy flow in both directions) can usually be implemented with a reasonable additional effort
- Today, non-isolating converters usually achieve efficiencies in the range of 97 to 99%

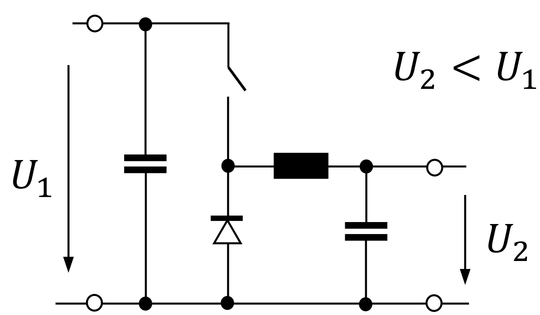
The Half Bridge as a Changeover Switch ■ a basic element in power electronics

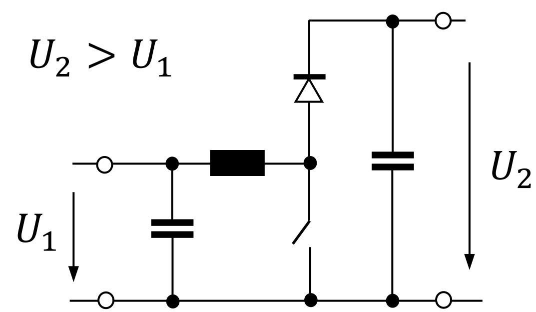


- The switching frequency f_s denotes the number of switching events per second, its reciprocal is the duration T of a switching period. The duty cycle is the percent ON time (in the above example of the top switch T_1) and can have the following range of values: $0 \leq D \leq 100\%$
- The mean value of the voltage u_{ac} (i.e. $\bar{u}_{ac}$) can be continuously adjusted via the duty cycle (D) and thus the output voltage (U_2) can be adjusted between zero and the input voltage (U_1)
- In order not to cause any perceptible noise, the switching frequency is selected above the human audible threshold (15 kHz) whenever possible

Energy flow

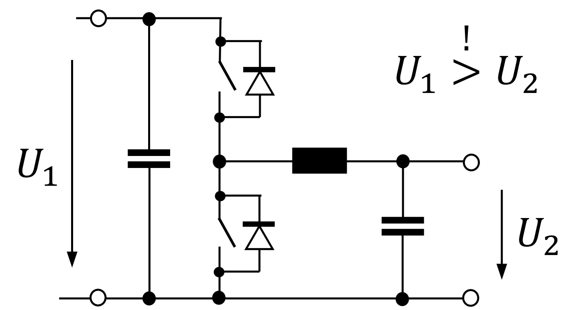
unidirektional



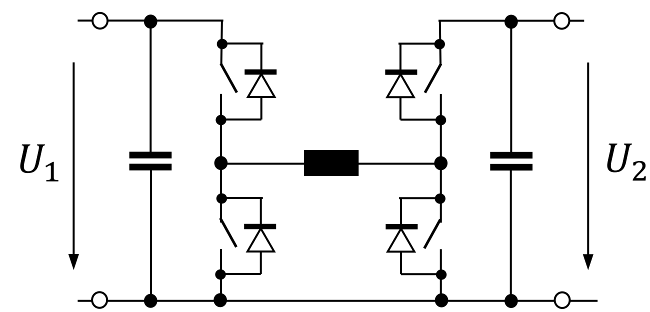


Caution: No current limitation possible in the case of undervoltage or short circuit at port U_2

bidirektional



Caution: No current limitation possible in the case of undervoltage or short circuit at port U_1



Any voltage and fault situation (except reverse polarity) can be managed!

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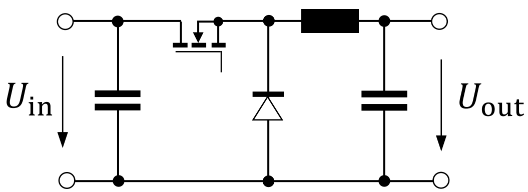
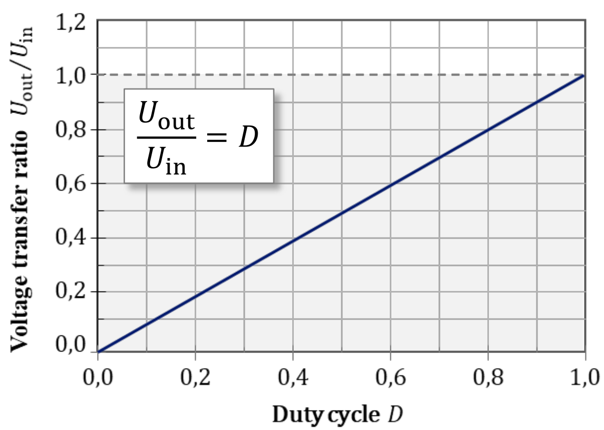
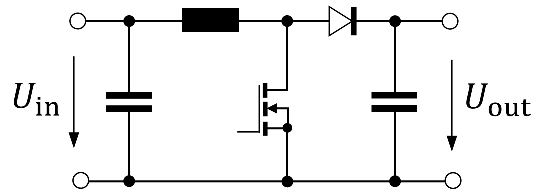
Basic Topologies (unidirectional)

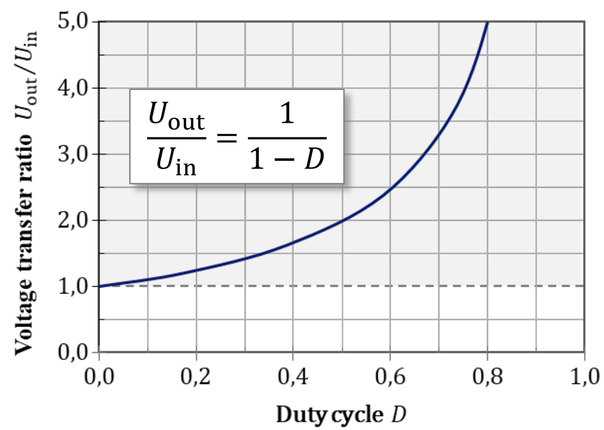
Buck converter



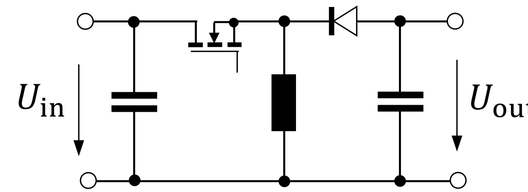


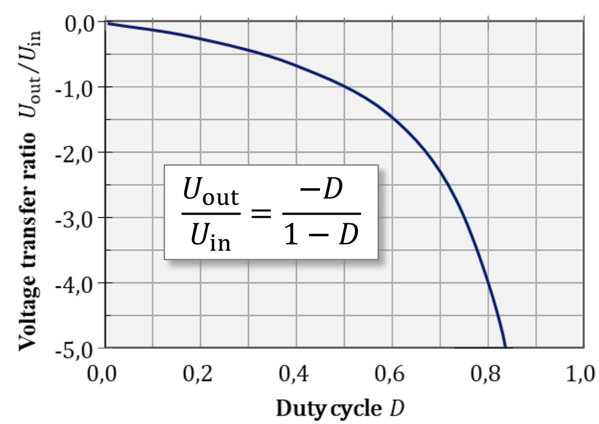
Boost converter





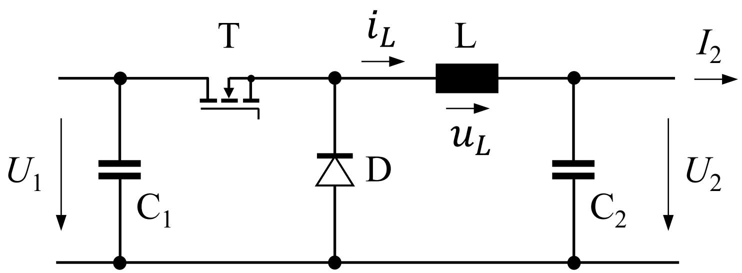
Buck-Boost converter

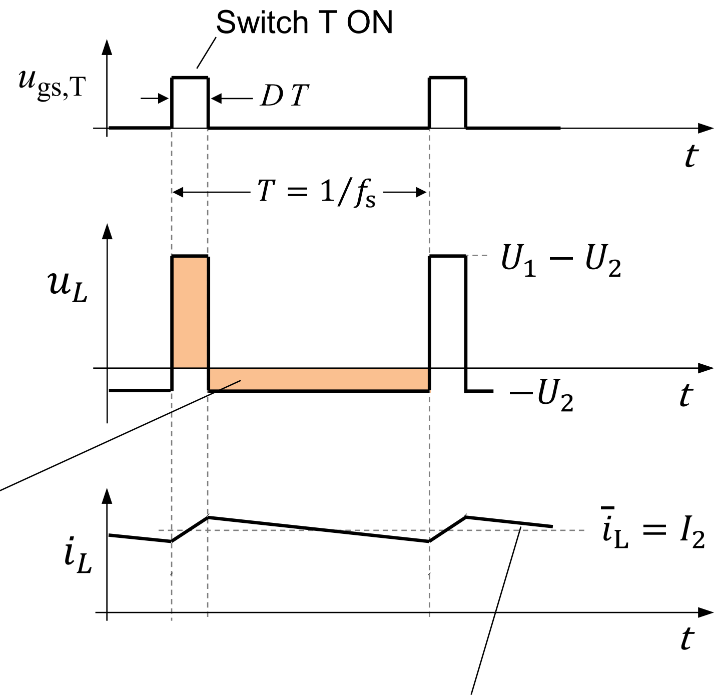




CAUTION: The given voltage transfer functions only apply to continuous conduction mode operation (CCM)!

How to Analyse Switchmode Power Converters?





The **basic equation of an inductance** is: $i_L = \frac{1}{L}\int u_L(t)\,dt$

i.e., an inductance integrates the applied voltage into a current!

Under steady-state conditions (no change in mean inductor current), the **voltage-time area** at an inductance must therefore always be zero over a switching period!

$$(U_1 - U_2)\,DT - U_2\,(1-D)T \overset{!}{=} 0$$

$$U_1\,D - U_2\,D = U_2 - U_2\,D$$

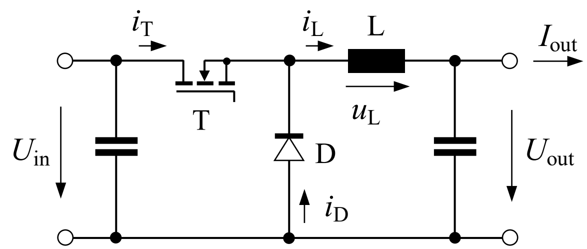
$$\boxed{U_2 = D \cdot U_1}$$

↳ Buck converter

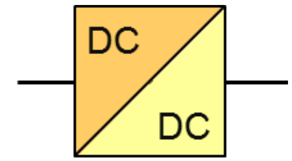
The slopes in inductor current can easily be derived using the basic equation in its differential form:

$$\frac{di_L(t)}{dt} = \frac{u_L(t)}{L}$$

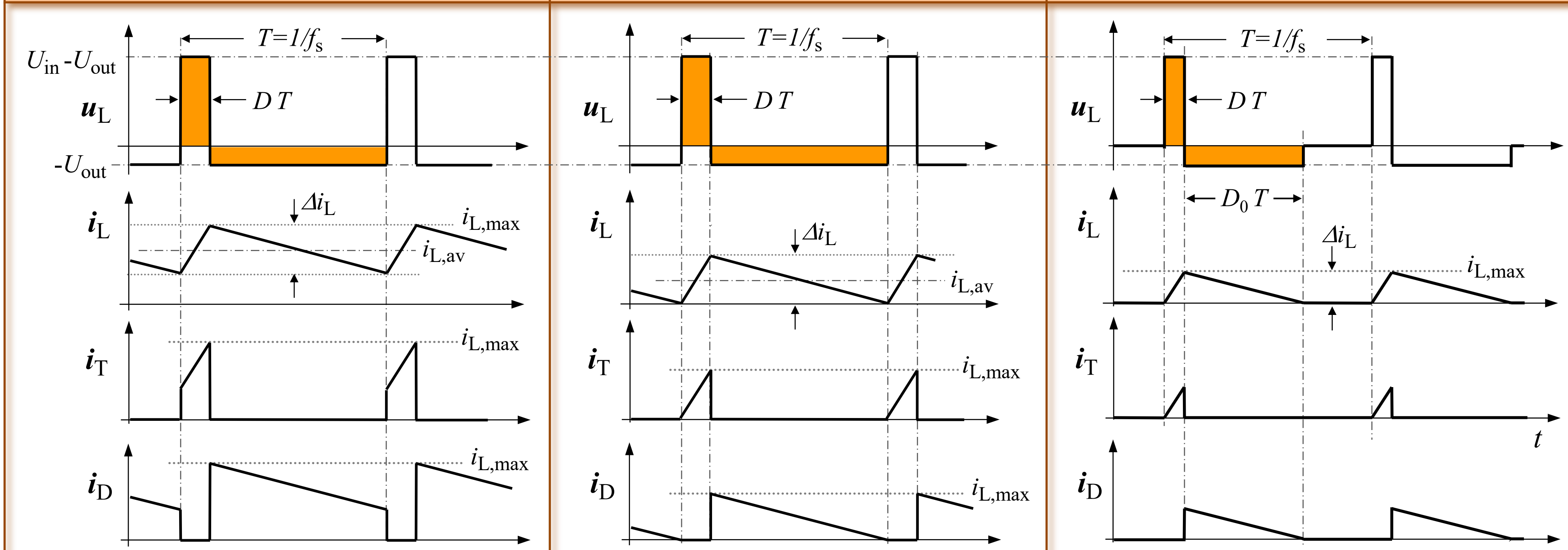
Buck Converter



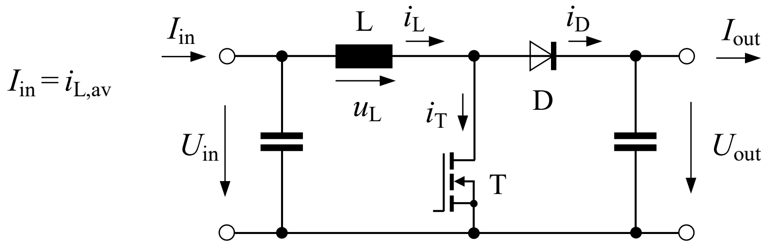
$I_{out} = i_{L,av}$

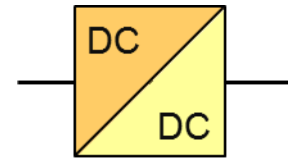


CCM Continuous Conduction Mode	BCM Boundary Conduction Mode	DCM Discontinuous Conduction Mode

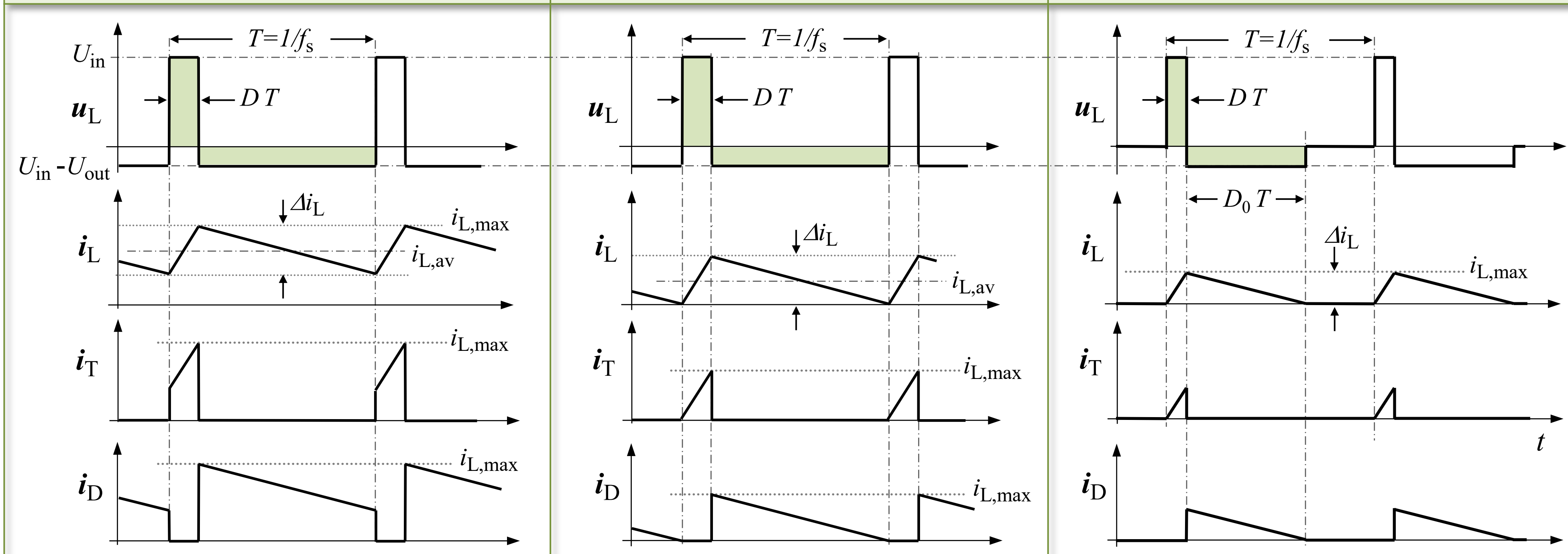


Boost Converter





CCM	BCM	DCM
Continuous Conduction Mode	Boundary Conduction Mode	Discontinuous Conduction Mode



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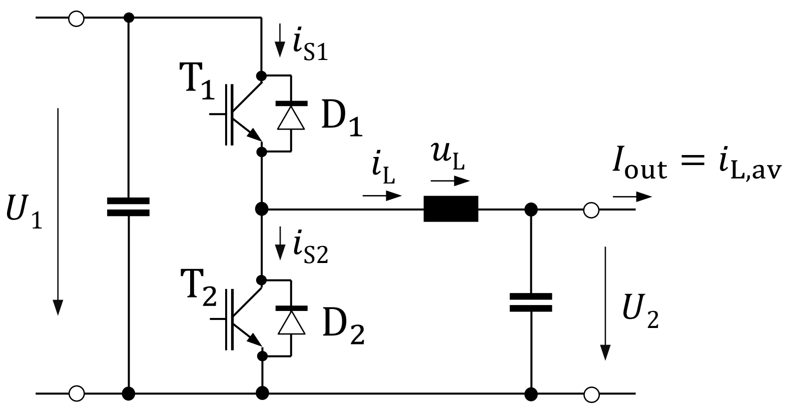
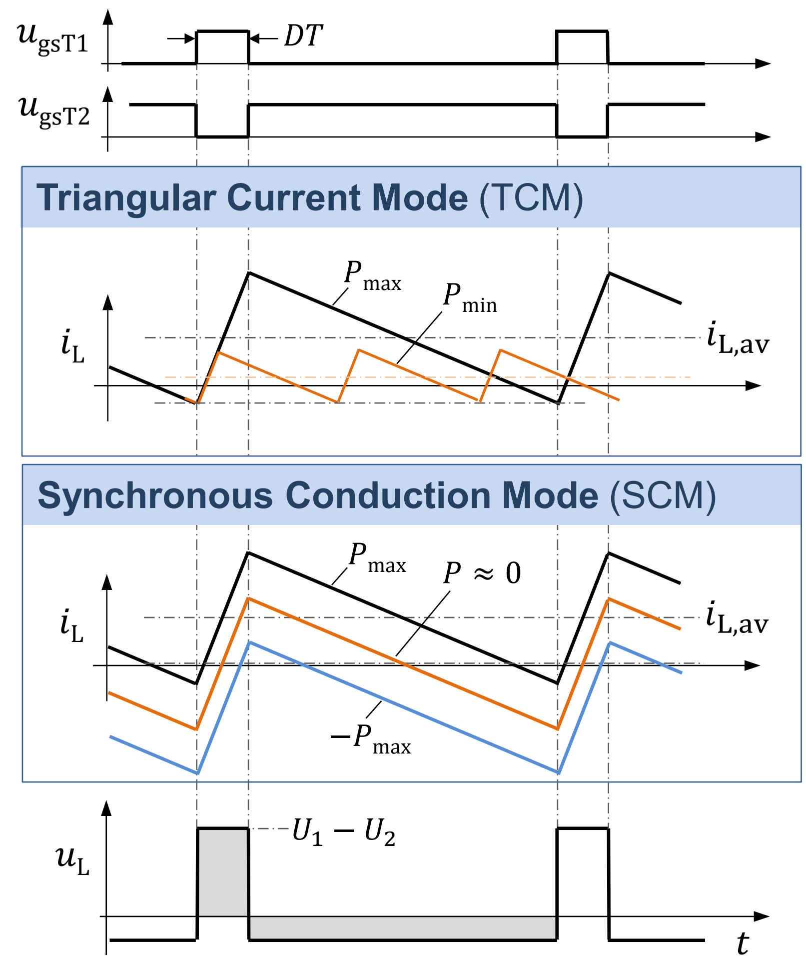
Buck/Boost Converter



Additional modes using complementary switching of T1 and T2

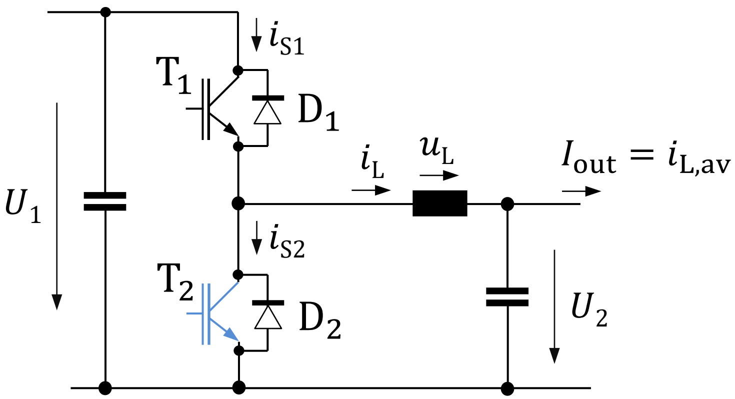


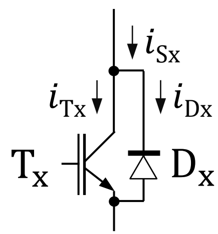
- In modes with **continuous inductor current** (CCM, TCM, SCM) the converter behaves like an ideal »DC transformer«, with a transformer ratio solely determined by the duty cycle.
- The direction of energy flow changes automatically depending on the voltage conditions at the terminals determined by external influences.
- Voltage sources at both terminals would - without counter-measures by a controller - lead to a current "run away" (integrator property of the inductor).
- A forced continuous inductor current operation can worsen the partial load efficiency, since reactive power is constantly oscillating. However, with Triangular Current Mode (TCM) soft switching becomes possible.

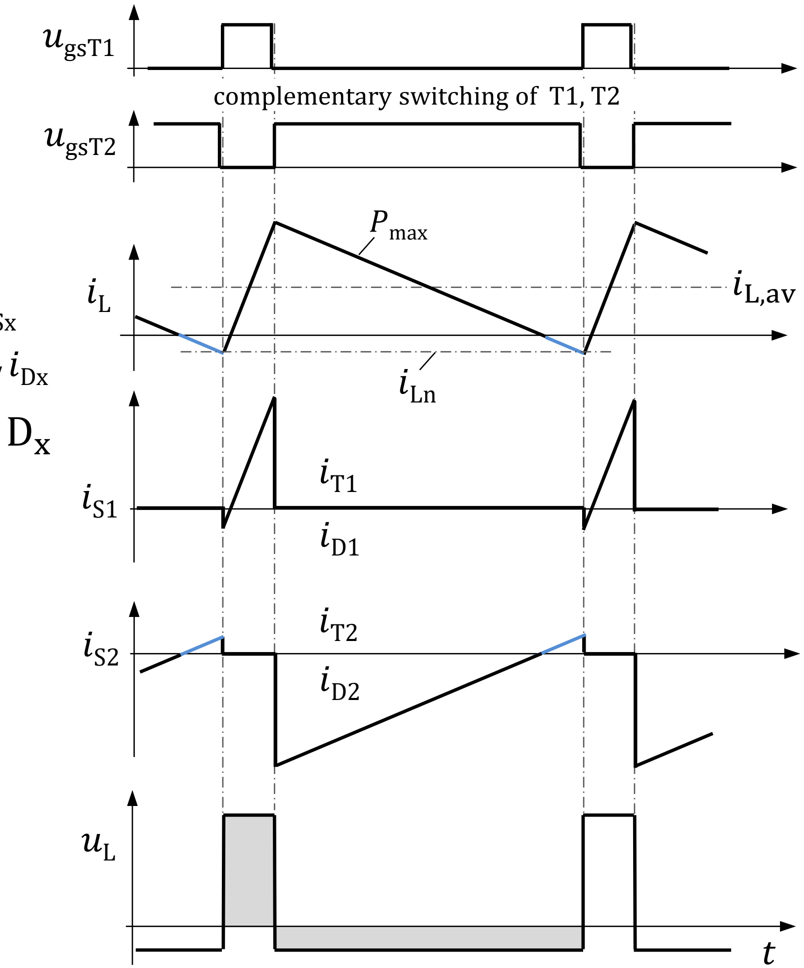
1) Spelling buck/boost to avoid confusion with the English term for the inverse converter (buck-boost)..

Minimizing Switching Losses in a »Buck/Boost Converter«

Triangular Current Mode (TCM)



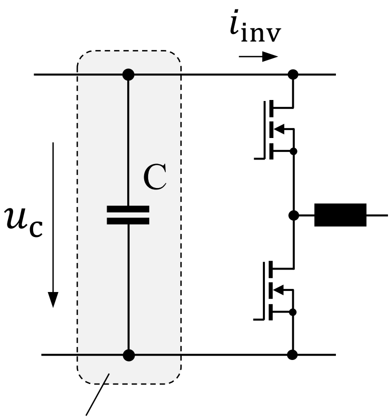




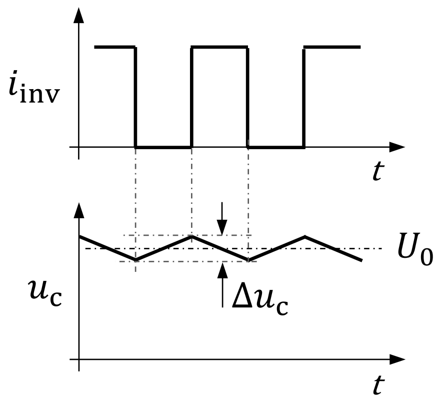
Some basic properties of TCM noticeable from the right diagrams

- Each transistor is turned on only at a time instance when the current is flowing through its anti-parallel diode. This means that turn-on always happens without voltage across the switch. This **zero voltage switching** (ZVS) allows to reduce switching losses dramatically.
- The inductor current stays continuous (i.e. TCM is a special case of CCM)
- In practice, the negative inductor current peak value (i_{Ln}) will be chosen only just as high that the energy stored in the inductor is sufficient to recharge the parasitic capacitances of the two switches
- This results in a load dependent variable switching frequency

The DC Link Capacitor Paradox



DC link capacitor

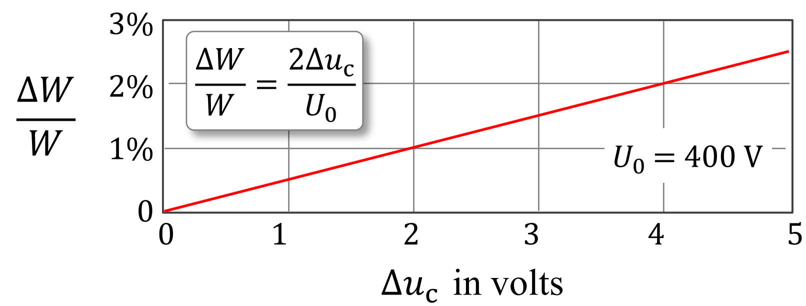


Energy installed in the DC link: $W = \frac{1}{2}\, C\, U_0^2$

of which is actually used:

$$\Delta W = \frac{1}{2}\, C \left[\left(U_0 + \frac{\Delta u_{\mathrm{c}}}{2} \right)^2 - \left(U_0 - \frac{\Delta u_{\mathrm{c}}}{2} \right)^2 \right] = C\, U_0\, \Delta u_{\mathrm{c}}$$

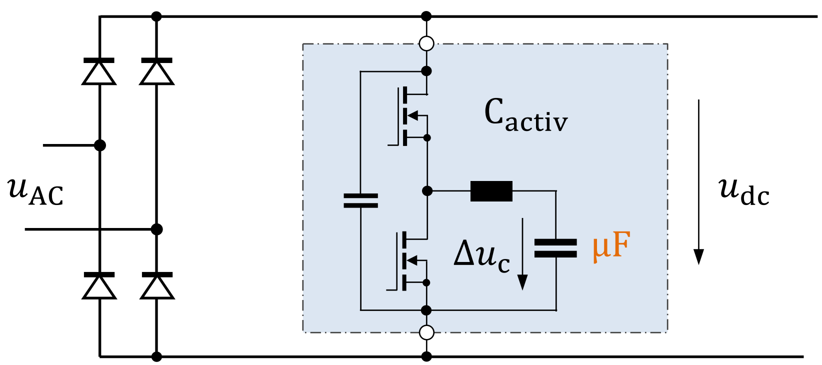
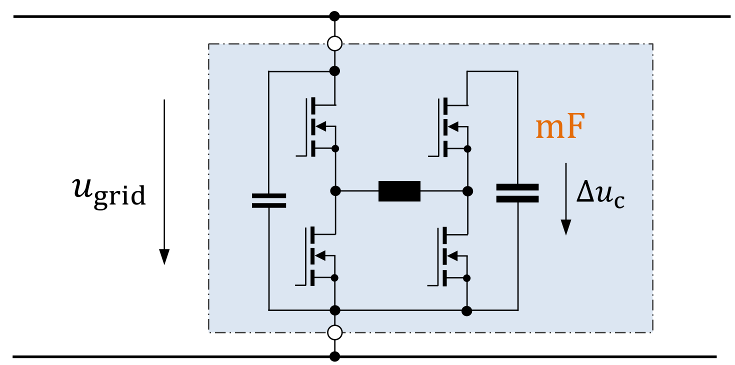
Ratio between used and installed energy:



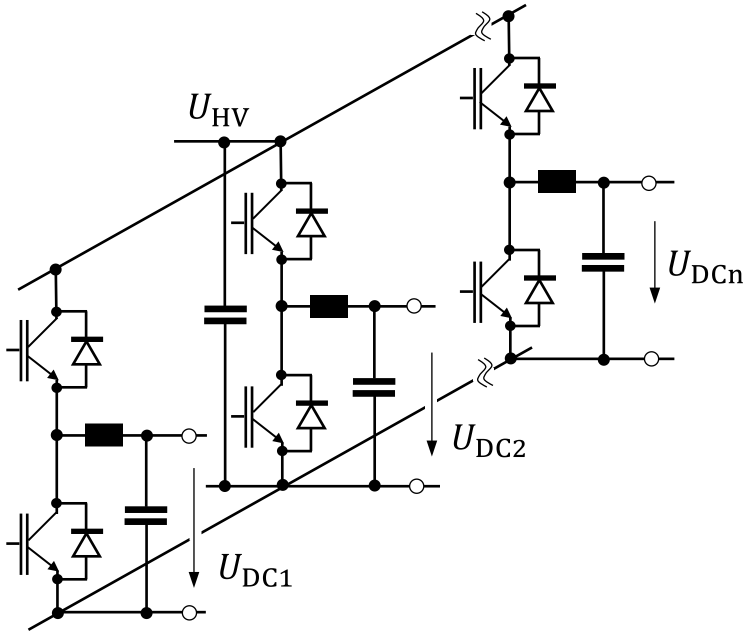
The widespread approach of reducing voltage ripple through more capacity in the system leads to more installed energy, of which, however, a decreasing proportion is actually used!

↳ A lot of volume, weight and costs for surprisingly little problem solving ☹

Active DC Line Filter and Power Support

Active Line Filter (differential mode filter)	**Active Power Support**
	
Advantages ■ Significant reduction in capacitor size for given requirements on low frequency filter characteristics ■ Replacement of lifetime limited electrolytic capacitors with long life film or ceramic capacitors ■ At $\Delta u_{\text{c}} = 0{,}75\ u_{\text{dc}}$ the degree of utilization of the stored energy is already more than 90%	**Advantages** ■ DC grid voltage stabilization in presence of loads with high inrush currents, while ■ decoupling the energy storage in case of faults for fault energy limitation ■ A well-defined fault current characteristic supports the triggering of protective elements such as fuses

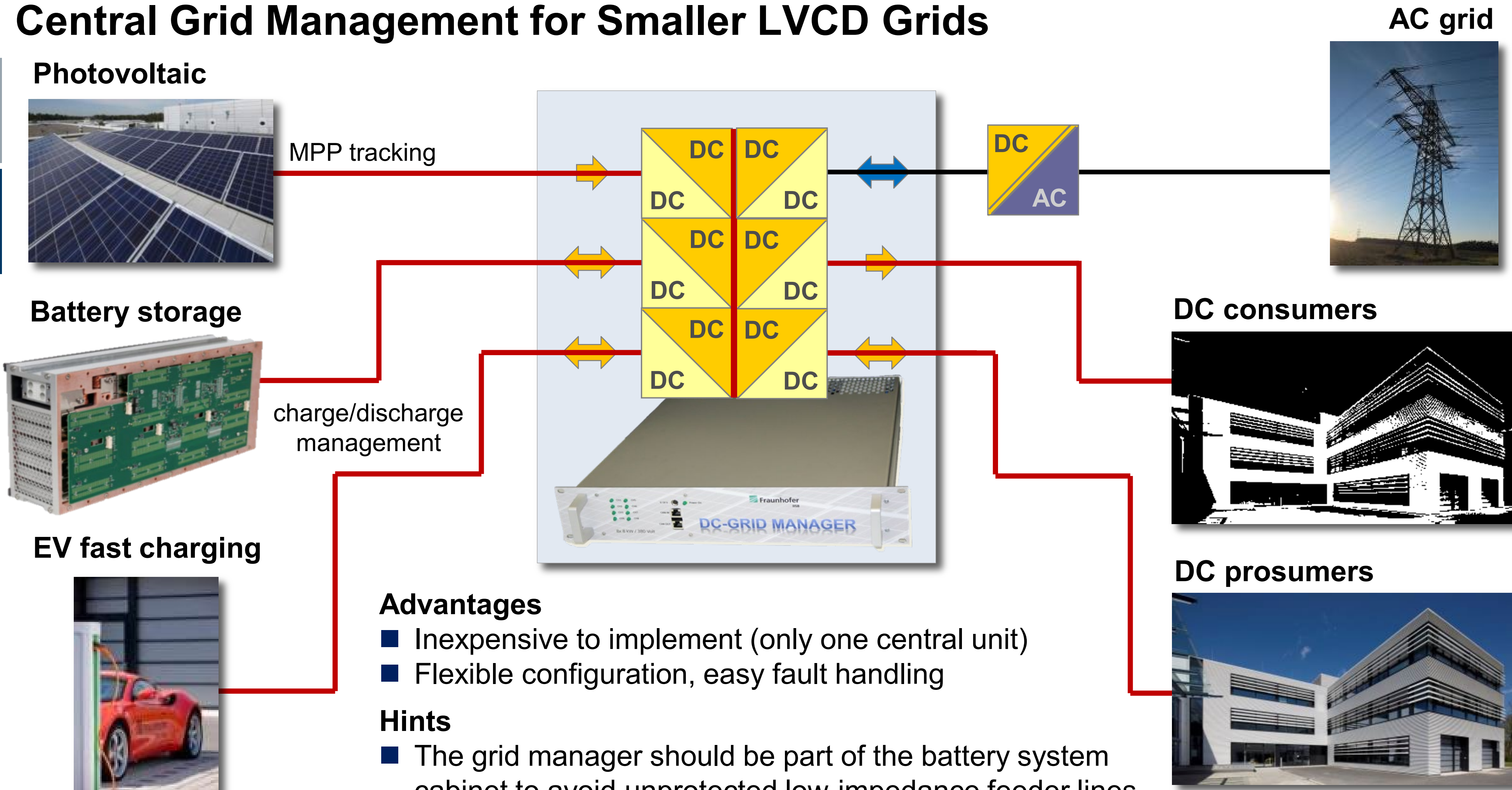
DC Grid Manager



Multi-channel Buck/Boost

- 8 channels à $20\ \mathrm{A}$ and $0 \ldots 400\ \mathrm{V}$
- Each channel can be configured individually for the specific application, running even complex control tasks
- LAN interface

Central Grid Management for Smaller LVCD Grids



Advantages

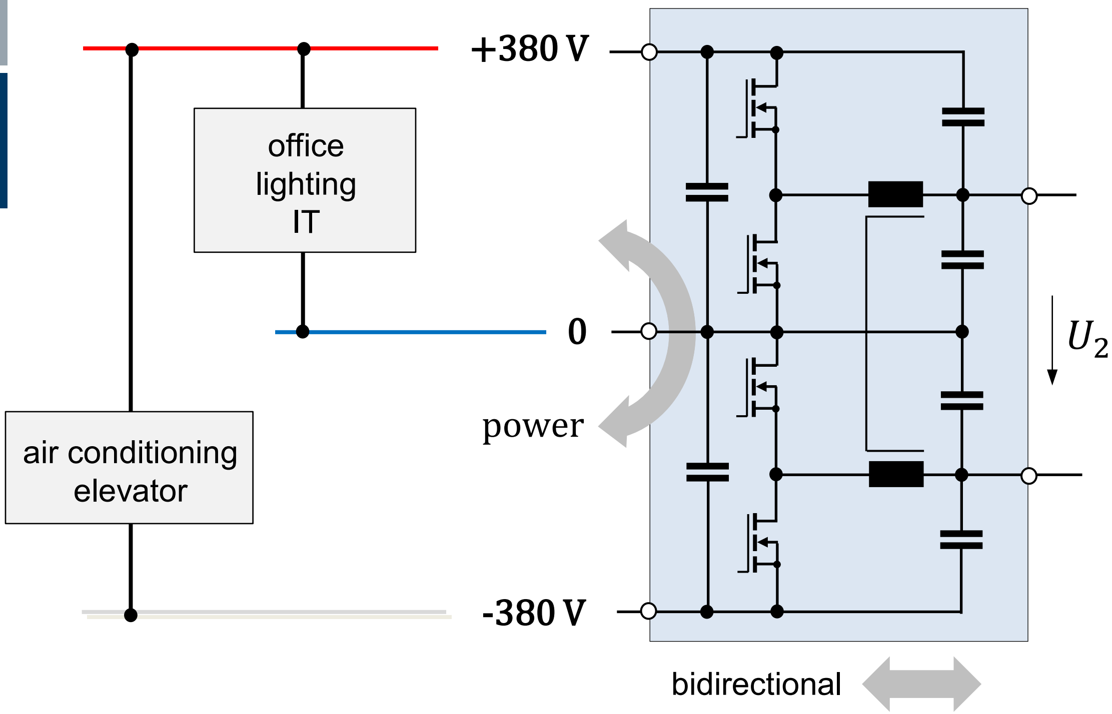
- Inexpensive to implement (only one central unit)
- Flexible configuration, easy fault handling

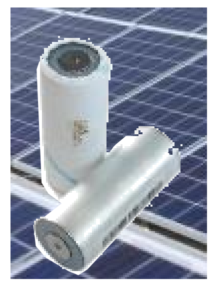
Hints

- The grid manager should be part of the battery system cabinet to avoid unprotected low-impedance feeder lines

A Buck/Boost Topology with Voltage Sharing and Load Balancing Capability

for bipolar DC grids





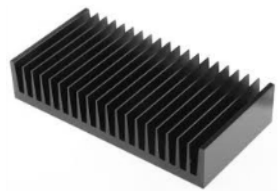
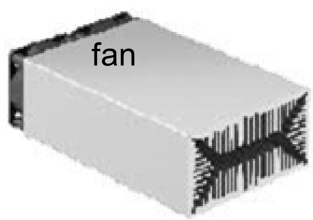
Voltage range U_2: 200…600 V
Max. power (at U_2): 6 kW
Max. balancing power: 2 kW

Air cooling possible thanks to SiC technology

- Active midpoint voltage stabilization
- The coupled inductors allow load balancing between the positive and negative line

Y. Han, M. März, et al.: *High Efficiency Control Method for Non-Isolated Three-Port DC/DC converter*. PCIM Asia 2017; Int. Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, 2017, pp. 1-7.

Efficiency improvement is not an end in itself

converter efficiency	losses	cooling measures
	at **10 kW** output power	
99.5%	50 W	None!
99%	100 W	
98%	200 W	
95%	500 W	

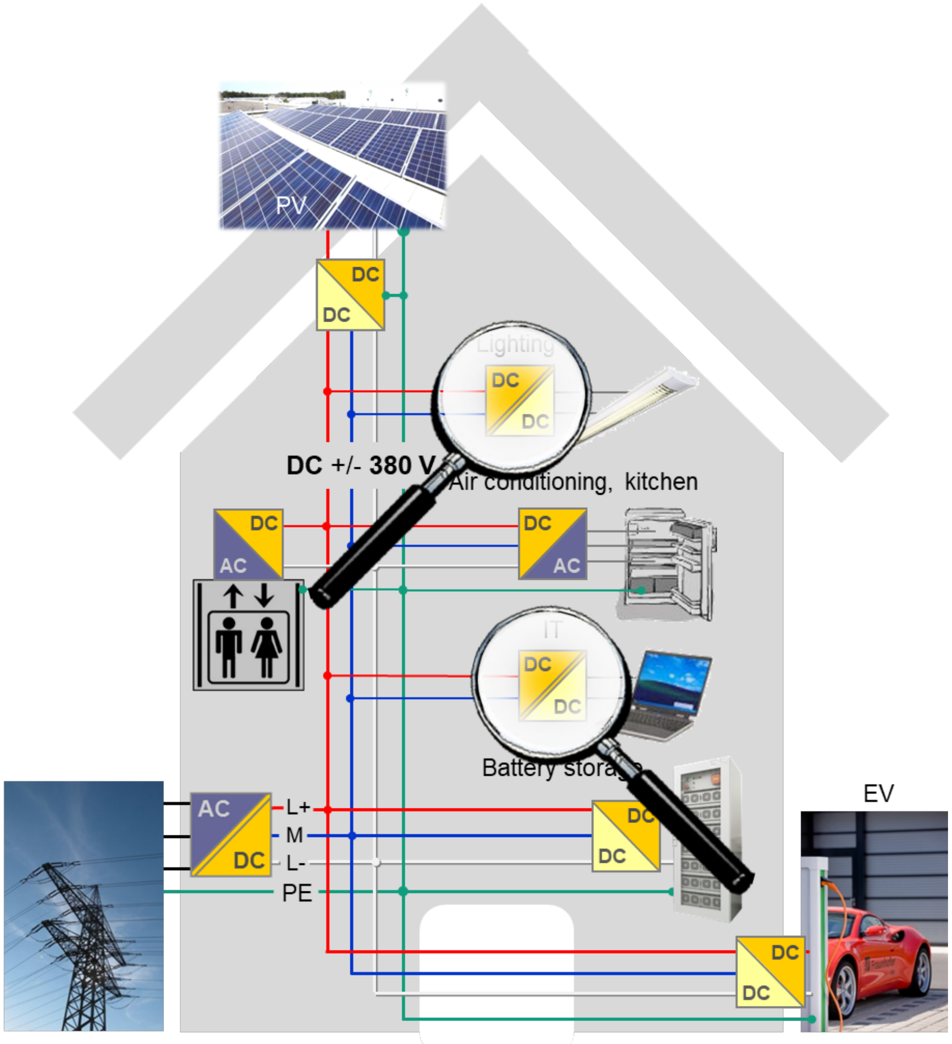
The fight for the last tenth of a percent of efficiency is less a question of energy efficiency at system level - the goal is rather:

- to get rid of all kinds of active cooling measures (especially wear parts like pumps and fans)
- to meet the growing demands for system reliability and service life (operating times from 20 to 40 years are a typically demand in energy infrastructure)
- to reduce the thermal load on the environment (e.g. to enable the integration of power electronics in Li-Ion battery systems)

Full-SiC DC/DC Converter (Buck/Boost)
- Voltage range: 90…800 V / 15 kW
- Volume: 3.05 litre
- Efficiency: up to 99.71 %

➜ Continuous operation at 10 kW output power without any active/forced cooling

At 380 volts and 10 A, it has less loss than this 5 m extension cable!



Isolating

DC/DC Converters

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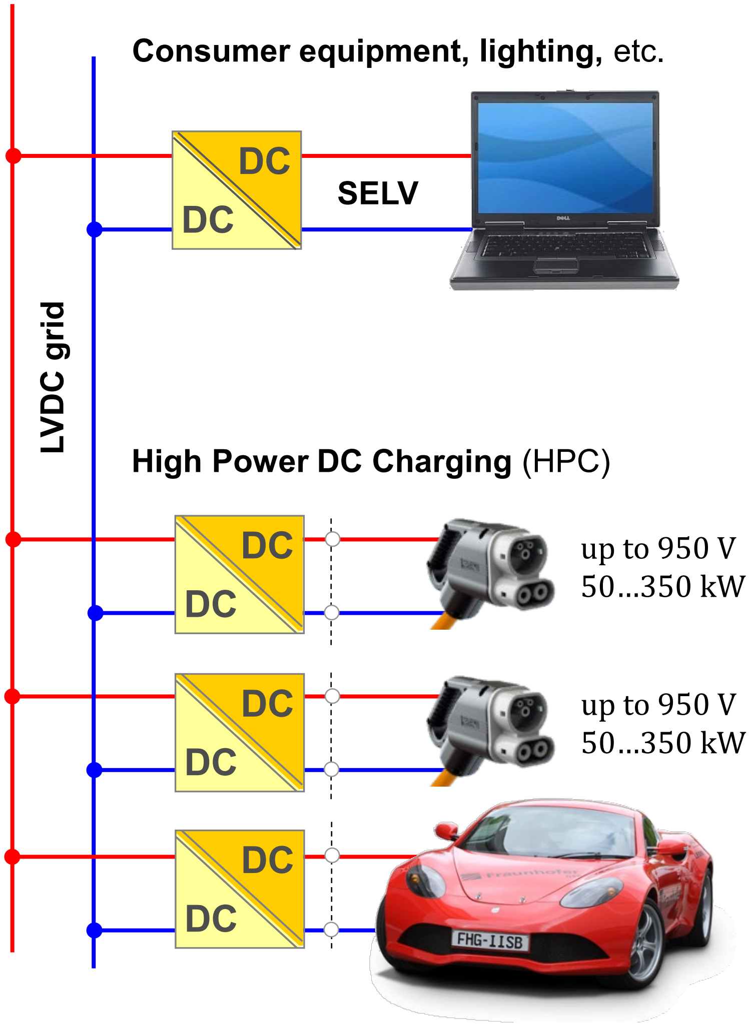
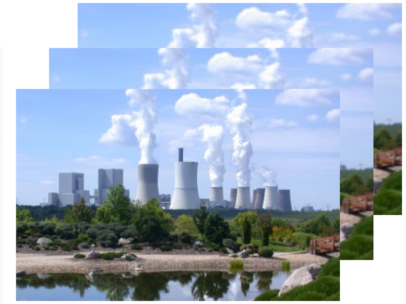


Isolating DC/DC Converters

- provide a (safe) electrical isolation between the input and output terminals (therefore sometimes also referred to as "DC transformer" for short in the following)
- are used to generate a Safe Extra Low Voltage (SELV) to ensure personal protection
- are used to eliminate potential references and break ground loops
- may be required as part of an overall safety concept at system level (high power DC charging points, e.g., must be galvanically isolated from each other)
- switchmode power supplies are traditionally uni-directional, but the number of applications that require bi-directional operation is increasing rapidly
- in contrast to non-isolating DC/DC converters, isolating ones require an inverter, a transformer and a rectifier and are therefore more complex, more expensive and slightly less efficient (typ. 90...95%)

Stand-by Energy Consumption

Stand-by losses of electrical appliances (EU total)[1)]	51 TWh/a
Electricity generation in Germany	650 TWh/a
Electricity requirement for all car traffic in Germany with electric cars	120 TWh/a



A minimum stand-by power consumption and high part-load efficiency are of particular importance for devices installed in infrastructure, as these are connected to the grid 24 hours a day, 365 days a year and cannot simply be switched off completely with a switch when not in use.

EU directive 1275/2008/EG (household and office equipment)

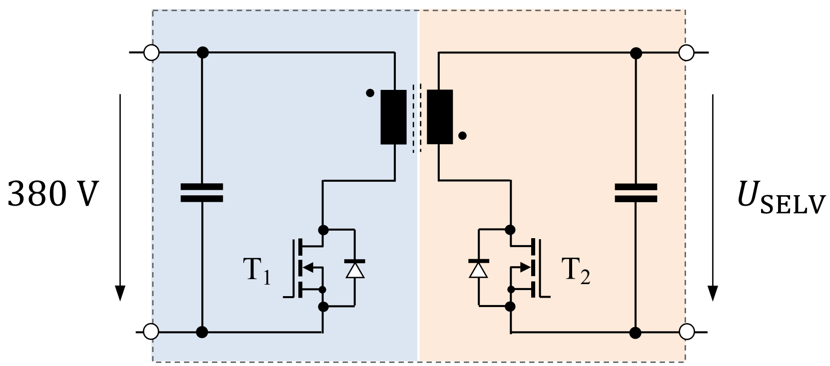
Nominal power	Stand-by	Stand-by with display function
0 bis < 50 W	0,3 W	1 W
≥ 50 W bis < 250 W	0,5 W	1 W

Energy costs
10 W ⇨ 87,6 kWh/a ⇨ 30 Euro/a[2)]
⇨ 32 kg CO_2/a

1) Source: Umweltbundesamt; Bildquellen: ANKAWÜ (D-SN-Boxberg_-_Kraftwerk_Boxberg.jpg); asianetindia.com (Steckerleiste); 2) Electricity price basis: 0,35 €/kWh

Common Low Power Topologies

Flyback Converter



P < 150 W

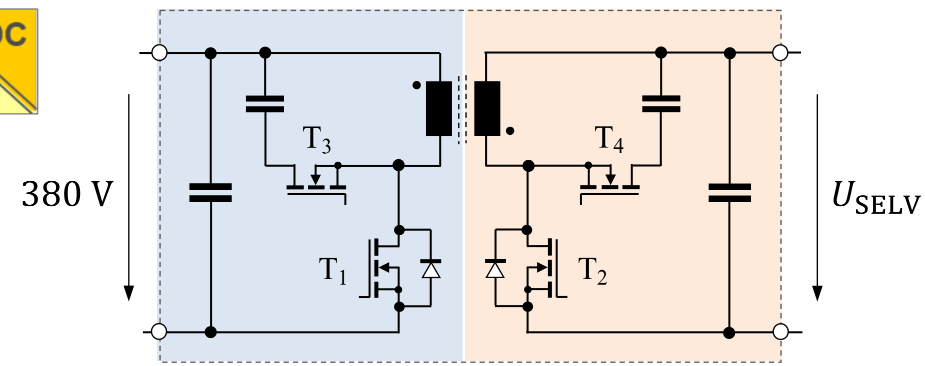
Advantages

- lowest component count (lowest cost)
- easy control and gate drive
- easy to realize bidirectionally
- intrinsic current source behavior (DCM)

Disadvantages

- very high voltage and peak current stress
- well coupled transformer is essential

Active Clamped Flyback



100 W < P < 400 W

Advantages

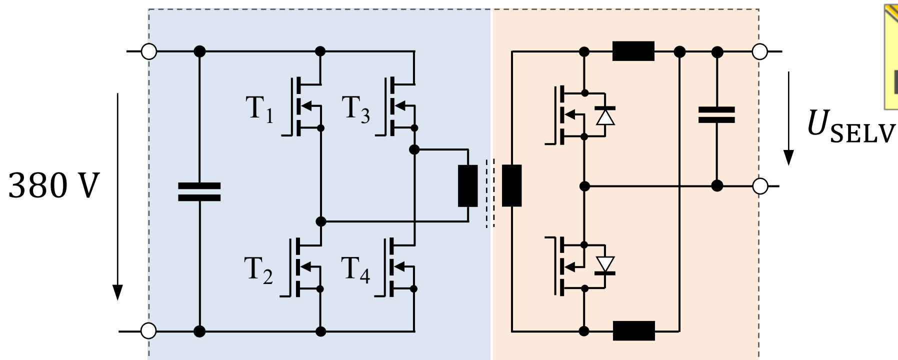
- low component count
- low switching losses, good EMC properties (ZVS)
- improved transformer utilization
- bi-directional operation with reasonable effort

Disadvantages

- high voltage and current stress (T_1 ... T_4)
- highside gate drivers required

Common Medium and High Power Topologies

Phase-shift Converter



P > 400 W

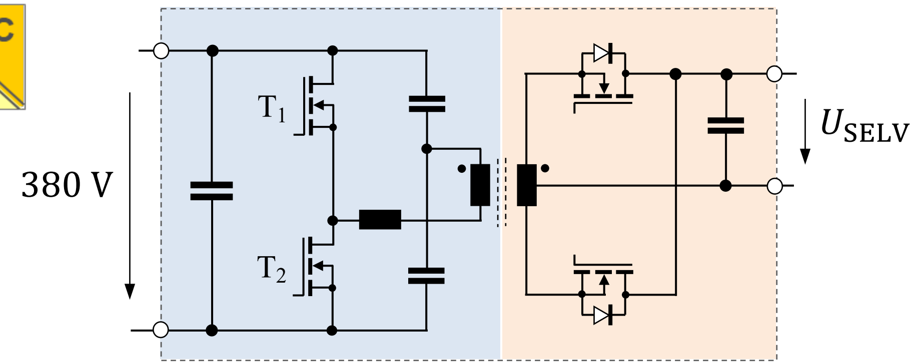
Advantages

- low switching losses, good EMC properties (ZVS)
- low voltage and current stress (MOSFET)
- high efficiency

Disadvantages

- basically unidirectional
- no "intrinsic" transformer flux balancing

LLC Resonant Converter



Power range: W to MW

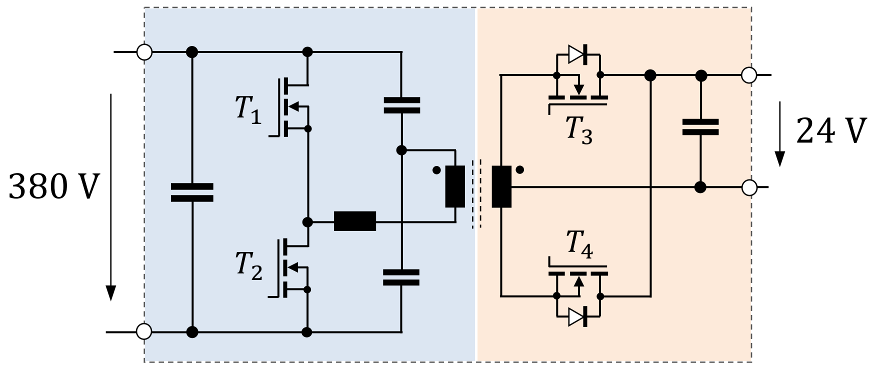
Advantages

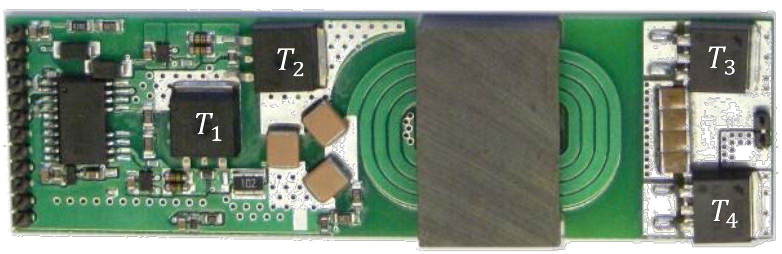
- very low switching losses (ZVS)
- circuit parasites can be advantageously integrated
- good EMC behavior but variable switching frequency

Disadvantages

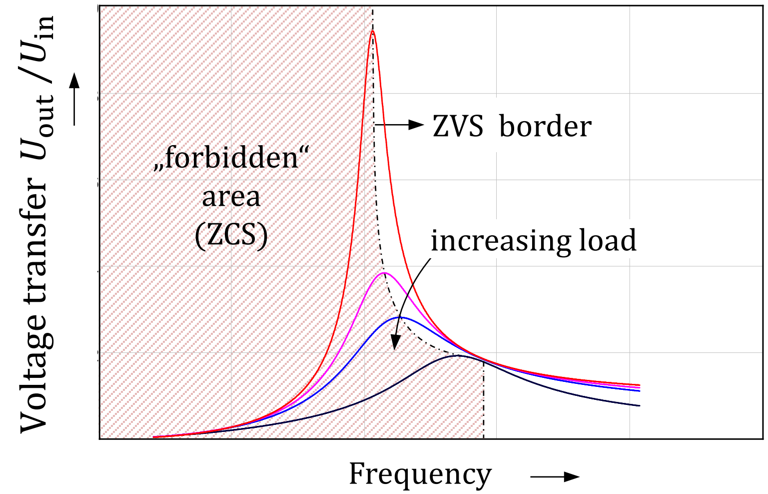
- low part load efficiency
- limited output voltage setting range

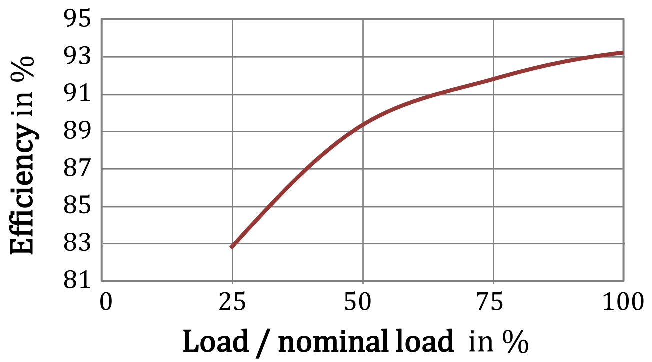
LLC Resonant Converter

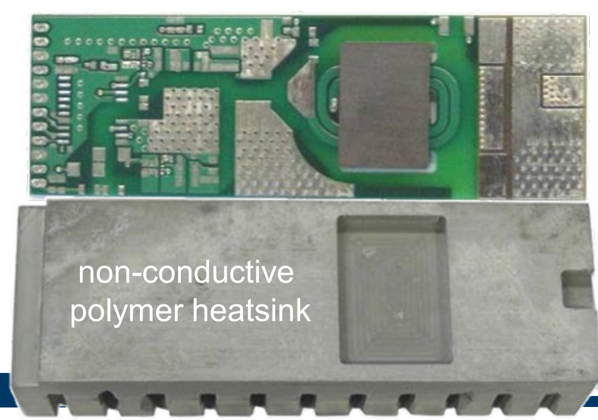




Output control via switching frequency







Technical data

- Input voltage (max.): 450 V
- Output voltage: 24 V
- Output power: **250 W**
- Efficiency: **93%**
- Switching frequency: **0,7…1,3 MHz**

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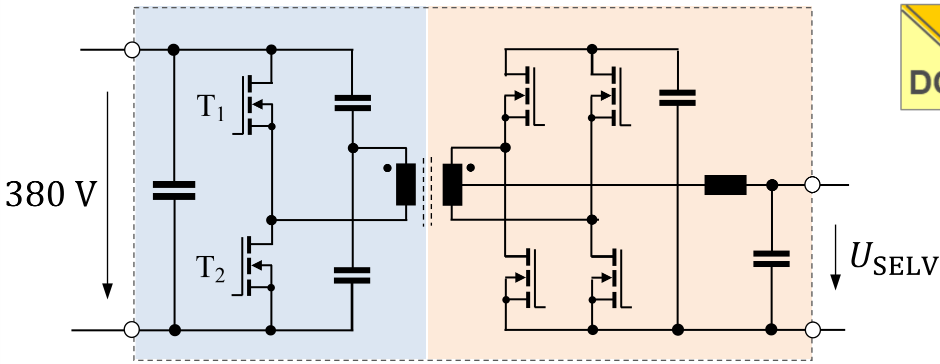
Bidirectional Topologies – two of a multitude of possible

Half-bridge with Current-fed Push/Pull



P > 150 W

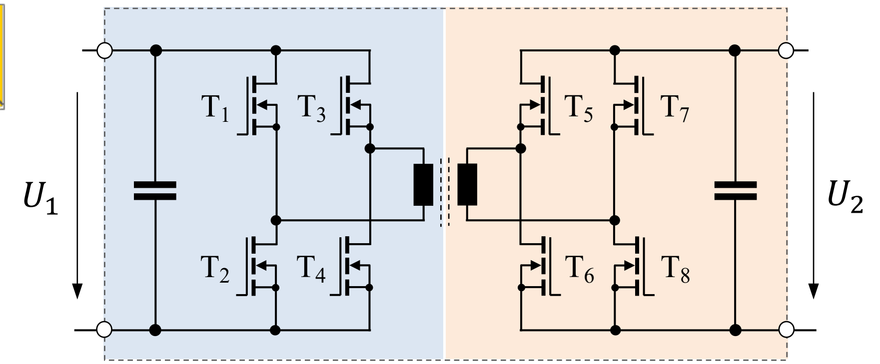
Advantages

- bidirectional wide voltage range
- low switching losses
- relatively low voltage and current stress
- intrinsic magnetic flux balancing

Disadvantages

- increased number of active and passive components
- tapped transformer required

Dual Active Bridge (DAB)



P > 400 W (up to MW)

Advantages

- fully bidirectional
- low number of passive components

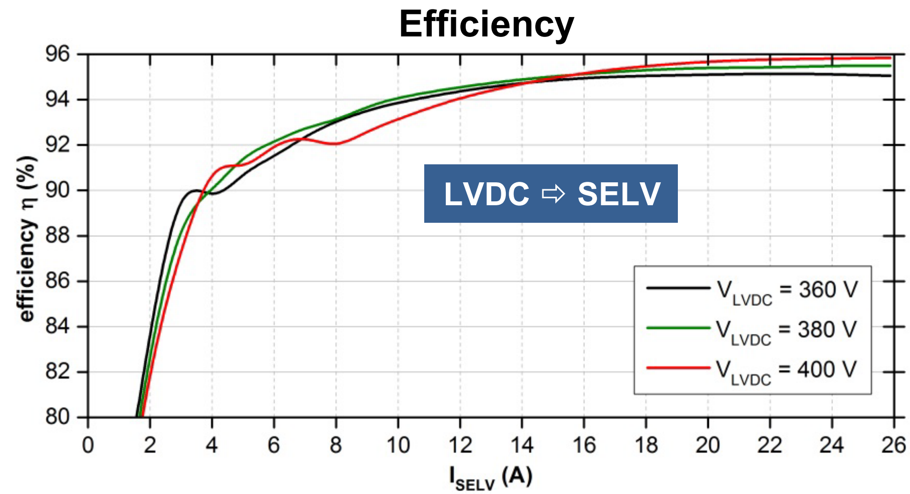
Disadvantages

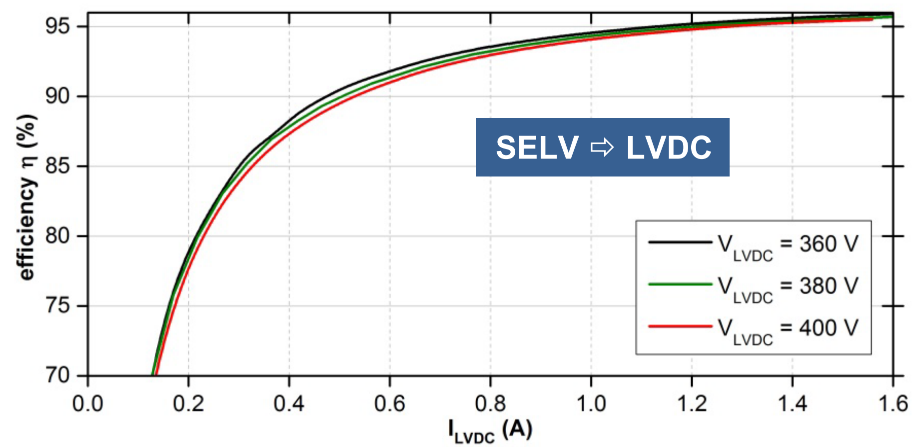
- limited performance in bidirectional operation with a wide input and output voltage range
- high number of active components
- complex control to exploit the whole topology potential

Bidirectional Coupling of a SELV and LVDC Grid

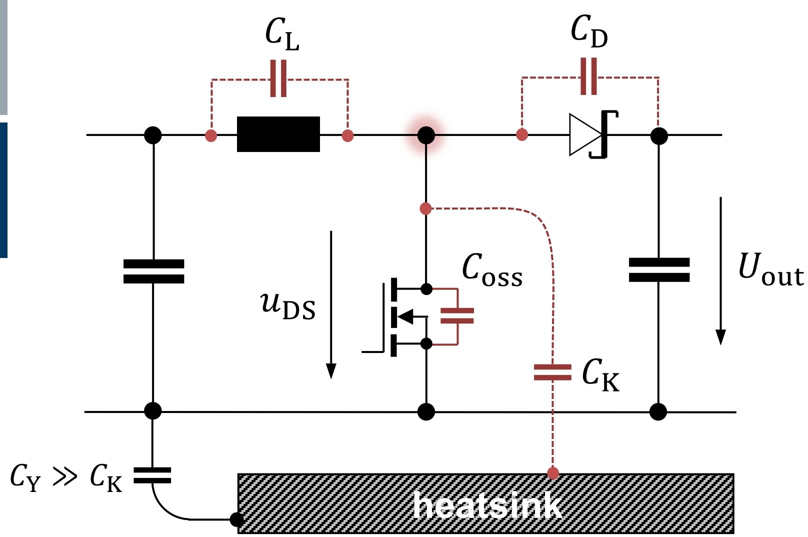
Topology
Half bridge (HV side) with current-fed push/pull (SELV side)

Technical data	
Input voltage range	360 V to 400 V
Output voltage	24 V or 48 V
Power (max.)	600 W
Efficiency	up to 96 %
Dimensions in mm	188 x 75 x 30





Degradation of Partial Load Efficiency Caused by Parasitic Capacitances



Numerical example	
Inductor winding capacitance C_L	$200\ \mathrm{pF}$
MOSFET output capacitance $C_{oss,eff}$	$90\ \mathrm{pF}$
Schottky diode junction capacitance $C_{D,eff}$	$50\ \mathrm{pF}$
Coupling capacitance to the heatsink C_K	$40\ \mathrm{pF}$
Total capacitive load C_{ges}	$380\ \mathrm{pF}$

↳ seen from the switched node, all these capacitances are connected in parallel!

The periodic discharging of the parasitic capacitances results in turn-on losses in the MOSFET

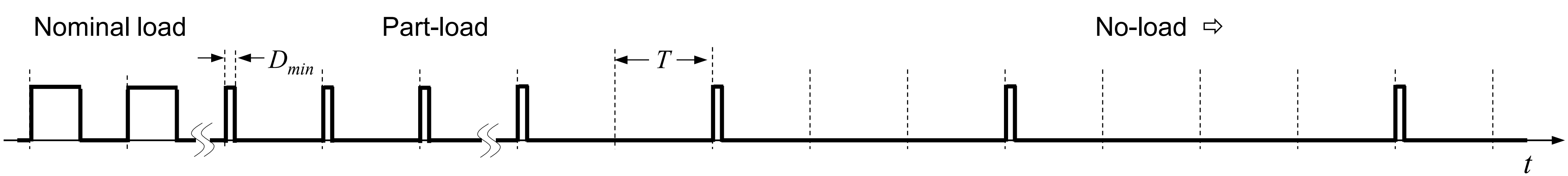
given by: $$P_{v,on} = \frac{1}{2} C_{ges}\, u_{DS,on}^2\, f_{sw} = \frac{1}{2} \cdot 380\ \mathrm{pF} \cdot (380\ \mathrm{V})^2 \cdot 250\ \mathrm{kHz} = 7\ \mathrm{W}$$

↳ Even at zero milliamps of output current almost 7 watts of "standby" power losses are produced!

Measures to Optimize Part-load Efficiency

- Minimizing the switching and gate-drive losses by:
  - using power semiconductors with better dynamic properties and lower capacitances (MOSFET, SiC, GaN,..)
  - using low-loss soft switching operations like ZVS, QR (quasi resonant), ZCS, etc.
  - reducing the number of switching processes with decreasing load (pulse skipping, raising off-time, ...)
  - minimizing the capacitive loading of hard-switched circuit nodes (e.g. by minimizing winding capacitances and parasitic layout capacitances)
  - switching off individual sub-converters in multiphase (interleaved) converters under part load
  - switching off the synchronous rectifier in low-load operation (saving gate drive power))
- Use of converter topologies with low reactive power
- Minimizing losses in passive components (e.g. core and winding losses in magnetic components)

Pulse Skipping



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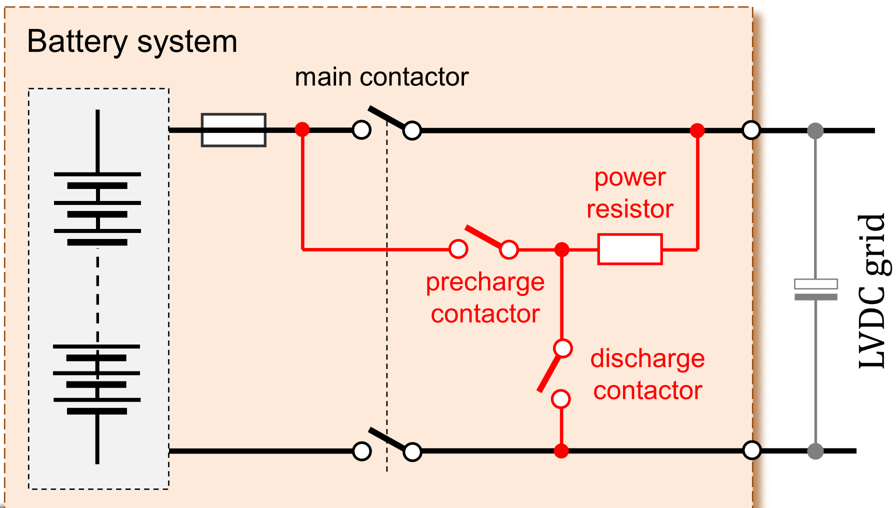
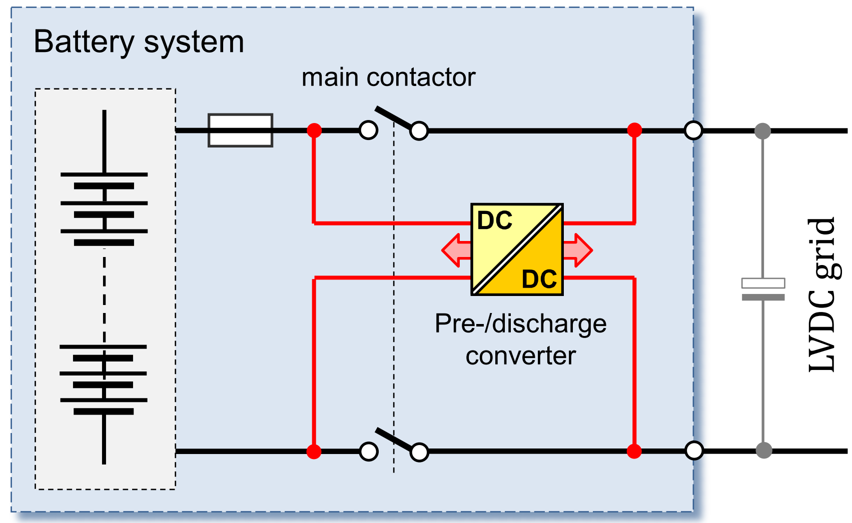
Pre-charging/discharging of Grid Sections or DC Links

a basic functionality in all DC grids

Traditional Solution



Modern Smart Solution



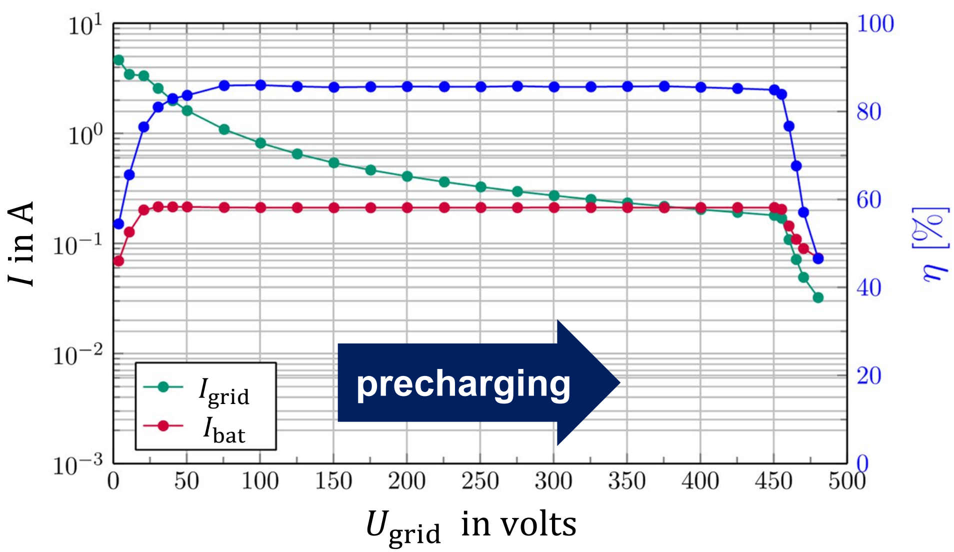
Bridging the main contactor requires a DC/DC converter with safe electrical isolation!

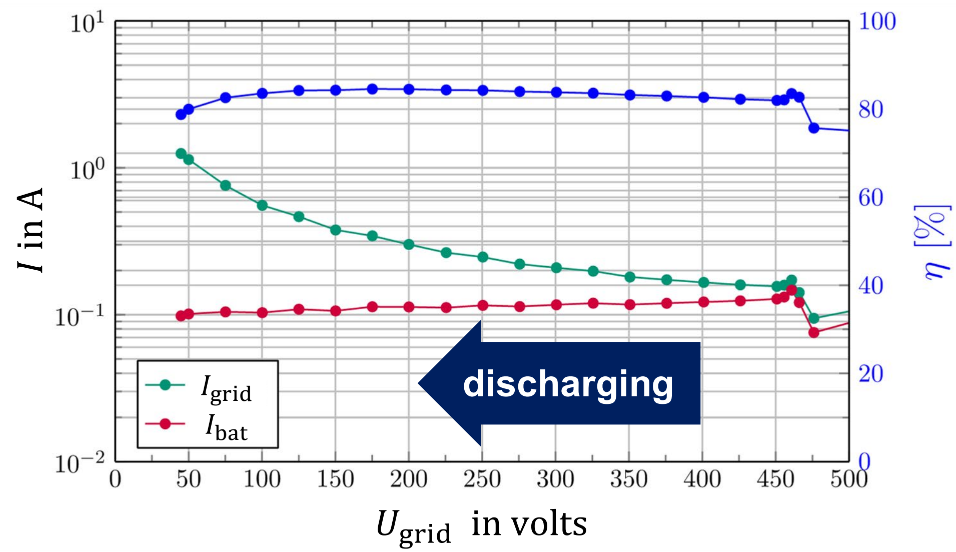
The replacement of electromechanical components with intelligent power electronics allows a significant reduction in volume, weight and costs

Pre-/discharge Converter - an implementation example

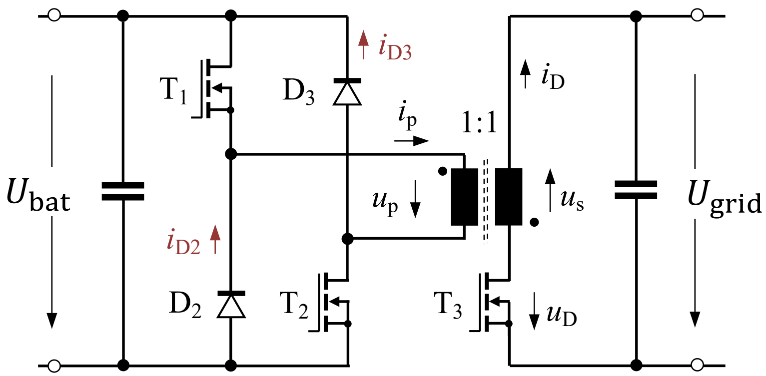
Technical data

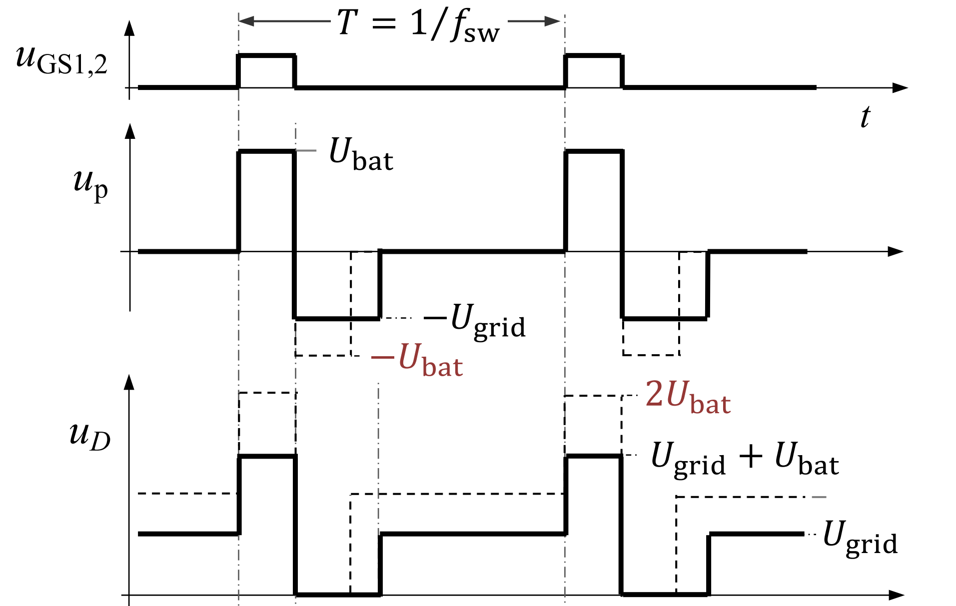
- Flyback principle (galvanically isolating, bidirectional)
- Quiescent current consumption: less than $1\ \mu A$
- Voltage range: up to $450\ V$
- Pre-/discharge power: $50\ W$ (i.e., charging $1000\ \mu F$ in $2\ s$ to $450\ V$)
- High level of functional safety



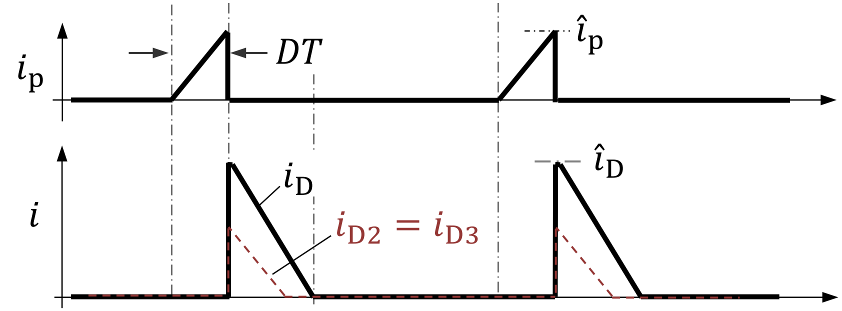


Pre-/discharge Converter

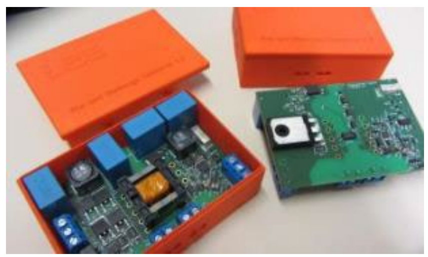




Waveforms for $U_{grid} < U_{bat}$ (black) and $U_{grid} \gtrsim U_{bat}$ (magenta):



Dual-switch Flyback

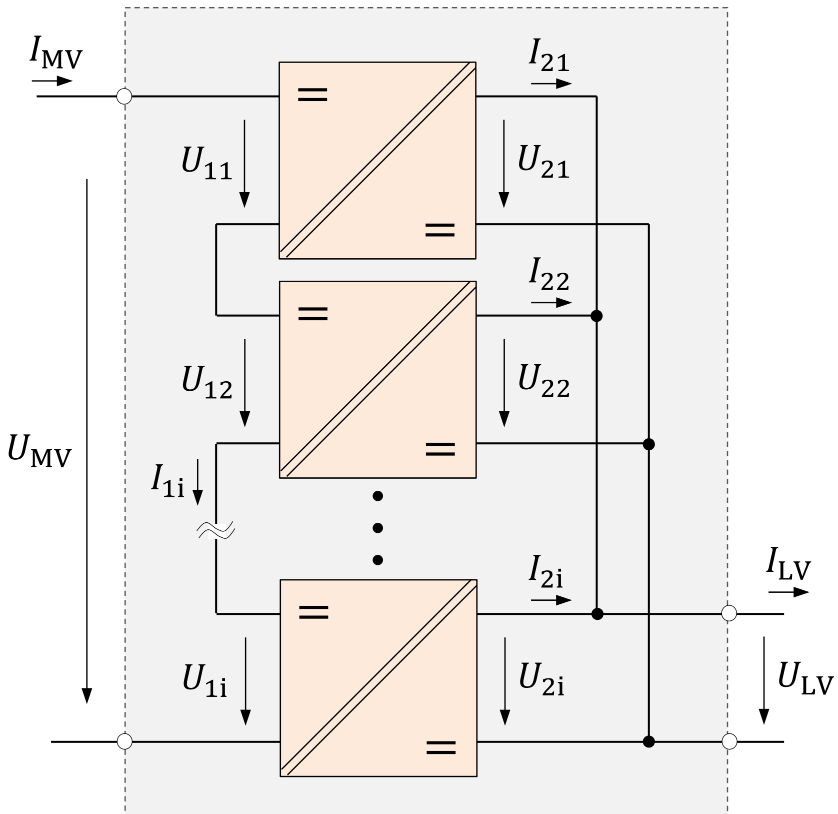


- Moderate voltage stress for the battery-side power semiconductors
- Fully bidirectional
- Intrinsic current source behavior (advantageous for charging capacitors)
- Intrinsic limitation of the grid-side voltage during pre-charging through the battery-side diode diagonal

M. Hoffmann, M. März: "A Pre- and Discharge Unit for Capacitive DC-Links Based on a Dual-Switch Bidirectional Flyback Converter“, *24th European Conference on Power Electronics and Applications (EPE'22 ECCE Europe)*, Hanover, Germany, 2022, pp. 1-10.

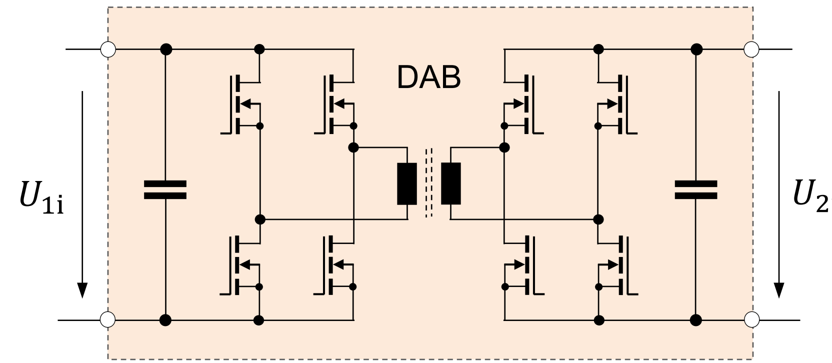
»DC Transformer« for Connecting a MV and LV DC Grid

Input Serial Output Parallel (ISOP) configuration



$U_{MV} = \sum U_{1i}$ $\quad I_{1i} = I_{MV}$ $\quad U_{2i} = U_{LV}$ $\quad I_{LV} = \sum I_{2i}$

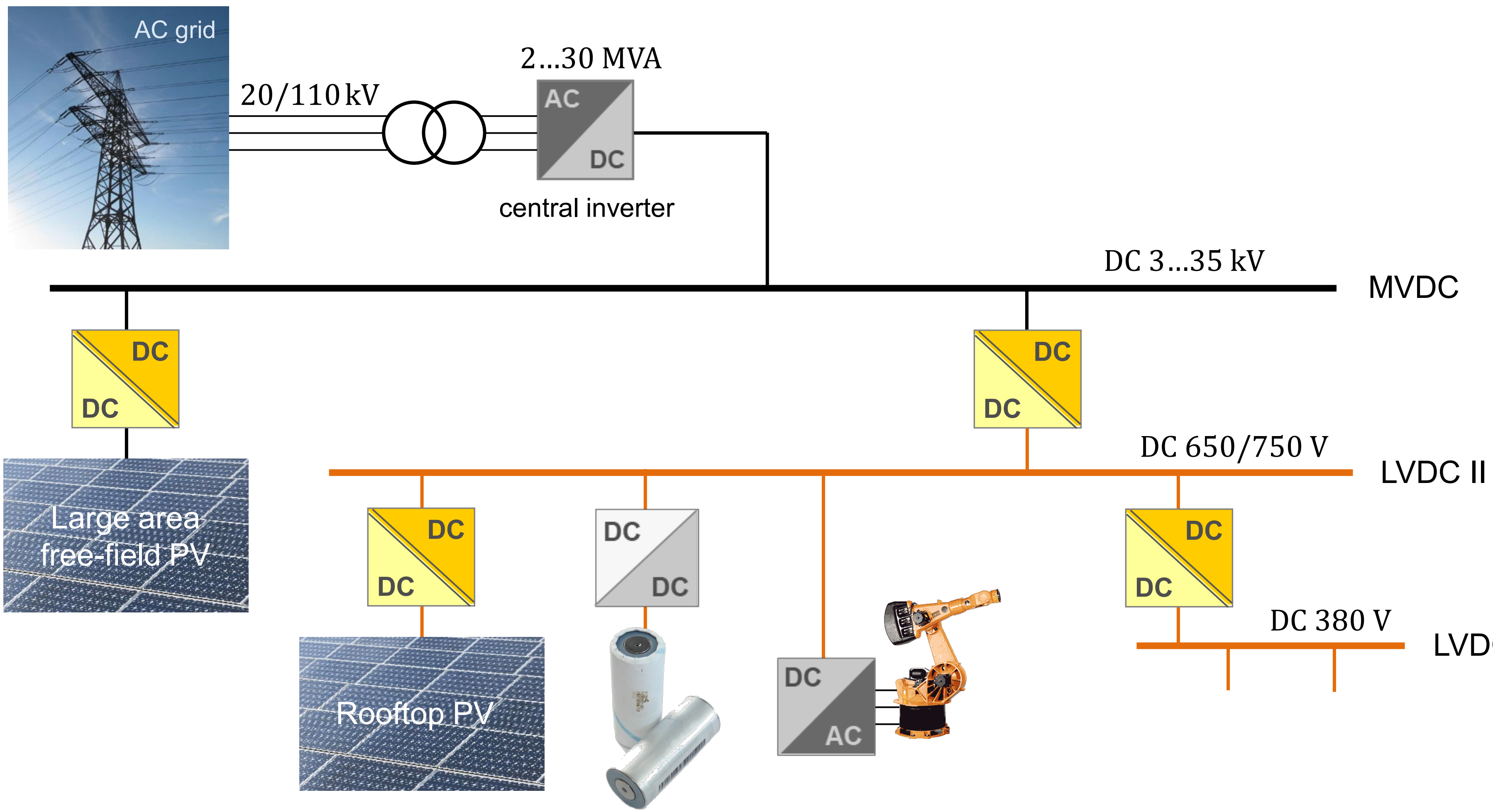
A possible isolating DC/DC converter cell



Features and challenges

- The series connection of individual converters allows operation at high voltages without having to use exotic very high-blocking power semiconductors
- A challenge is the equalization of the voltages U_{1i} to avoid destructive consequences for the converters
- There are also major challenges with regard to the electrical insulation within the transformer and of the power semiconductors against the heat sinks

Possible DC Grid Structure of a Medium-sized Industrial Plant



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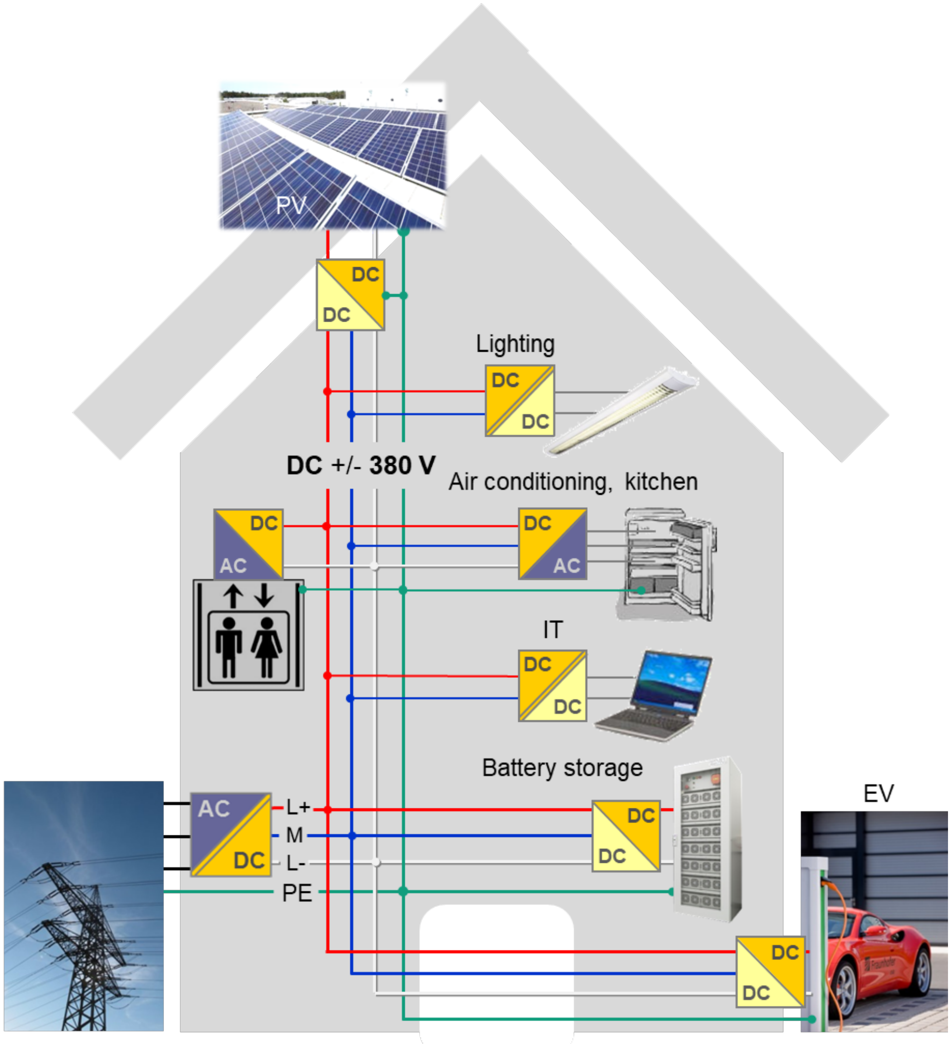
Supplying SELV Appliances from an LVDC Grid

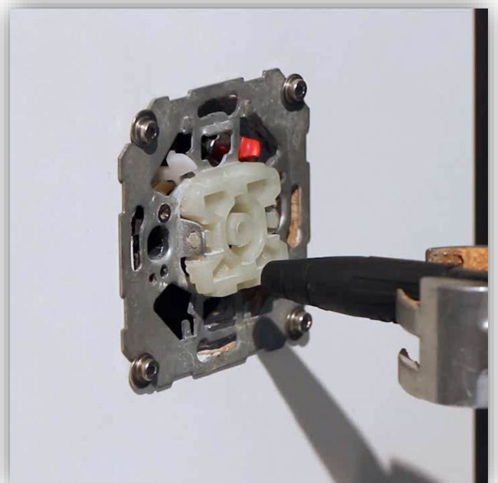
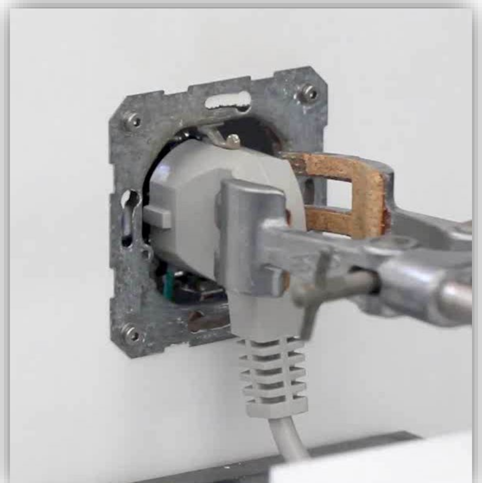
Vehicle Power Supply

- Wide input voltage range: 450 V to **800 V**
- **5 kW** continuous output power
- Output voltage: 24 V or 48 V
- Efficiency up to **94,8 %**
- Volume: **1 Liter** (5 kW/liter)
- Switching frequency: 200 kHz
- **Cost effective** full silicon design (no SiC or GaN)



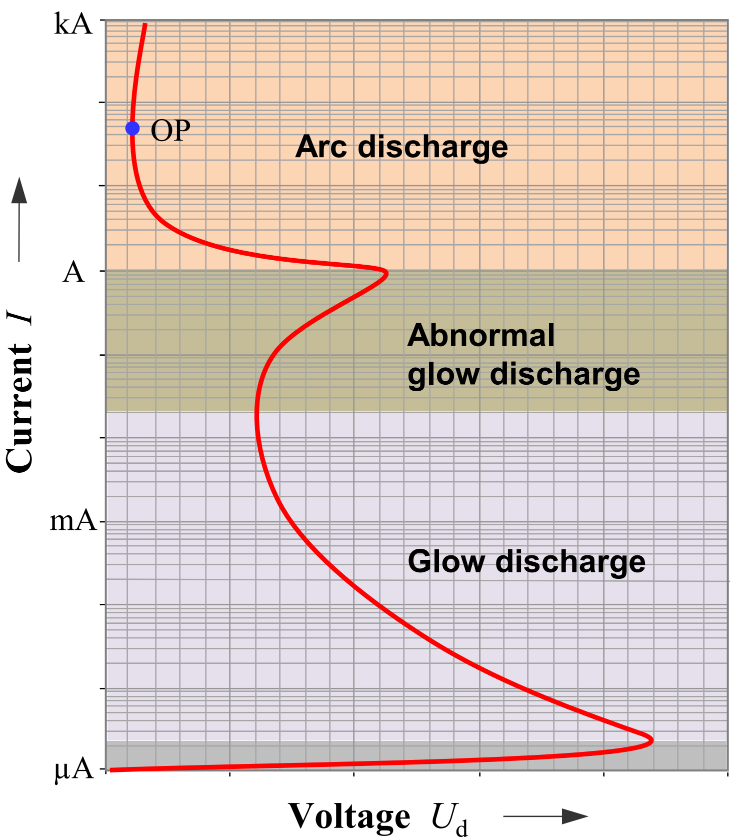
Switches, Plugs and Protection Devices

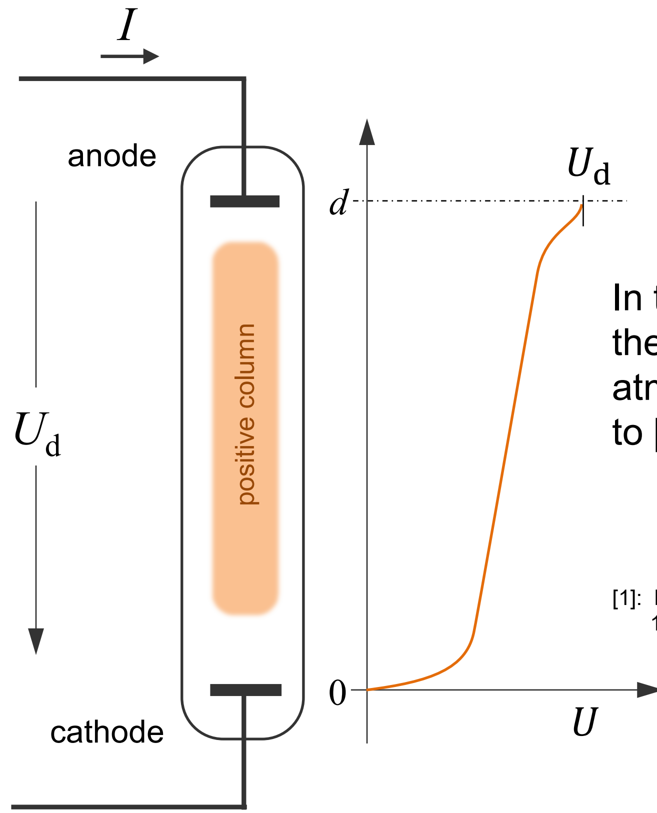
Mechanical Breaker - a special challenge in DC-grids

AC Switch	AC Wall Plug	AC Circuit Breaker
		
DC 380 V / 10 A	**DC 380 V / 10 A**	**DC 380 V / 10 A**

Never abuse AC components for operation under DC voltage!

Gas Discharges





In the arc discharge area (OP) the operating voltage in air under atmospheric pressure is according to [1] approximately:

$$U_\mathrm{d} = 40\ \mathrm{V} + 10\,\frac{\mathrm{V}}{\mathrm{cm}} \cdot d$$

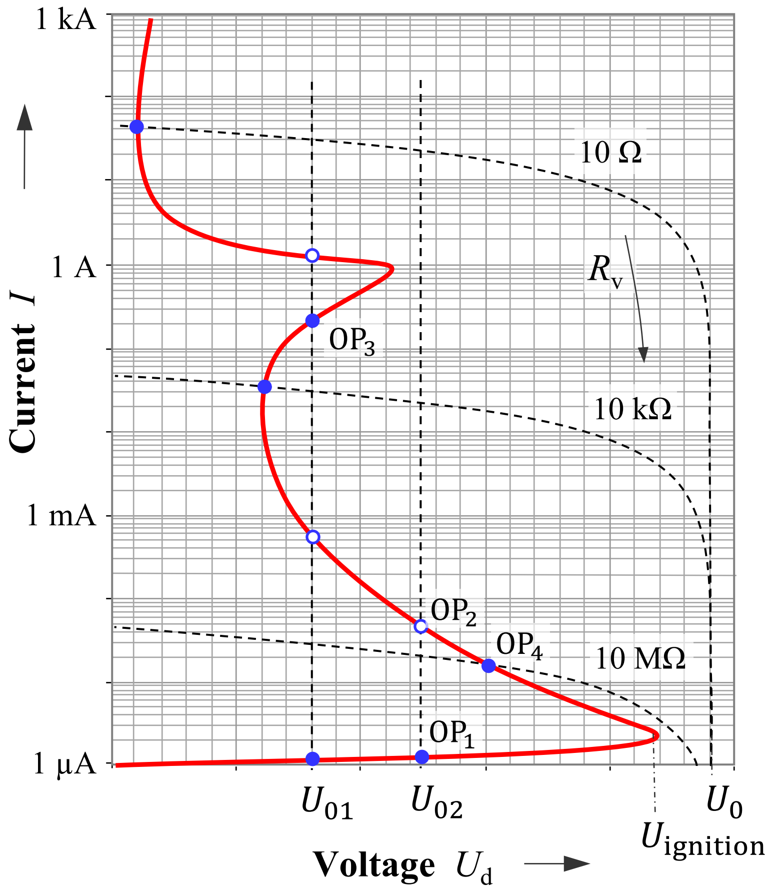
[1]: Kiefer G.: VDE 0100 und die Praxis. VDE Verlag, 10. Auflage , S. 649

Stable glow discharges are hardly to obtain under atmospheric pressure (except Corona discharges)!

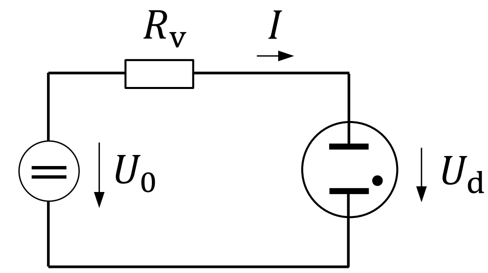
x-axis more precisely[1)]: $\frac{E}{p} \propto U_\mathrm{d}\big|_{p \cdot d = \mathrm{const.}}$

1) E = electric field strength; p = gas pressure

Gas Discharges



- ● : Stable operating points (OP)
- ○ : Unstable operating points



$$U_d = U_0 - R_v \cdot I$$

Properties

- Operating points in areas of the discharge characteristic with a negative differential resistance are only possible if the discharge is operated on a current source – or using a voltage source with a series resistor whose value is greater than the differential resistance of the discharge in the operating point (see OP_4)
- Example left: if a voltage U_{02} was applied to the electrodes, no discharge would occur (OP_1). However, if an ignition were to occur (due to external influences), the discharge would immediately turn into an arc discharge (since OP_2 is unstable).
  With a voltage U_{01}, on the other hand, the discharge would "hang" in the area of the abnormal glow discharge (since OP_3 is stable).

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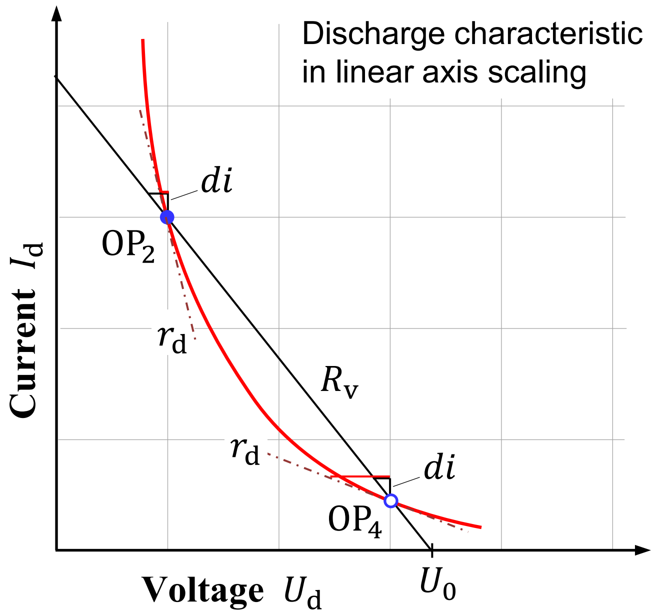
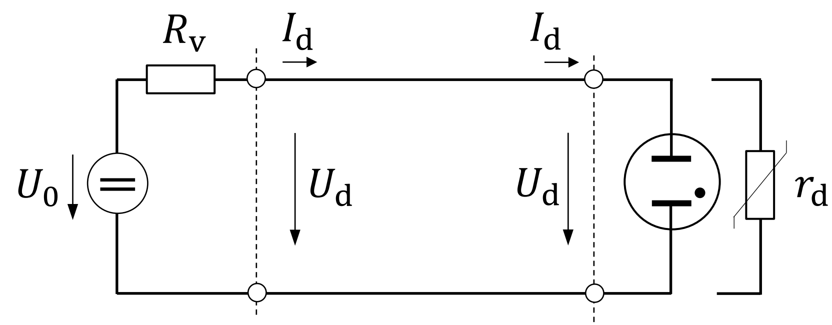
Gas Discharges

What distinguishes stable from unstable operating points?



In OP_4, a differential increase in the current reduces the burning voltage of the discharge more than the additional voltage drop at the ballast resistance R_v can compensate ⇨ the current continues to rise and the discharge runs into the stable operating point OP_2.



The internal resistance R_v of the source is **positive**, despite the falling current-voltage characteristic, because it holds:

$$U_d = U_0 - R_v \cdot I_d$$

⇨ **Source arrow system**

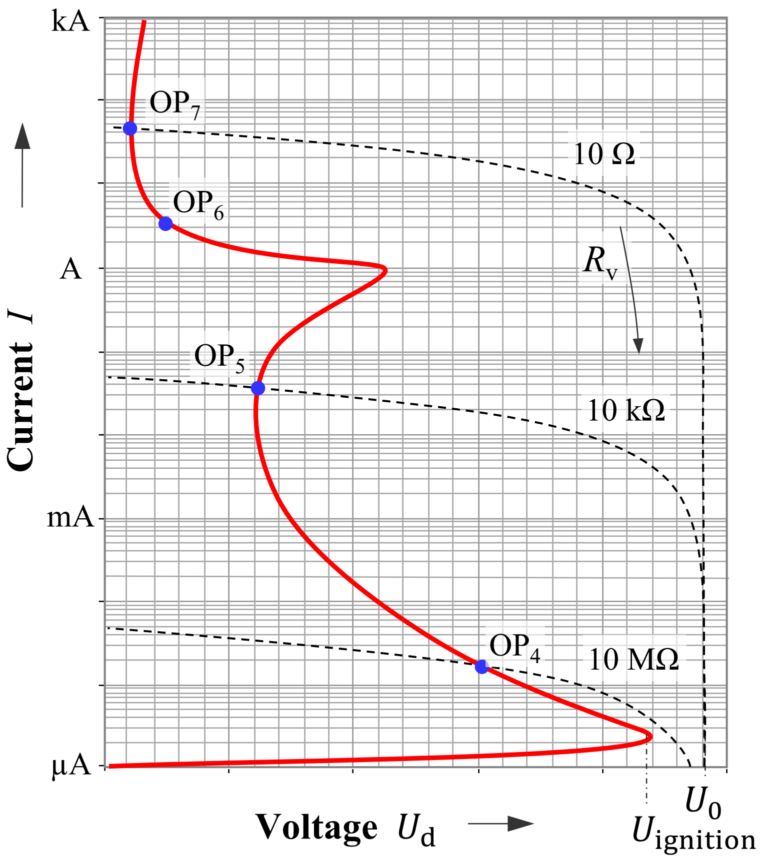
The differential resistance r_d of the gas discharge, on the other hand, is **negative** at the operating points AP_2 and AP_4

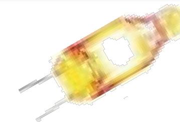
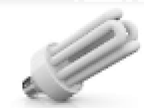
⇨ **Consumer arrow system**

If $r_d < -R_v$ holds, a gas discharge can stimulate oscillations!

$$I_d = \frac{U_0}{R_v + r_d}$$

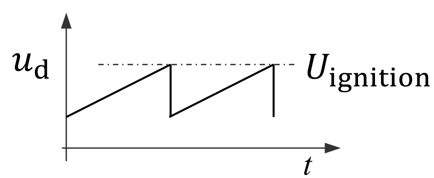
Gas Discharges

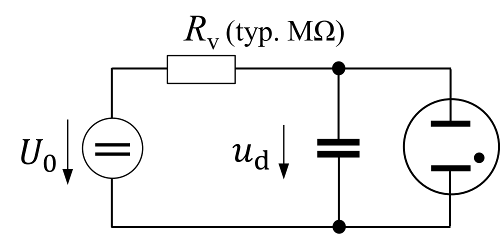


OP	Discharge form	Application
OP4	Glow discharge	▪ Glow indicators ▪ Phase checker 
OP5	Glow discharge	▪ Fluorescent tubes ▪ CO_2 or HeNe laser 
OP6	Arc discharge	▪ Xe headlights ▪ Beamer 
OP7	Arc discharge	▪ Arcing faults ▪ Arc welding

In characteristic curve areas with a negative differential resistance, gas discharges are able to stimulate oscillations!

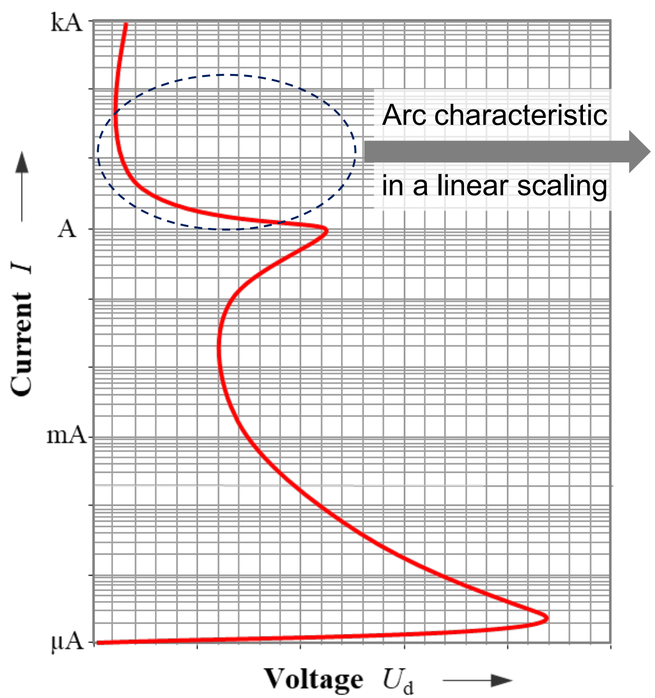
Example: **Sawtooth generator**

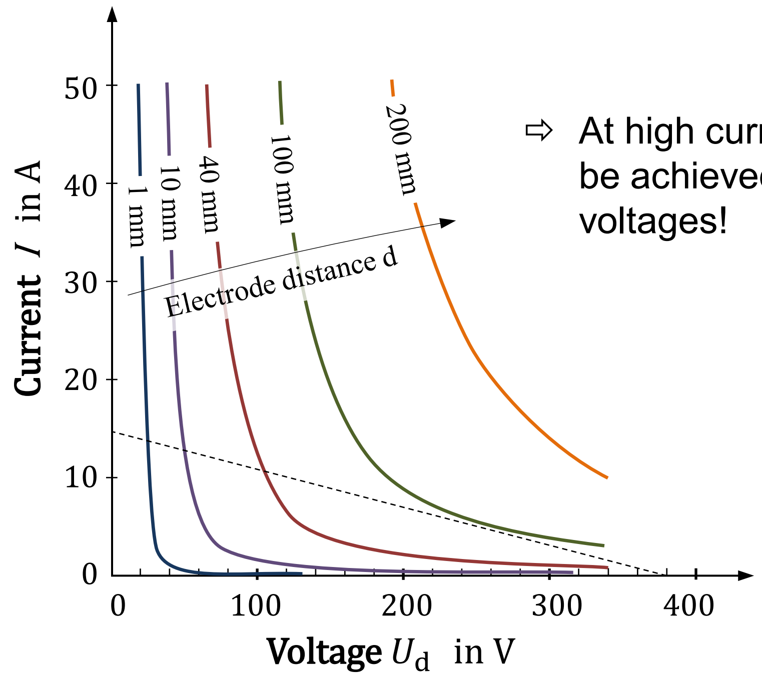




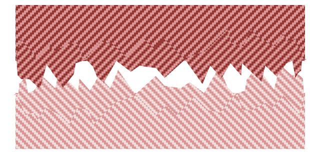
While series inductances tend to stabilize (current source characteristic), even the smallest parallel capacitances can lead to oscillations!

Arcs over Opening Contacts

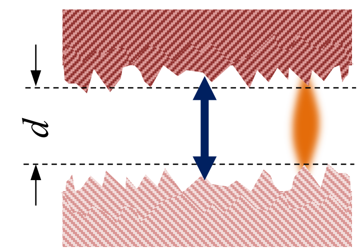




Contact closed



⇨ At high currents, very long arc lengths can be achieved even with relatively low voltages!



Opening contacts
⇨ Ignition in the arc area of the discharge characteristic

Cu electrodes, air under ambient pressure, DC voltage
According to C. E. Sölver, *Electric Arcs and Arc Interruption*. Götenburg, Sweden: Chalmers Univ. Technol., 2006, EEK 195 High Voltage Technology, Lecture 7.

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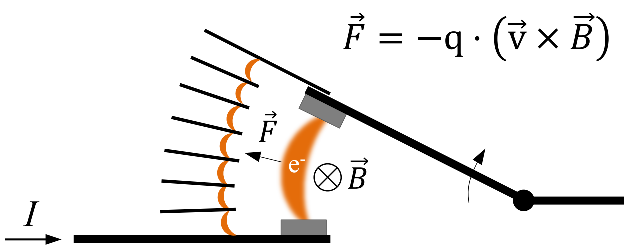
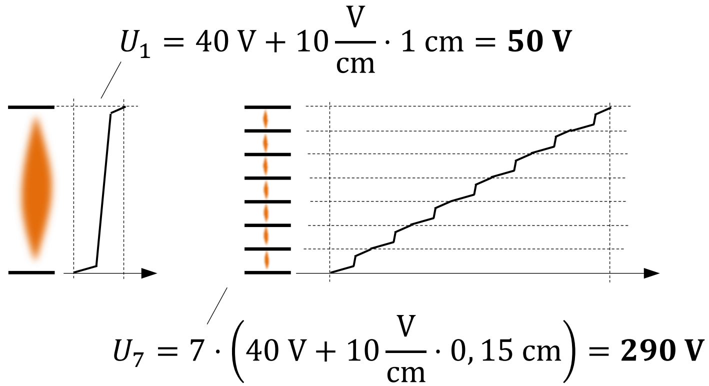
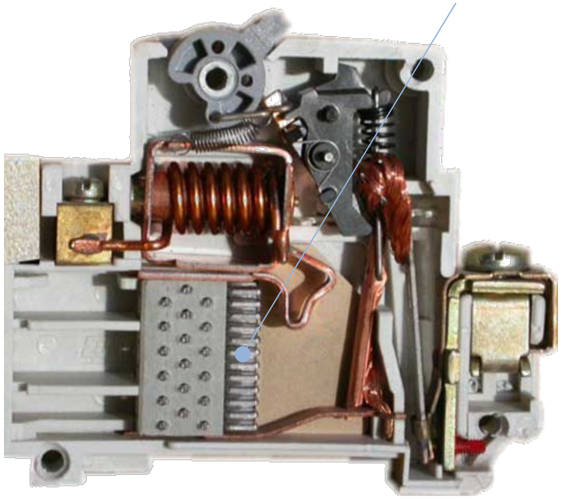
Blow Magnets and Extinguishing Chambers

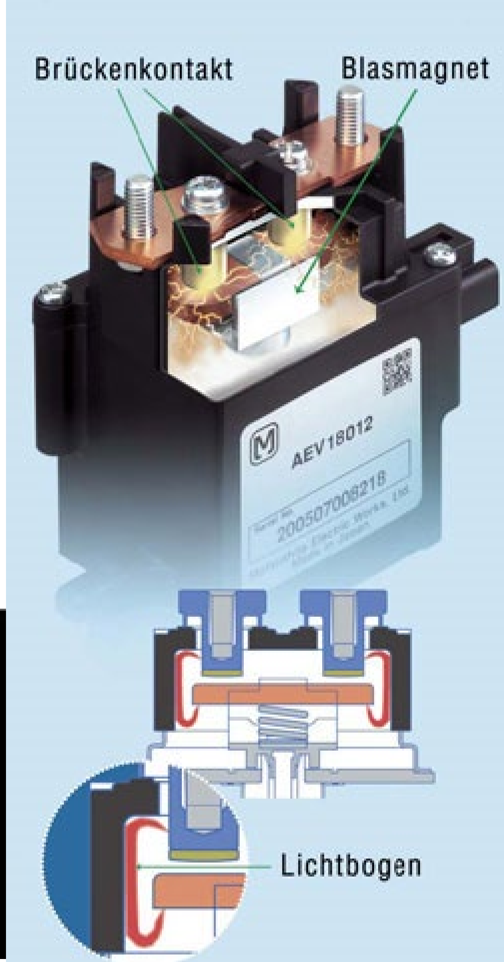


The $\vec{B}$-field of the blow magnet drives the arc into the arc splitter plates

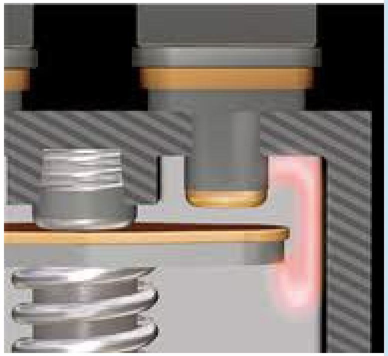


A separation into many individual arcs increases the total arc voltage and supports the arc extinction through a cooling effect





CAUTION
Observe the often prescribed current flow direction when applying DC contactors!



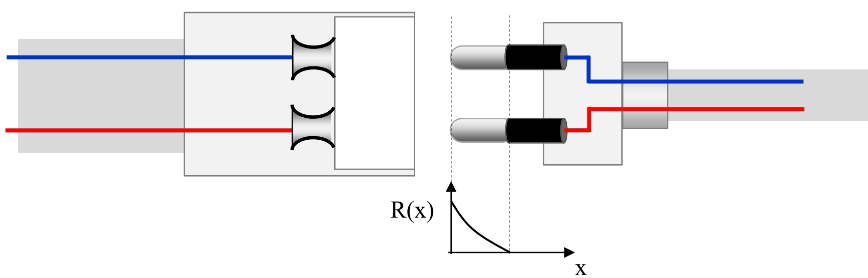
Source: Panasonic

LVDC Rated Conventional Plugs

Picture source: Safe-D-Grid® 400 from Anderson Power Products (APP)

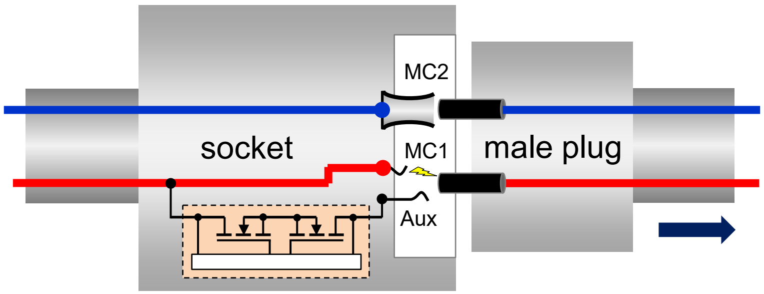
- LVDC specified connectors can be realized conventionally, when only a limited number of mating cycles is required
- Important in this case: Material selection, contact design and pull-off force characteristic
- Example: Safe-D-Grid® 400 from APP (specified for 250 mating cycles under full load (30 A @ 400 V DC)

Resistive Contact Tips



- Resistive contact tips (e.g. made of SiC ceramics)
- Automatic pre-charging functionality for capacitive loads when plugged in
- Potential problems with constant power loads (e.g. switchmode power supplies)
- The error case "incomplete plugging" must be caught in a suitable manner

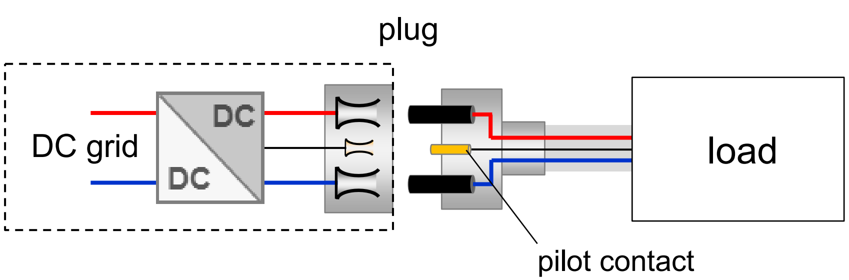
Hybrid Connector



According to ideas from
DE102 25 259 B3 (SMA), DE20 2009 004 198 U1 (E-T-A) and JP 5862818B1

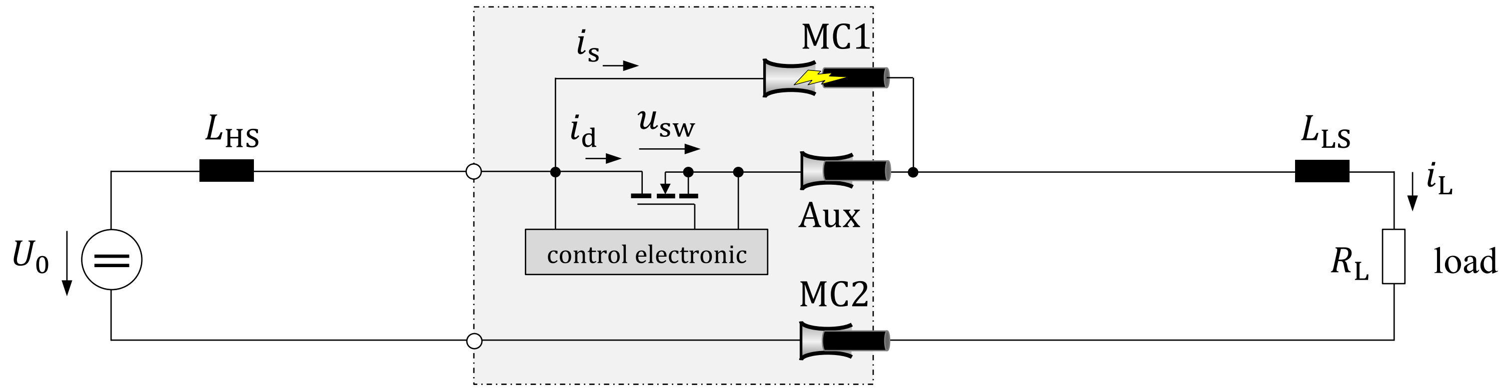
- Functional principle: MC1 opens first. The voltage across the emerging arc allows the semiconductor switch to be turned-on, resulting in an immediate arc re-extinction. The semiconductor switch then interrupts the load current arc-free before the two contacts MC2 and Aux open.
- No auxiliary supply necessary, because of self-powering from the arc voltage emerging across MC1
- No static conduction losses in the semiconductor switch
- Limited turn-off capability against line inductances
- Greatly limited wear out because of arc-free current interruption

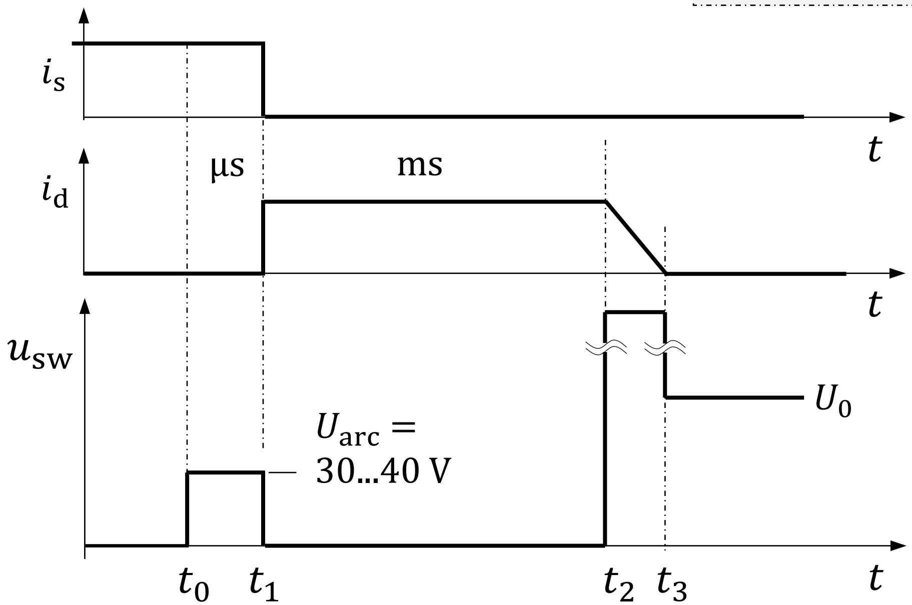
Pilot Contact



- Plugging always takes place **without current**
- Signaled by a leading disconnecting pilot contact, the end device turns-off the load current before the main contacts open.
- When plugged-in, the load current is only switched-on after the main contacts have closed, which is signaled by the last closing pilot contact.
- Pilot can also be evaluated on source side to turn-off the voltage

Hybrid Connector – functional principle





t_0 : Moment of opening of main contact MC1

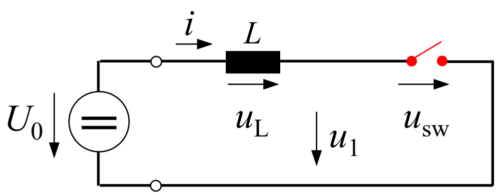
t_0 - t_1 : The arc voltage between MC1 and Aux provides energy to supply the control electronic (⇨ small local buffer capacitor necessary)

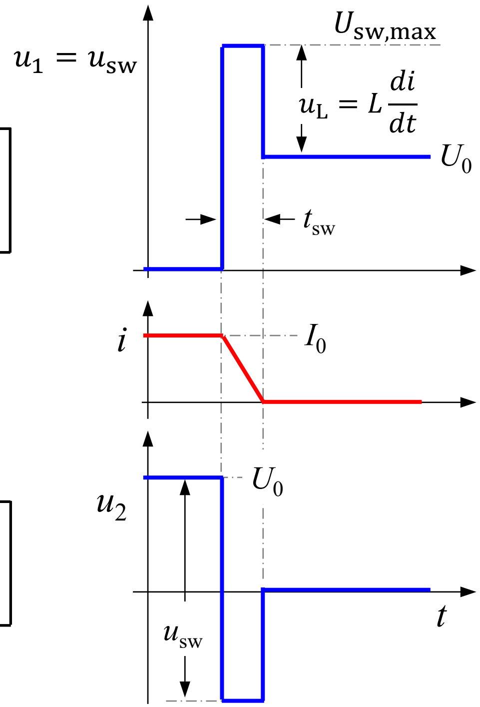
t_1 - t_2 : Transistor turns-on and takes over the load current (⇨ arc extinction), turn-on duration must be long enough to prevent a re-ignition of the arc (typical several milliseconds)

t_2 - t_3 : Transistor turns-off the load current in a controlled manner before the mechanical contacts MC2 and Aux open; overvoltage protection necessary!

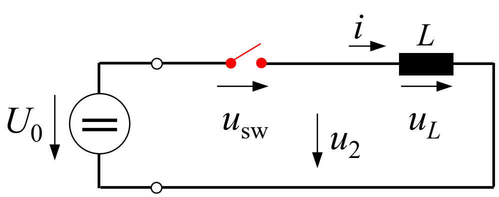
Turn-off against Line Inductances

Lowside configuration





Highside configuration



- A reduction of the load current requires a negative voltage (u_L) at the line inductance, that always leads to a voltage across the opening switch higher than the source voltage!
- The voltage stress on the switch is independent of the position of the line inductance always $U_0 + |u_L|$

The voltage across the switch can be limited either

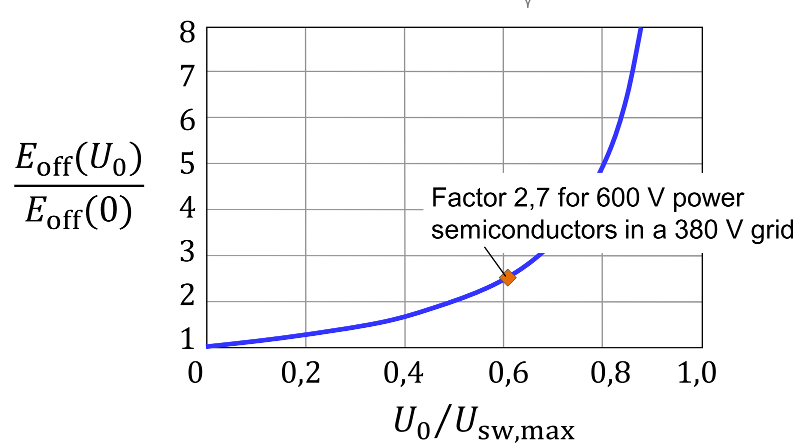
- **through a surge protector element** or
- **by switching off sufficiently slowly**.

In the latter case, the following must apply to the switching time:

$$t_\mathrm{sw} \geq \frac{L\, I_0}{(U_\mathrm{sw,max} - U_0)}$$

The energy generated in the switch during turn-off is:

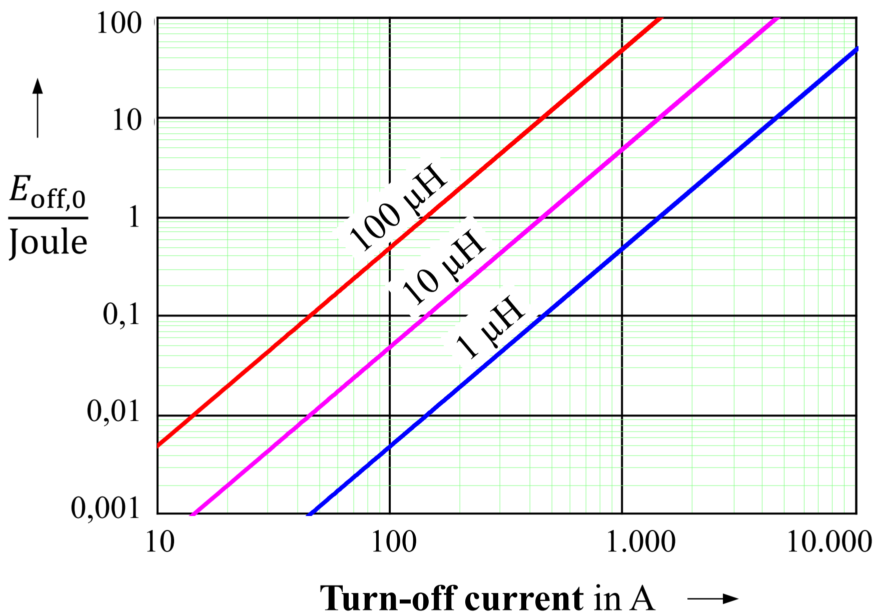
$$E_\mathrm{off} = \frac{1}{2} L\, I_0^2 \underbrace{\left(\frac{U_\mathrm{sw,max}}{U_\mathrm{sw,max} - U_0}\right)}$$



Turn-off against Line Inductances

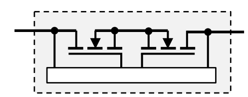
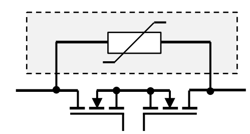
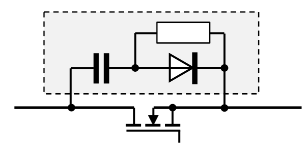
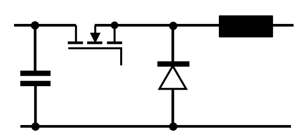
Turn-off energy

$$E_{\mathrm{off}} = E_{\mathrm{off,0}} \cdot \left(\frac{U_{\mathrm{sw,max}}}{U_{\mathrm{sw,max}} - U_0} \right)$$



Rule of thumb: The inductance per unit length of an installation cable (2-wire) is approximately $1\ \mu\mathrm{H/m}$

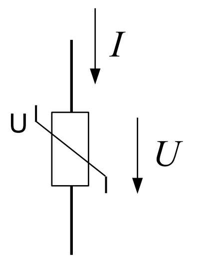
Attention!
Design criterion for overvoltage protection is not the nominal current but the **short-circuit current** to be switched off!

Protection circuit	Protection element	Energy rating[1)]
	**Avalanche-rated** switch or **active clamping**	0,1 to 1 Joule
	**Varistor**	10 J to 10 kJ
	Disadvantages: relatively "soft" clamping and aging	
	**RCD snubber**	0,1 J/µF [2)]
	Disadvantages: expensive and voluminous	
	**Freewheeling diode**	„unlimited“
	Disadvantages: useful only on the load side and not applicable in two-wire installations	

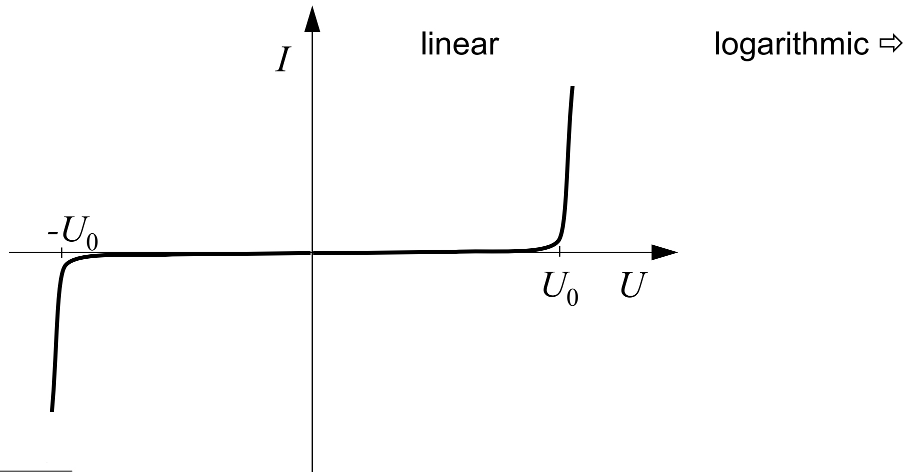
1) typical value ranges 2) in a 380 V grid with 600 V power semiconductors

Varistors as Overvoltage Protection Elements

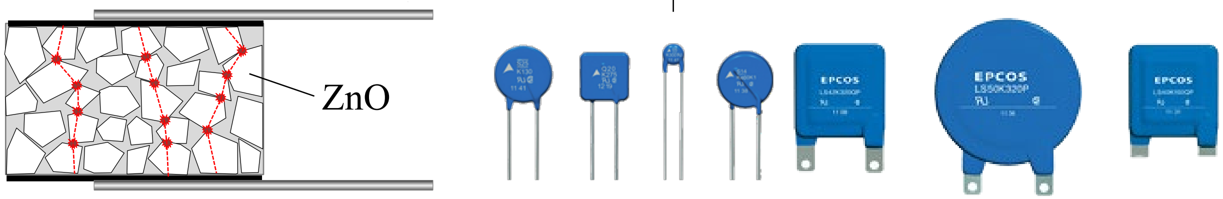
Circuit symbol



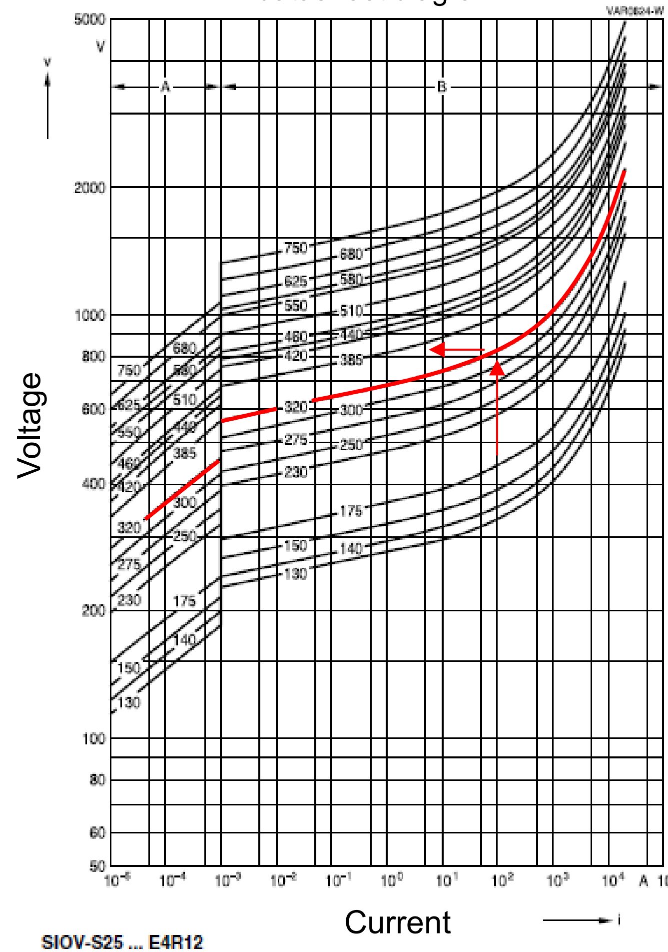
Characteristic



Structure



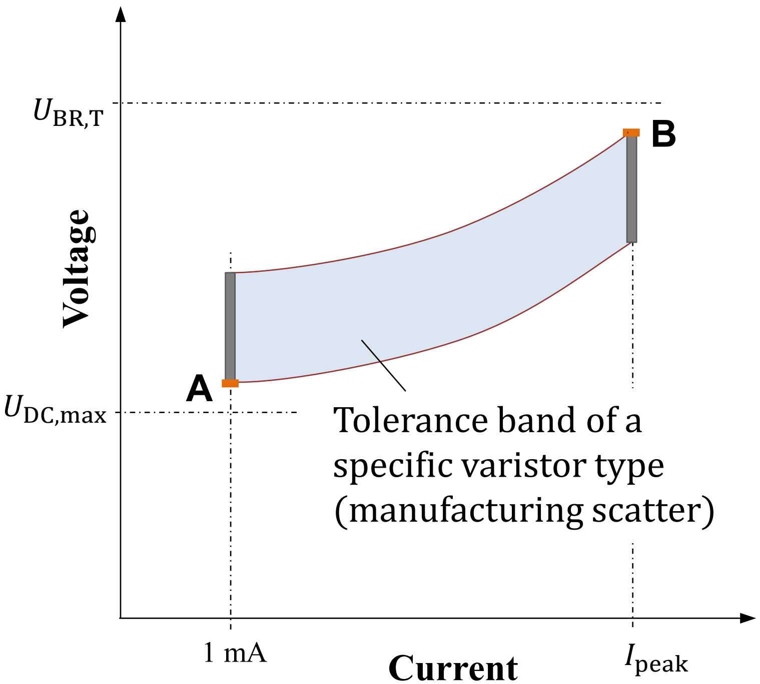
datasheet diagram



- Sintered metal oxide ceramic (ZnO), with barrier layers forming at the grain boundaries (⇨ symmetrical current-voltage characteristic).
- The breakdown voltage U_0 of the component results from the number of series-connected barrier layers (i.e. from the grain size and thickness of the active material), the energy absorption capacity from the volume of the active material.

Picture source: EPCOS/TDK

Varistors as Overvoltage Protection Elements



A: Leakage current criterion

A varistor whose "breakdown voltage" is at the **lower limit** of the tolerance band (manufacturing variance) must not exceed the leakage current limit (generally 1 mA) at the maximum voltage $U_{\mathrm{DC,max}}$ applied in nominal operation.

B: Protection level criterion

A varistor device of the same type, whose "breakdown voltage" is at the **upper tolerance limit**, must, on the other hand, be able to reduce the voltage to less than $U_{\mathrm{BR,T}}$, i.e. the breakdown voltage of the device to be protected, at the maximum pulse current I_{peak} occurring in a specific application!

Example referring to the varistor characteristics on the slide before:

SIOV S25K320 (max. permissible DC voltage according to the datasheet 420 V; note that RMS values for AC voltages are plotted in the given datasheet diagram)

⇨ with a surge current of 100 A, the worst-case scenario is a voltage just over 800 V across the varistor

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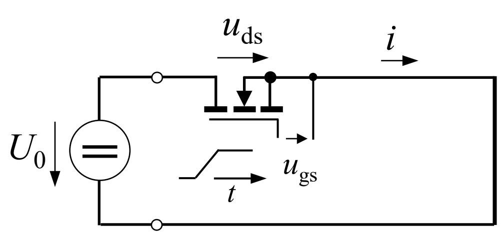
Switching off Short Circuits with current-limiting semiconductor switches

Short circuit type 1

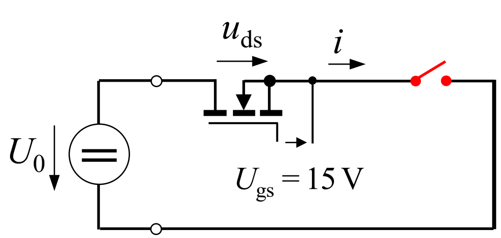


Switching on to an existing short circuit

Characteristic

- MOSFET / IGBT switches limit the short-circuit current to comparatively low values during switch-on (i.e. while the gate voltage is running up)
- A simple desaturation monitoring is generally sufficient as a criterion for triggering the short-circuit shutdown

Short circuit type 2



Short circuit while the switch is fully turned-on

Problem

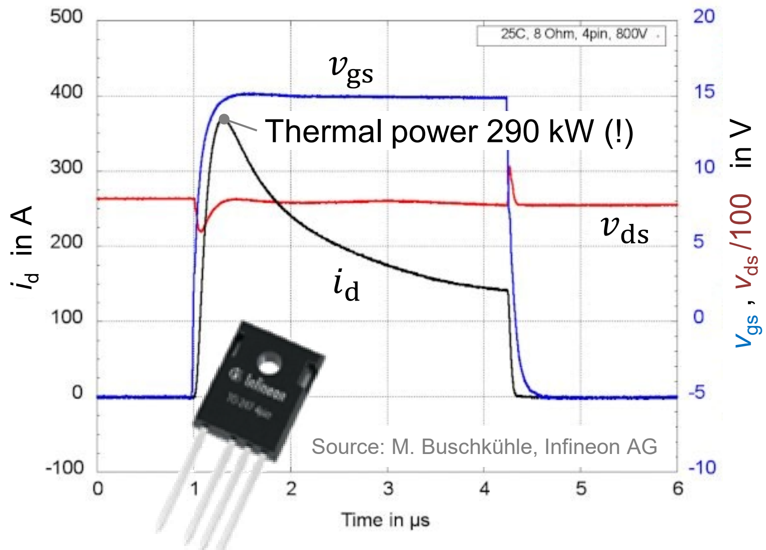
- The fully open switch only limits the current at very high levels. This is especially true if the DC switch has been designed "generously" (with regard to chip area or R_{ON}) in order to minimize conduction losses.

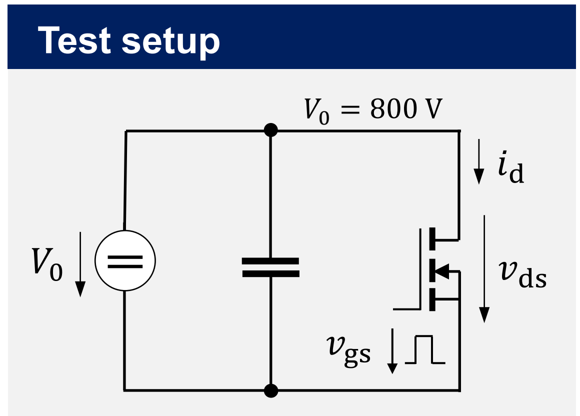
Possible solutions

- An additional current sensor, which can detect the short circuit based on the current value, or even better, based on the steepness of the current slope.
- Keeping the semiconductor switch "ON" in conjunction with a suitably dimensioned series connected interrupting element (e.g. a fuse)

Switching off Short Circuits with current-limiting semiconductor switches

Short circuit current characteristic
SiC-MOSFET (CoolSiC™) 1200 V, 45 mΩ





Extract from data sheet SiC-MOSFET IMW120R045M1

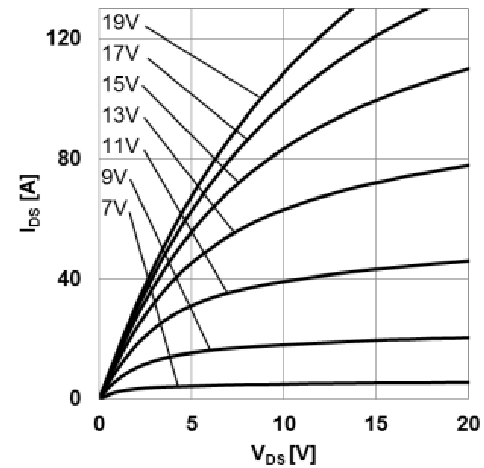


Figure 8 **Typical output characteristic, V_{GS} as parameter** (I_{DS} = f(V_{DS}), T_{vj}=175°C, t_P = 20µs)

- The current-limiting properties of MOSFETs and IGBTs are a key to make short circuits manageable
- **Problem:** The short-circuit current level cannot be taken from most transistor data sheets, as the output characteristic is usually insufficiently represented (since most semiconductor manufacturers foolishly limit themselves in the data sheets to an area close to the origin of the 1st quadrant)!

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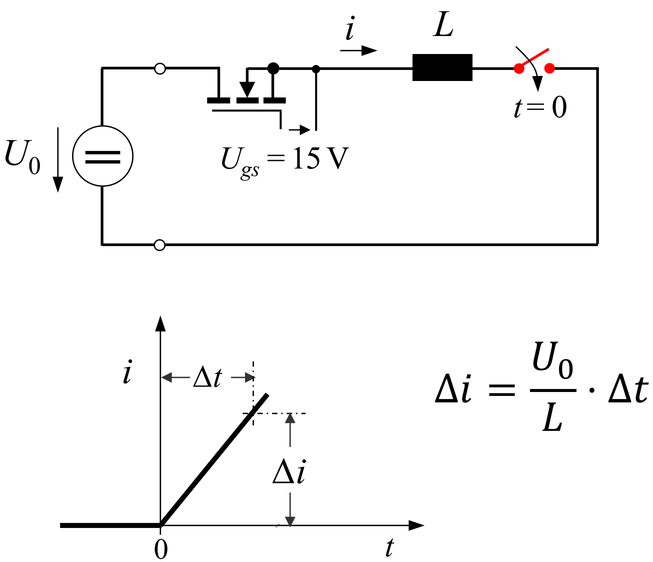
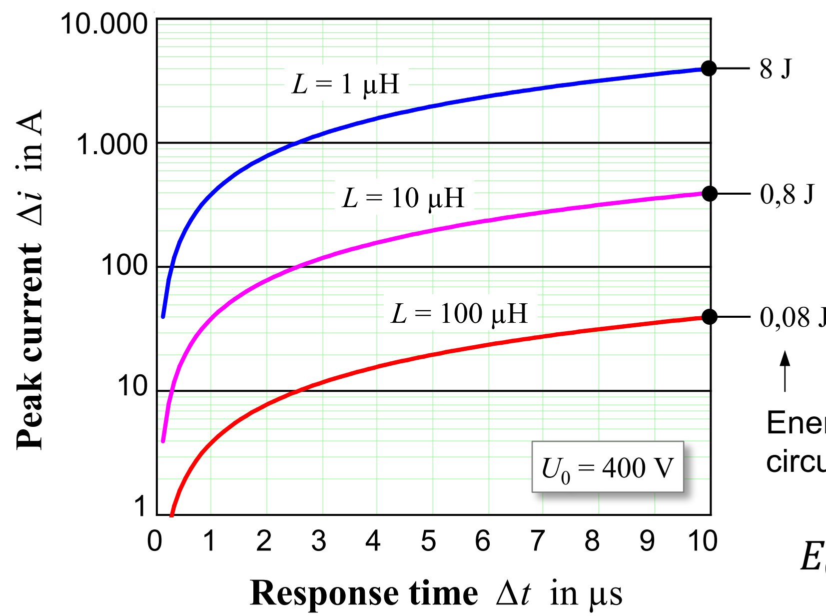
Switching off Short Circuits **without current limitation** in the circuit

Short-circuit current as a function of the response time to a fault event for various circuit inductances



$$\Delta i = \frac{U_0}{L} \cdot \Delta t$$

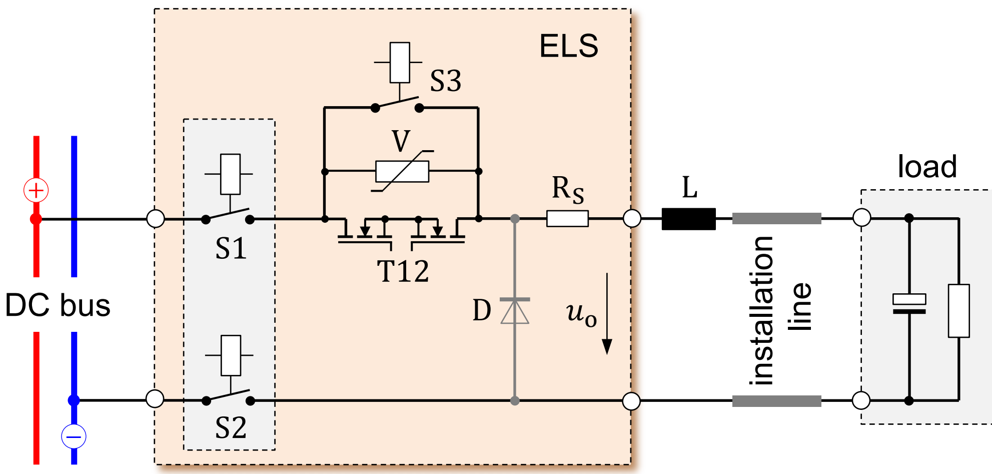


Energy stored in the circuit after 10 µs:

$$E_0 = \frac{1}{2} L \, \Delta i^2$$

Inductance in the circuit increases the turn-off energy for a given current - but it also increases the available response time by limiting the current slope in the event of a fault.

Electronic Line Switch (ELS)



T12	Semiconductor switch (MOSFET, IGBT) for fast turn-off; two anti-serial switches necessary in case of bidirectional current flow
V	Overvoltage protection
R_S	Current sensor
S1, S2	Mechanical switches for electrical isolation (since open semiconductor switches are not permitted in terms of personal protection)
S3	Mechanical switch bridging the semiconductor switch to minimize conduction losses (in case of a "hybrid switch")
D, L	Optional for fault current rise limitation and precharging of load capacitances by a transient buck operation using T12

Basic functions

- Switching on/off the load line
- Electrical insulation of the switched-off load line
- Overcurrent and short circuit protection
- Voltage monitoring
- Precharging the load circuit (optional)
- Intelligent load line and load monitoring, e.g. arc detection (optional)

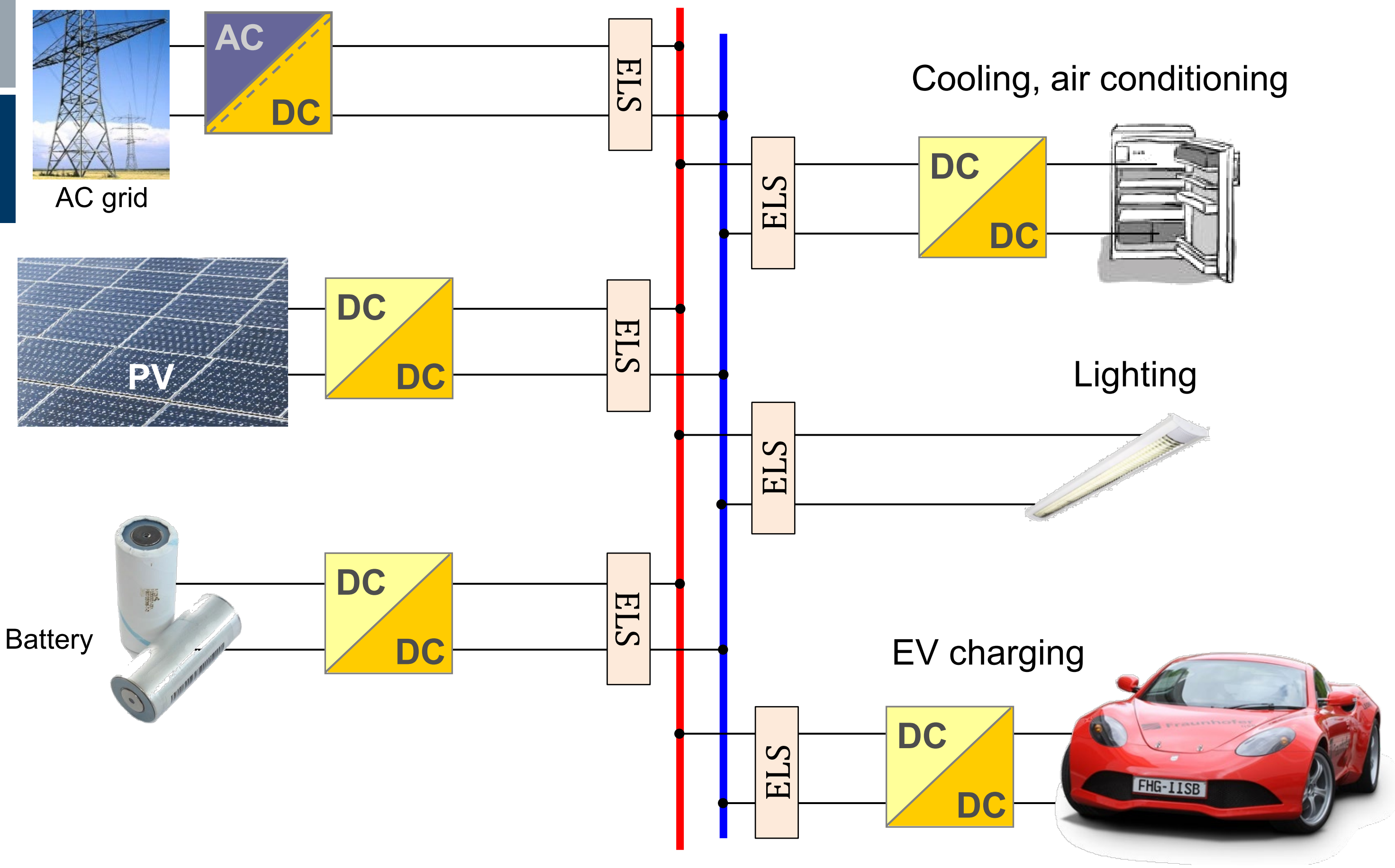
Semiconductor switch (ELS without S3)

- Very fast turn-off ($< 30\ \mu s$)
- Very low fault energy ($\ll 1\%$ compared to a mechanical switch)
- Considerable cooling effort (IGBT) oder very high cost (MOSFET)

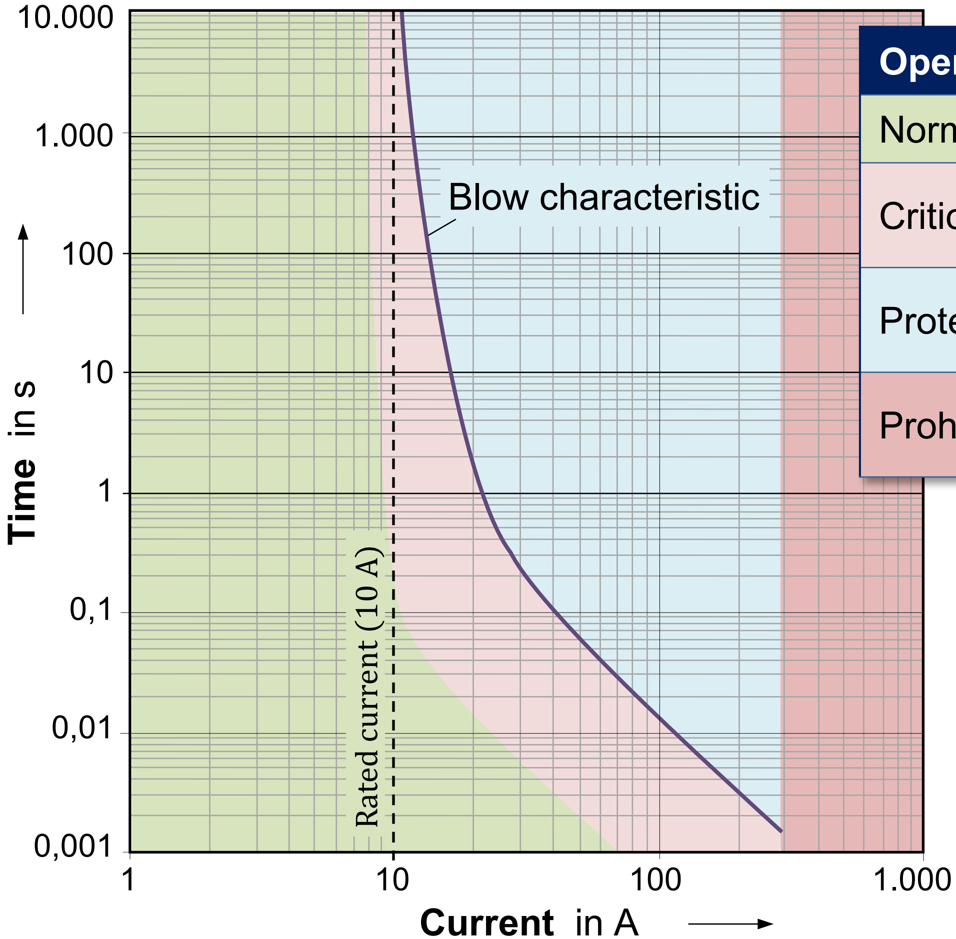
Hybrid switch (ELS with S3)

- Much lower cost at comparable conduction losses
- Slower fault turn off due to the mechanical switch S3 (> 5ms)
- Short arc at S3 (compare slide "hybrid connector")

Electronic Line Switches (ELS)



Operational Areas of a Fuse



Operational area	
Normal operation	Voltage drop and power loss as specified
Critical operation	Severe warming results in diffusion and aging (consider also repetitive current peaks)
Protection area	Fuse opens within the specified current-time characteristic
Prohibited operation	**Interrupting rating** exceeded, risk of the fuse bursting

Example: from data sheet Littlefuse® - 487 Series

Amp Rating	Max Voltage Rating (V)	Interrupting Rating	Nominal Cold Resistance (Ohms)	Nominal Melting I^2t (A^2 sec.)
8	420VDC 420VAC	300A@420VDC 200A@420VAC	0.0134	65
10			0.0093	130
12.5			0.0078	170
15			0.0075	190
16			0.0064	260
20			0.0043	390

Operational Areas of a Fuse

Area A
Heat conduction

Stationary balance between electrical power dissipation and heat dissipation:

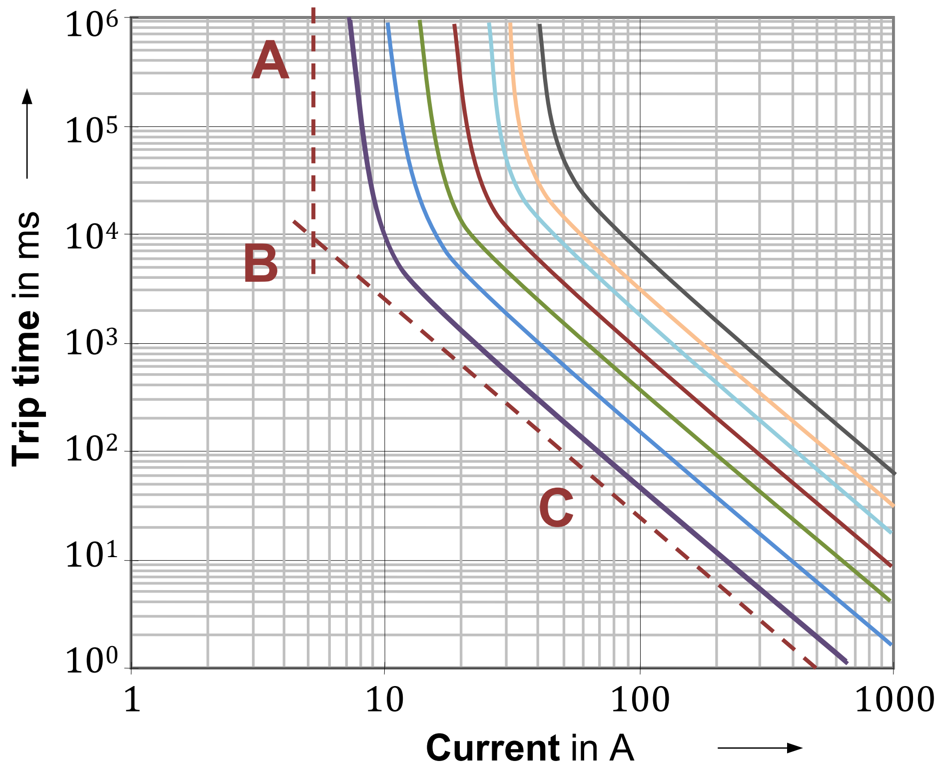
$$P_{el} = P_{th}$$

$$I^2\, R_{el} = \frac{\Delta T}{R_{th}}$$

R_{th} : thermal resistance in K/W
ΔT : heating in K
R_{el} : electrical resistance in Ω

Area B
Transition area

Typical blow characteristic
of fuses, cables or printed conductors



Area C
Adiabatic heating

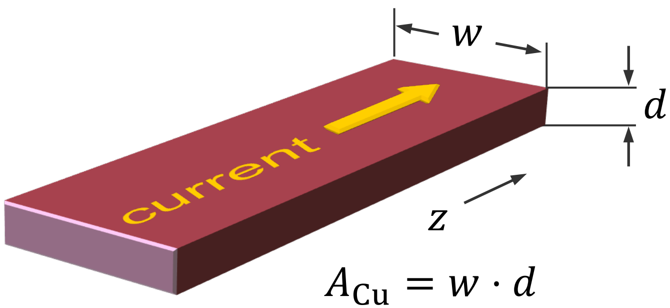
Heat dissipation is negligible due to the shortness of the event; all of the energy goes into heating the loss-generating material volume (fuse wire)

$$I^2\, R_{el} = C_{th}\, \frac{dT}{dt}$$

C_{th} : heat capacity in Wsec/K
dT/dt : heating gradient in K/sec

Blow Characteristic in the Area of Adiabatic Heating

Example
Current-carrying conductor



$$A_{\mathrm{Cu}} = w \cdot d$$

Power loss in a conductor section Δz

$$P_{\mathrm{el}} = I^2 \cdot R = I^2 \cdot \frac{\rho_{\mathrm{el}}\,\Delta z}{A_{\mathrm{Cu}}}$$

Adiabatic heating of the conductor section mass

$$P_{\mathrm{el}} = C_{\mathrm{th}} \frac{dT}{dt} = \rho_{\mathrm{m}}\, c_{\mathrm{p}} \cdot (A_{\mathrm{Cu}}\,\Delta z) \cdot \frac{dT}{dt}$$

Equating delivers

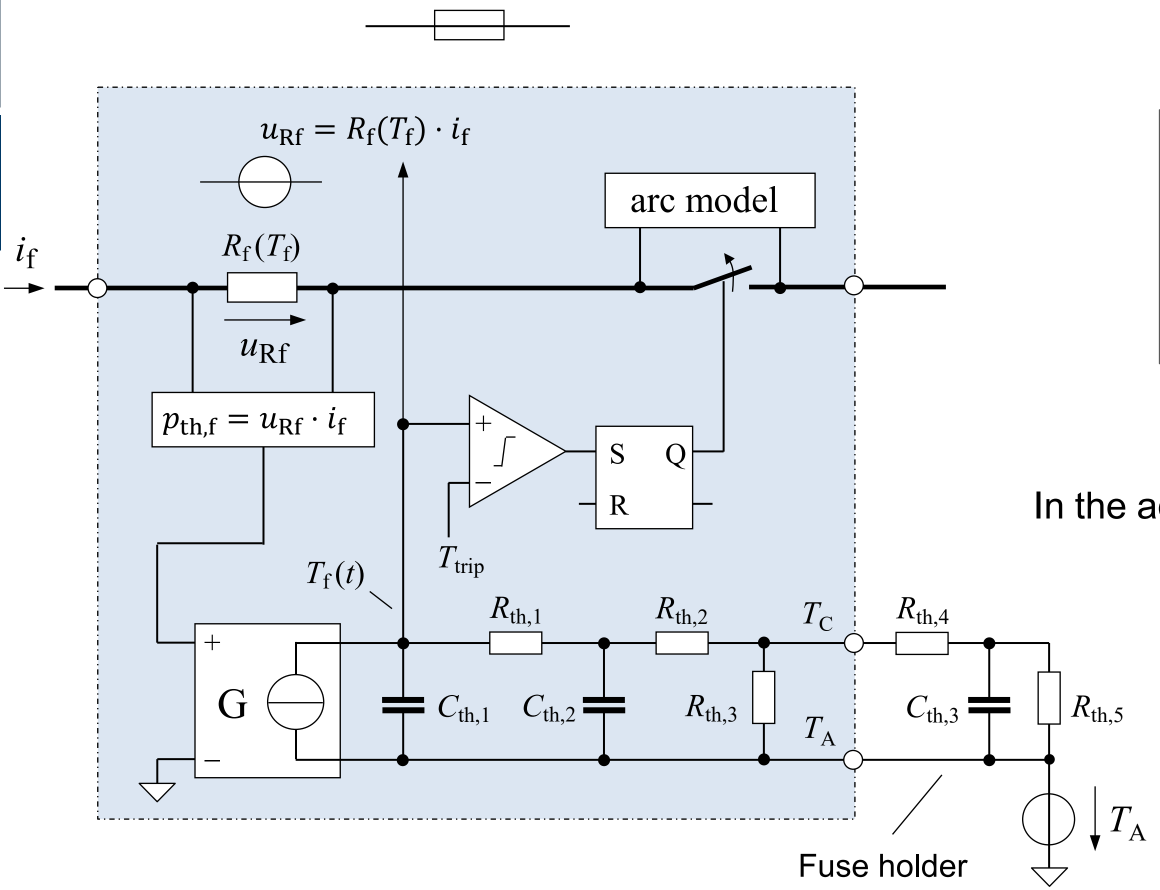
$$I^2 dt = \underbrace{\frac{\rho_{\mathrm{m}}}{\rho_{\mathrm{el}}}\, c_{\mathrm{p}}\, A_{\mathrm{Cu}}^2}_{\text{Material and geometry parameters}} \cdot dT$$

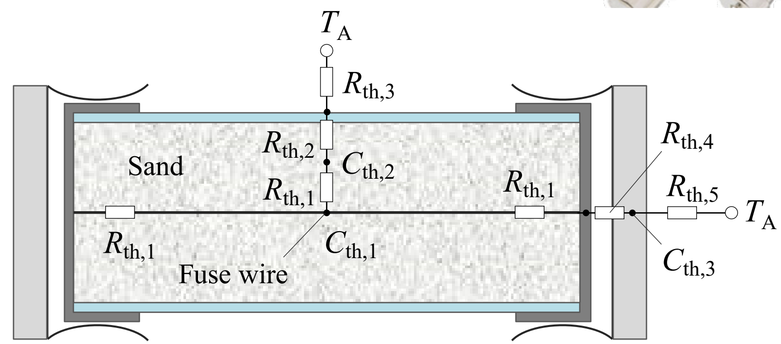
The adiabatic heating is a function of the I²t value!

This consideration is generally applicable to short-term (surge current) events in case of volume heating (e.g. for fuses, cables, conductors, power semiconductors, etc.)

c_{p} : spec. heat capacity in J/(g·K)
ρ_{m}: spec. weight in g/cm3
ρ_{el}: spec. electrical resistance in Ωcm

Electric-thermal Model of a Melting Fuse





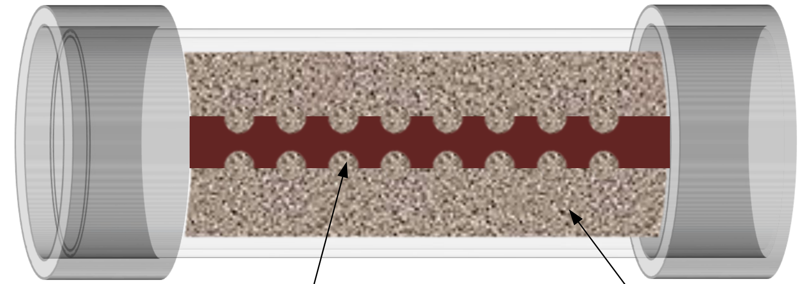
In the adiabatic operating range it applies approximately:

$$P_{th,f} = i_f^2 \cdot R_f = C_{th,1} \frac{dT_f}{dt}$$

$$\boxed{I_f^2 \, dt \approx \frac{C_{th,1}}{R_f} \Delta T_{f,melt}}$$

$\Delta T_{f,melt}$ = necessary heating to the melting point of the fuse wire

Increasing the Interrupting Rating under DC Operation

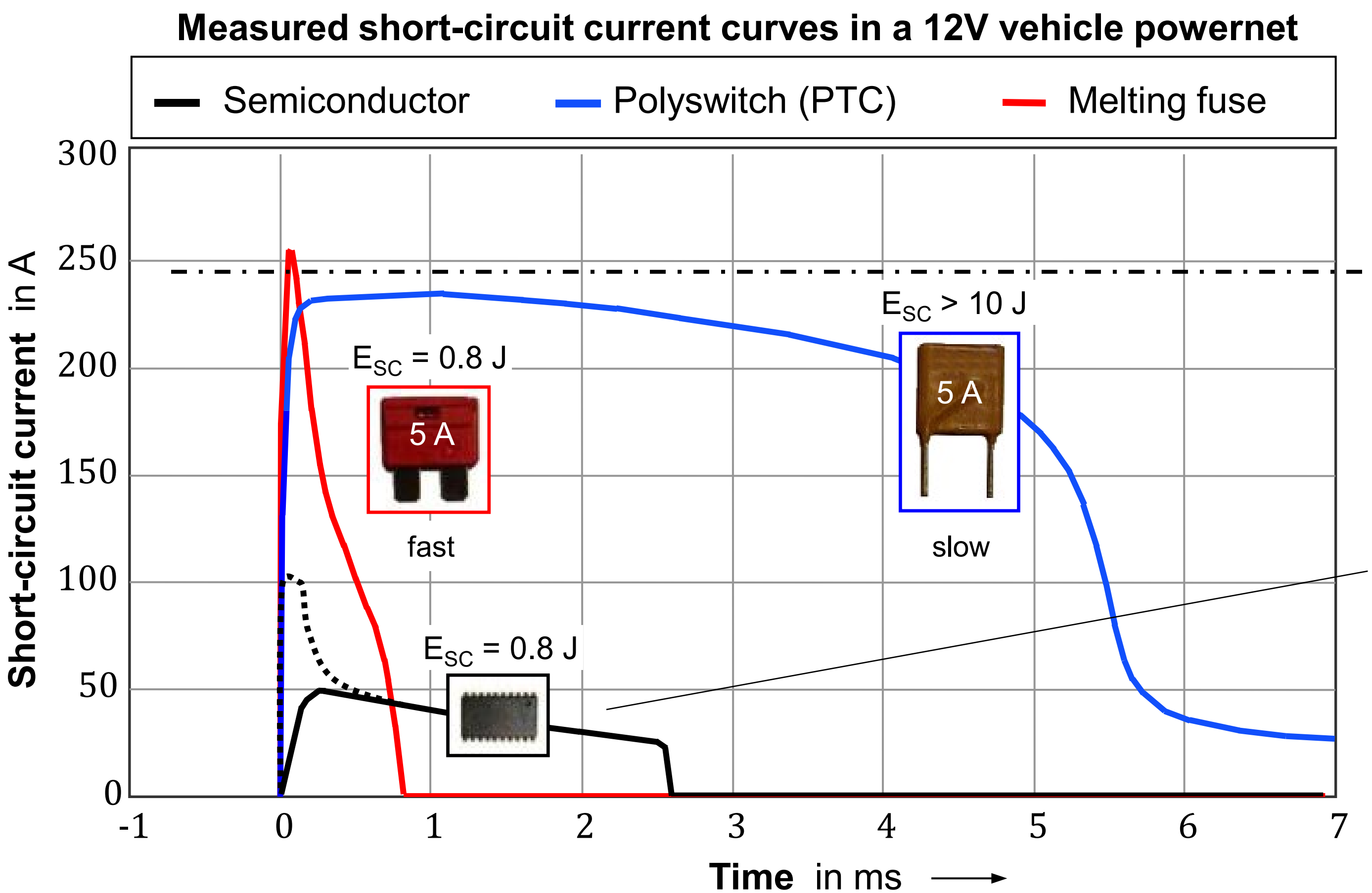


- Distribution of the voltage over several arcs in series through well-aimed weakenings in the "fuse wire"
- Cooling the arcs and avoiding arc-over by embedding the fuse wire in a high-melting isolating material (e.g. sand)
- Use of robust fuse bodies (ceramic instead of glass) to withstand the expansion pressure

Important

- With a view to the interrupting rating - especially in grid applications - the maximum inductive energy in the circuit (mostly described via a maximum time constant L / R) must be observed!
- **In many DC applications, the current limitation of switching converters and the resulting low short-circuit current limit the use of fuses** (risk of operation in the critical characteristic area just above the nominal current)

Short-circuit Current Characteristics of Different Types of "Fuses"



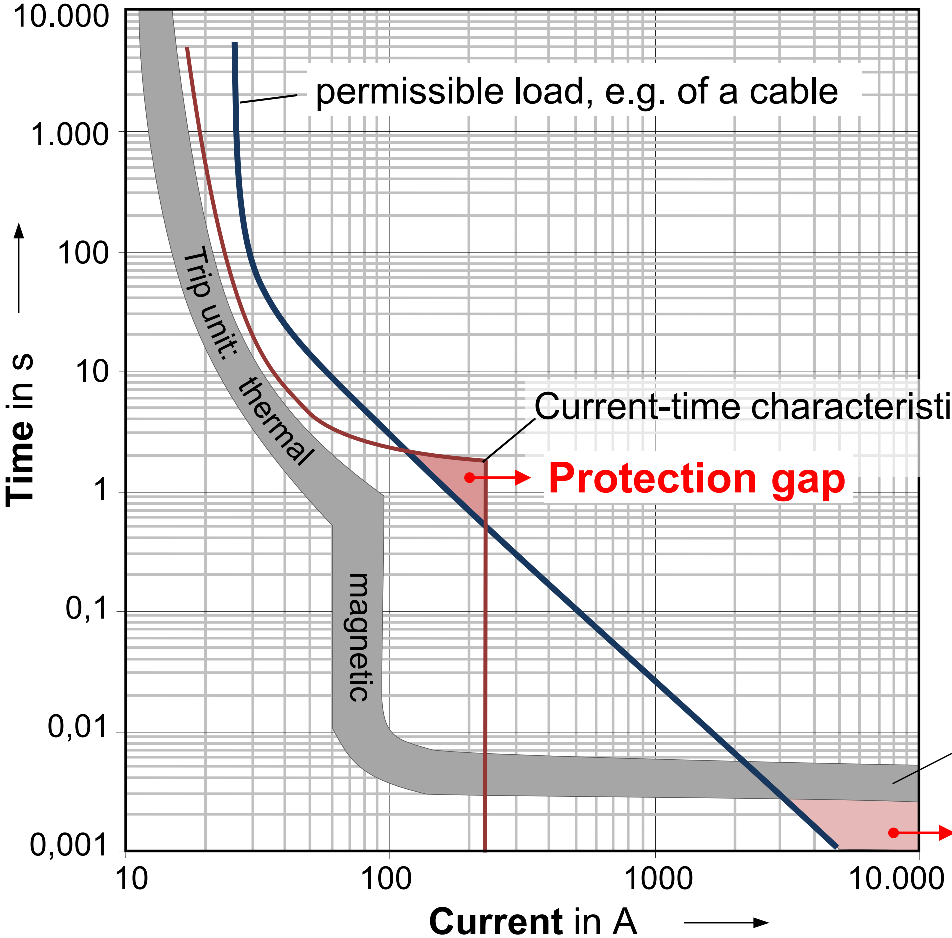
Traditional fuses

Short-circuit current level only limited by the circuit's internal resistance

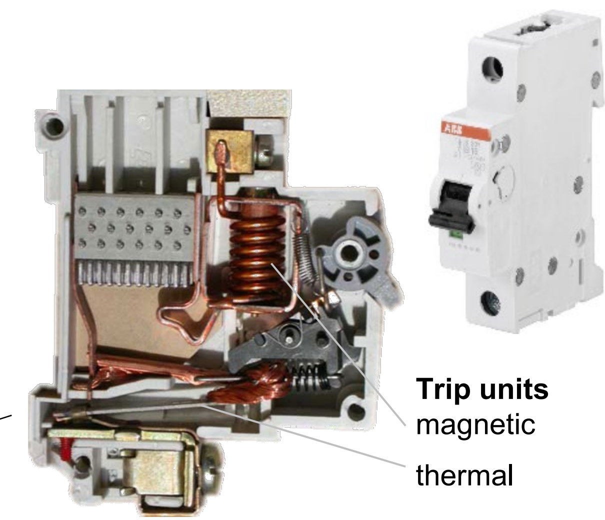
Semiconductor breaker

- Short-circuit current generally limited by the switch (e.g. by MOSFET output characteristic)
- Current-time characteristic can be largely free determined by the circuit engineer

Be careful to avoid protection gaps!



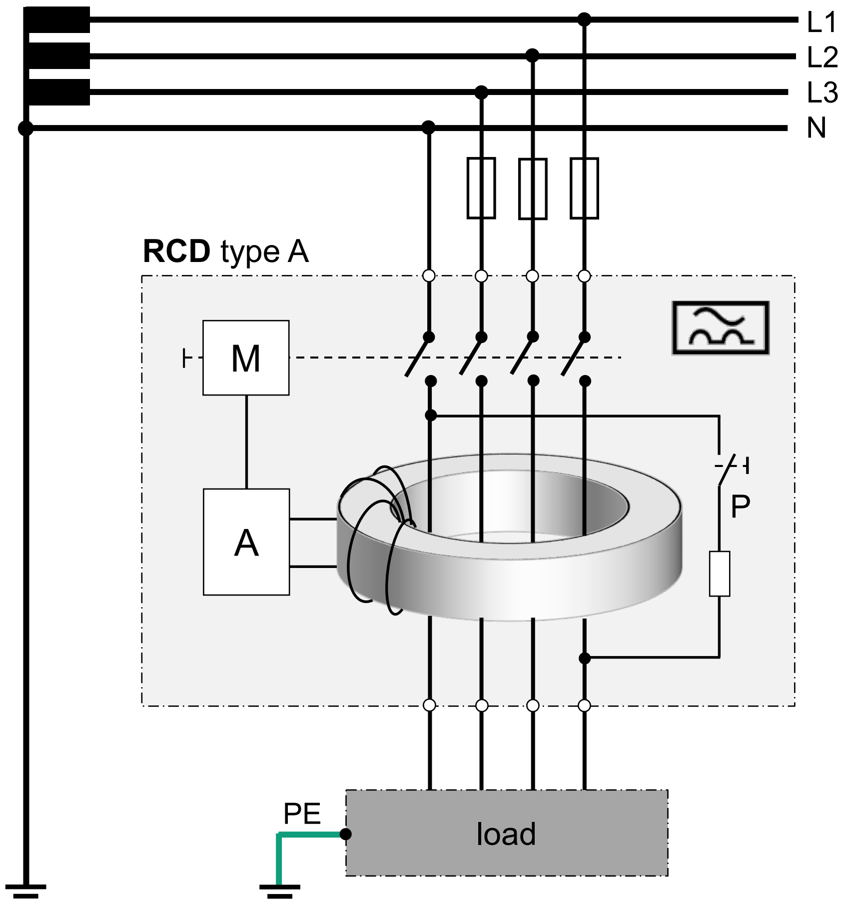
A view on the stationary currents only is generally not sufficient to avoid protection gaps!



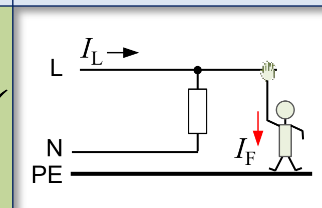
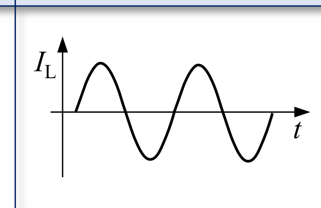
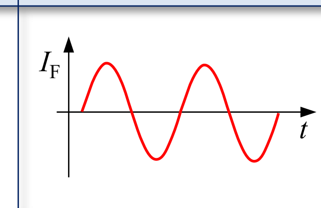
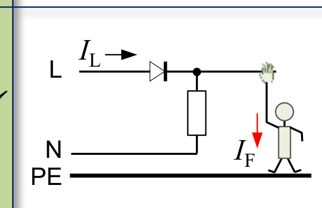
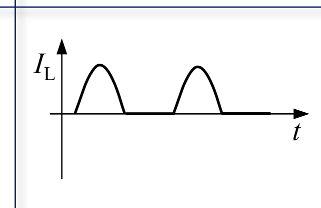
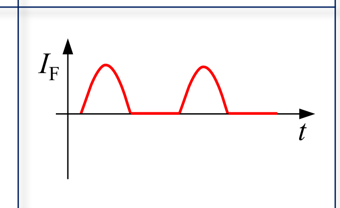
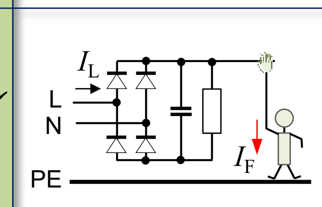
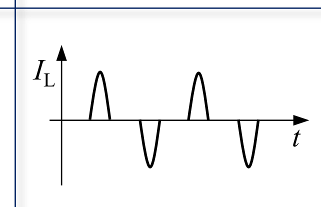
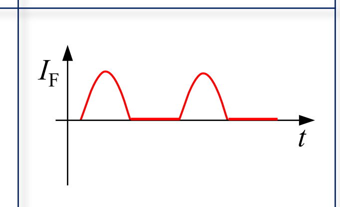
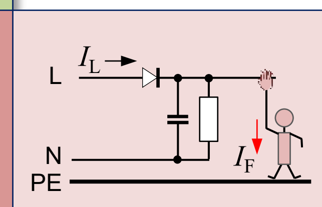
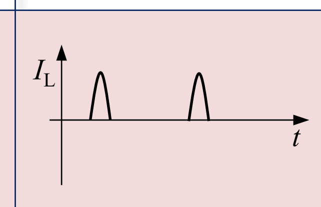
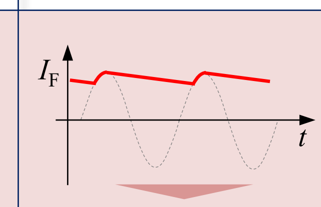
Circuit breaker
10 A, type C

Protection gap - caused by the inertia of the mechanical contact system - but check whether such huge short-circuit currents can even occur in the affected circuit (in DC grids usually only possible in the immediate vicinity of Li-Ion batteries)

Residual Current Circuit Breaker (RCD type A)

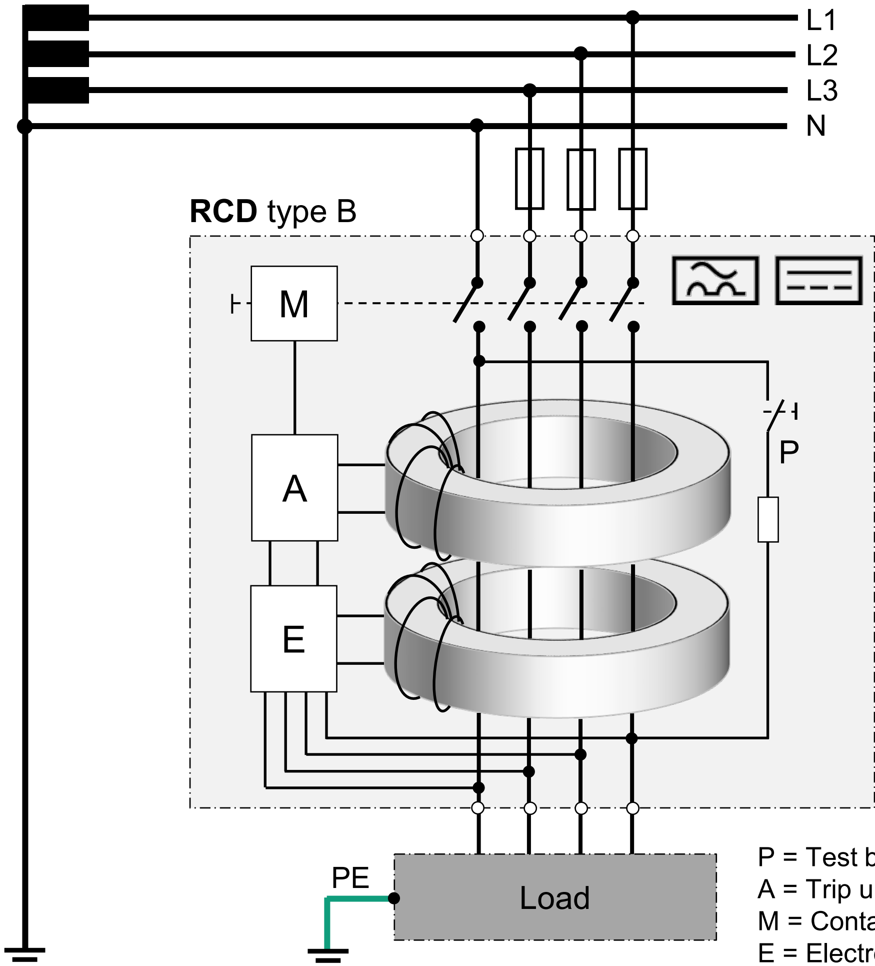


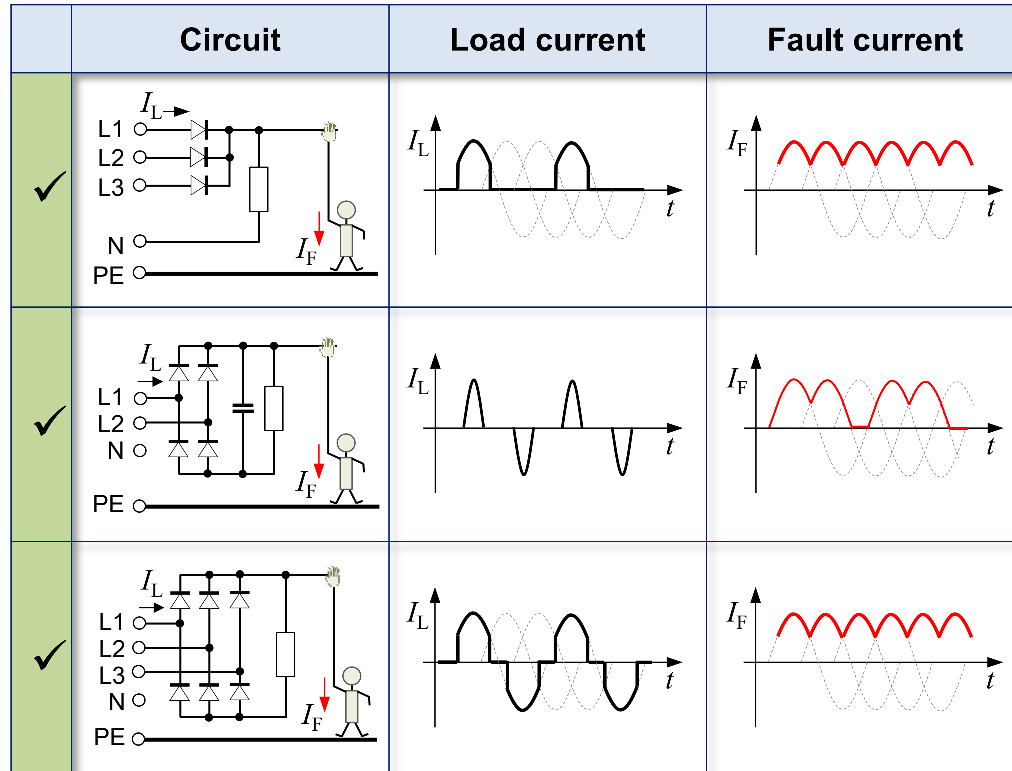
A = Trip unit; M = Contact actuation mechanism; P = Test button

	Circuit	Load current	Fault current
✓			
✓			
✓			
✗			

A non-vanishing DC component in the fault current (typ.> 6 mA) causes type A RCDs to go blind!

Residual Current Circuit Breaker (RCD type B - universal current sensitive)





P = Test button
A = Trip unit
M = Contact actuation mechanism
E = Electronics for tripping with smooth DC residual currents

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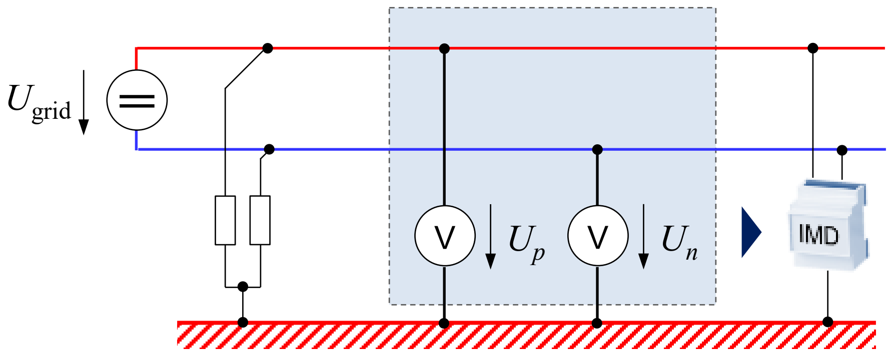
Insulation Monitoring (IMD)

Voltage measurement



Advantage

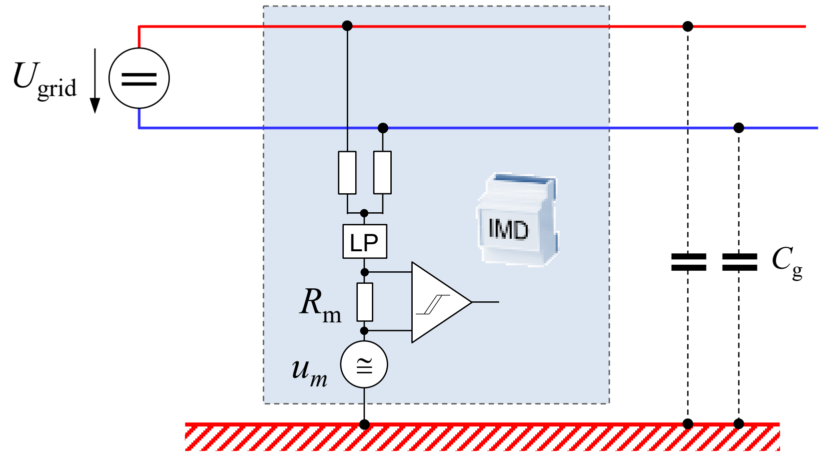
- Can be realized simple and inexpensive

Disadvantage

- Earth symmetric faults can not be detected

IMD: Insulation Monitoring Device

Active monitoring methods



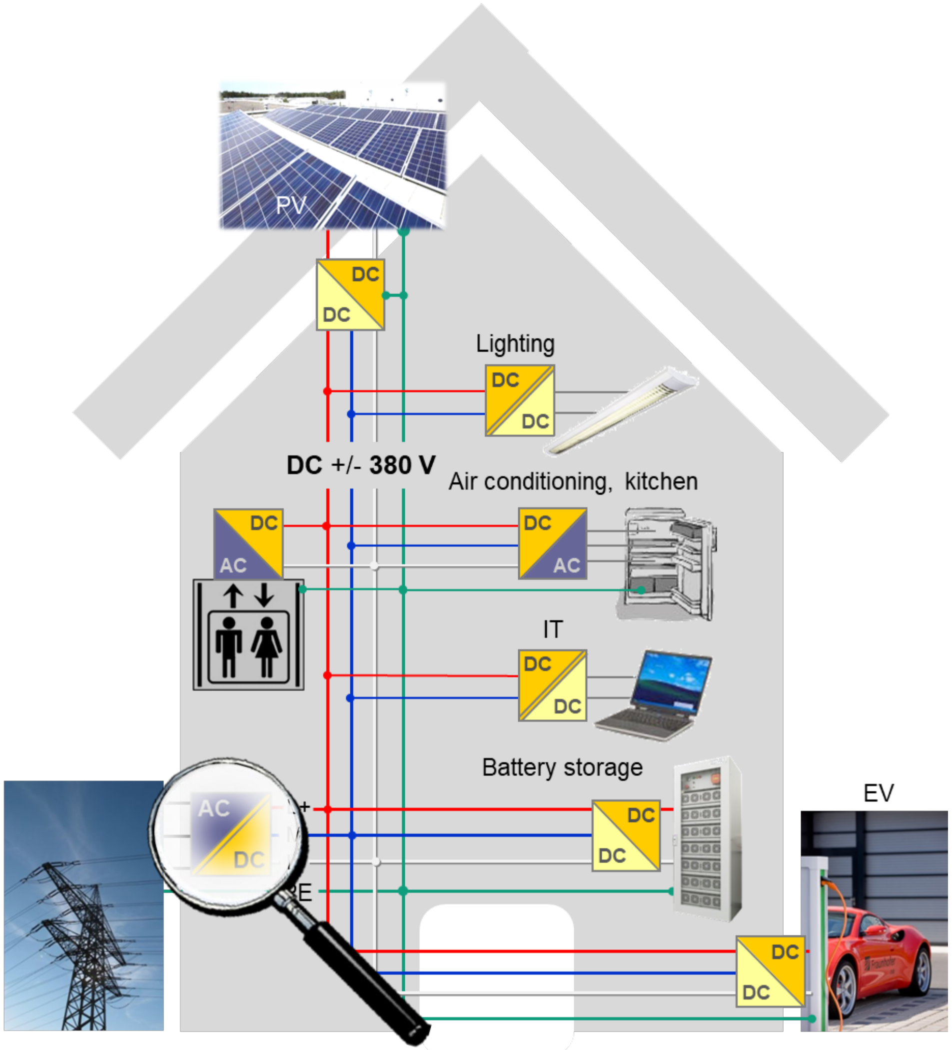
Principle

- A test voltage source (DC or AC) drives a current through the resistor R_m in the event of an insulation fault

Problem

- Common-mode noise also drives a current through R_m (⇨ lowpass LP)
- Large ground capacitances limit the measuring frequency and thus the fault detection latency

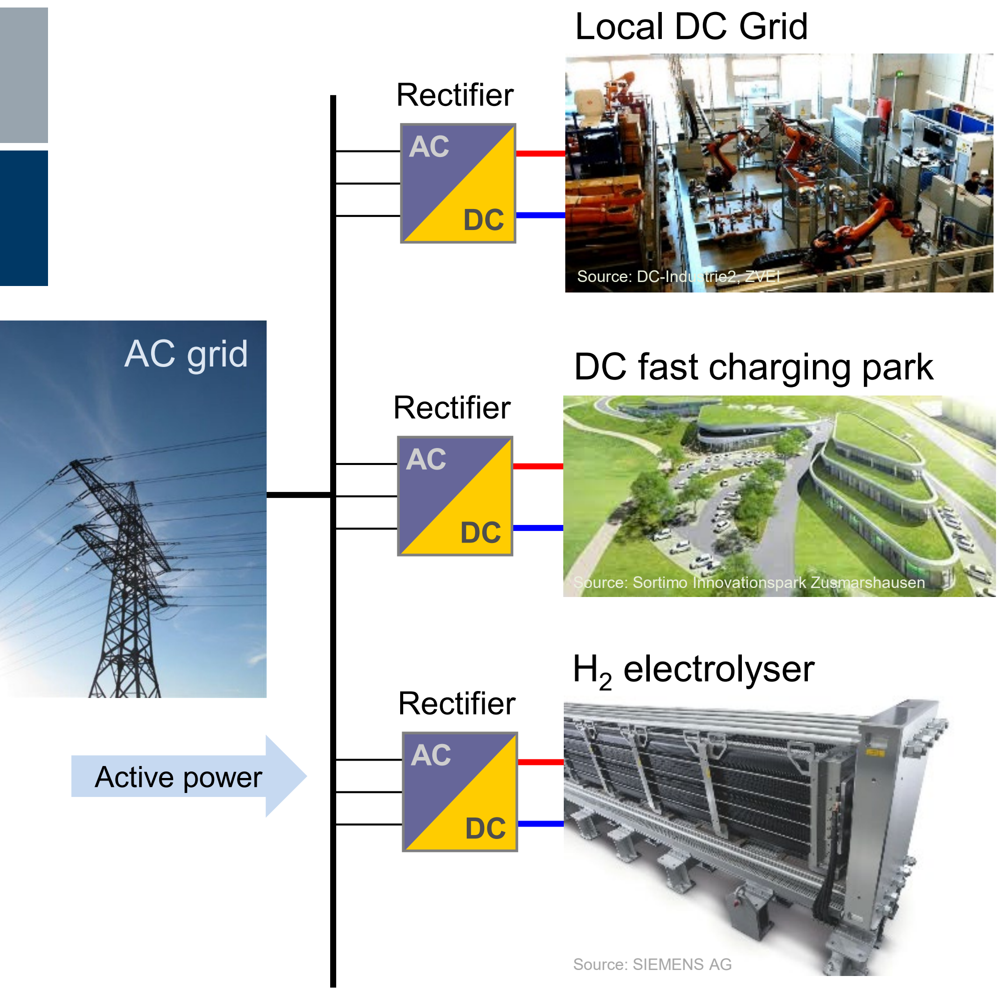
Room for Notes



DC/AC

Inverters and **Rectifiers**

Rectifier



The task of a rectifier is to enable energy to flow from AC to DC. In doing so, only **active power**

$$P = U \cdot I_1 \cdot \cos \varphi_1$$

should be taken from the AC grid.

This makes it necessary to minimize both the phase difference φ_1 between current and voltage, and the distortion of the AC current!

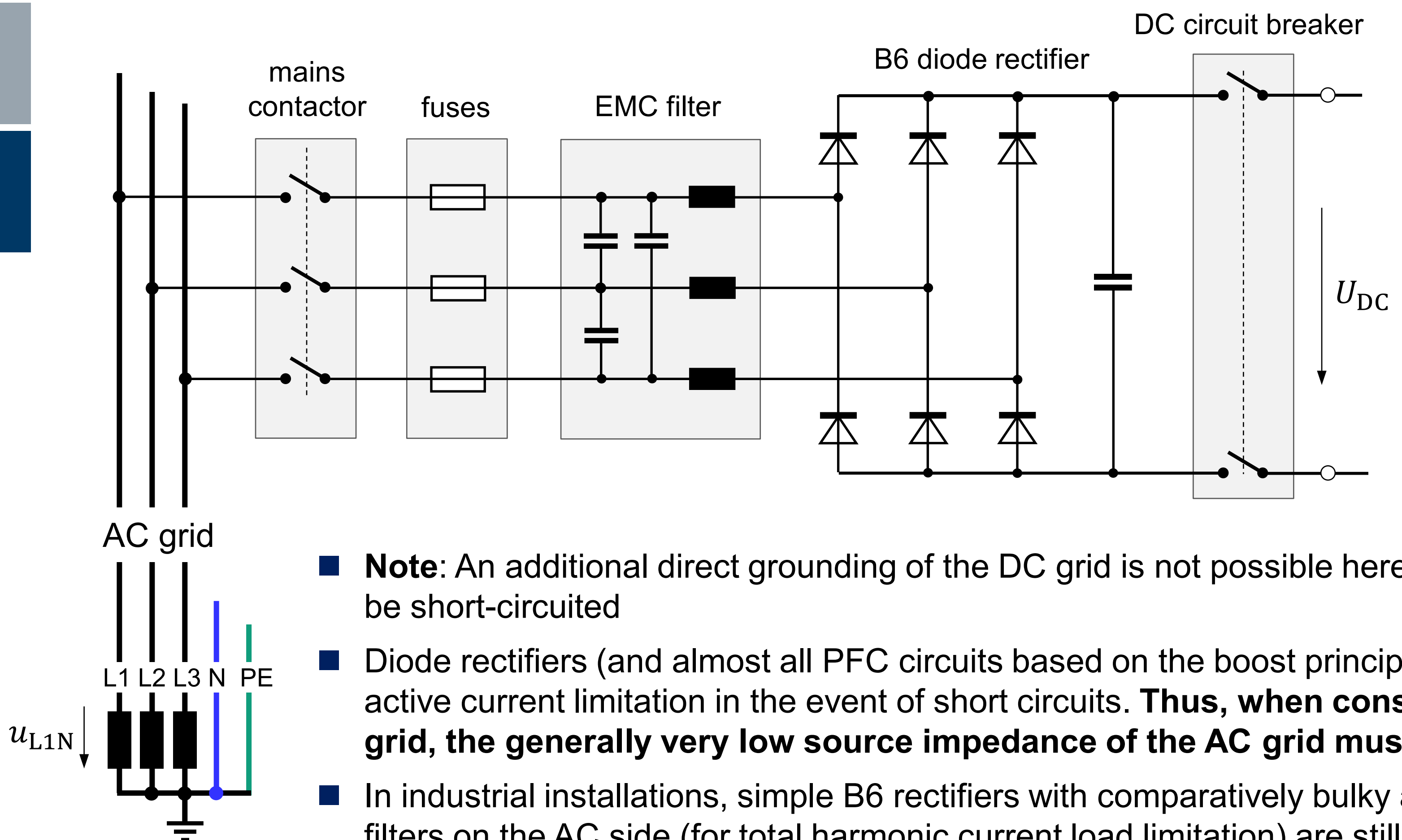
Standards such as the IEC 61000-3 limit the **Total Harmonic Current** (THC) content:

$$\mathrm{THC} = \sqrt{\sum_{\mathrm{i}=2}^{40} I_{\mathrm{i}}^2}$$

This generally requires active or passive filtering measures.

(the aforementioned indices identify the harmonics, $\mathrm{i} = 1$ corresponds to the fundamental mains frequency (e.g. 50 Hz))

DC Grid Directly Fed from AC with Grounding via the AC Grid



Europe

$U_N = 230$ V
$f = 50$ Hz

With

$u_{L1N} = \sqrt{2}\, U_N \sin(\omega t)$

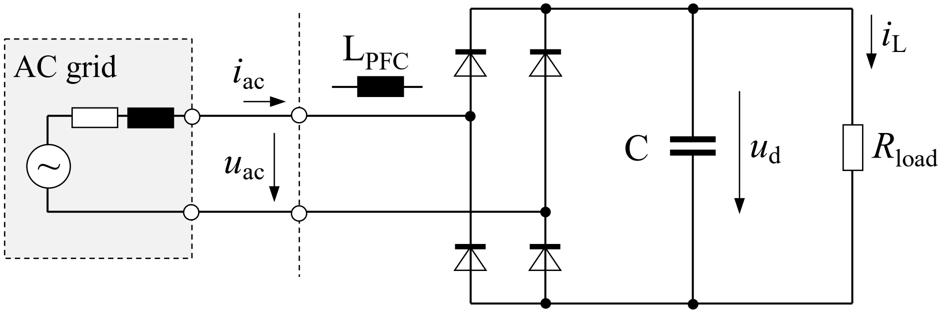
$U_{DC,B6} = \frac{3\sqrt{6}}{\pi} U_N$

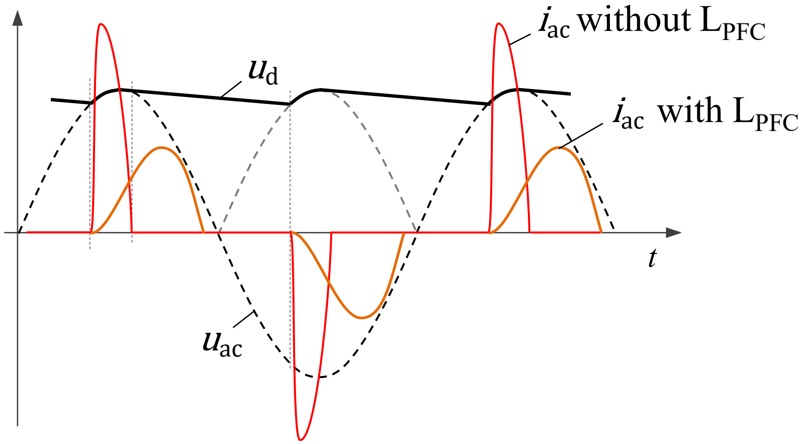
follows:

$U_{DC} \approx 540$ V

- **Note**: An additional direct grounding of the DC grid is not possible here, since the rectifier would be short-circuited
- Diode rectifiers (and almost all PFC circuits based on the boost principle) offer no possibility of active current limitation in the event of short circuits. **Thus, when considering faults in the DC grid, the generally very low source impedance of the AC grid must be taken into account**!
- In industrial installations, simple B6 rectifiers with comparatively bulky and heavy passive EMC filters on the AC side (for total harmonic current load limitation) are still widespread.

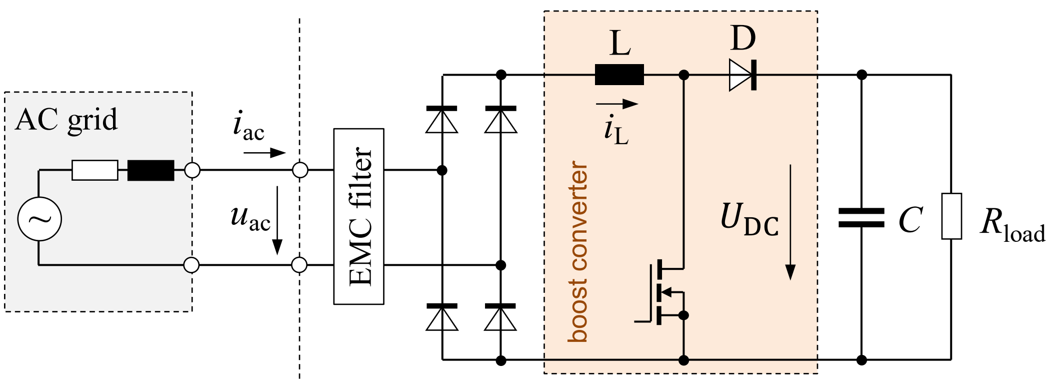
Power Factor Correction

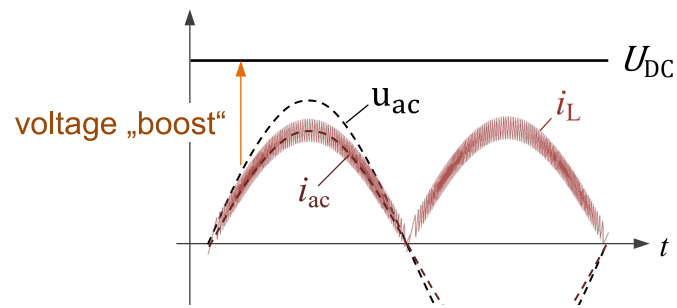




- A simple diode rectifier causes high current peaks (i_{ac}) and thus interference on the AC grid
- A choke (L_{PFC}) can be used to smooth the current slope, but it is bulky and heavy due to the low mains frequency!

Active Power Factor Correction (PFC)



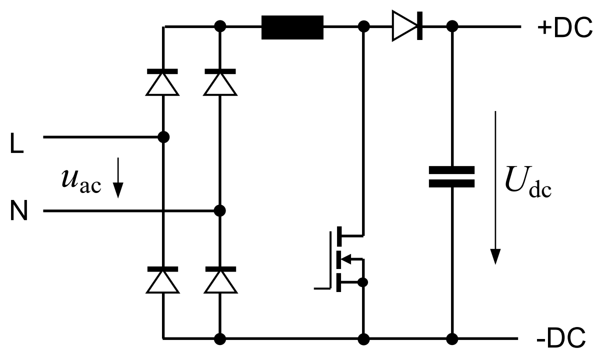


⇨ A boost converter allows current to be pushed onto the DC side even at low AC voltages and thus enables a sinusoidal mains current to be drawn

Friedrich-Alexander-Universität Technische Fakultät
LEHRSTUHL FÜR LEISTUNGSELEKTRONIK
Fraunhofer IISB

Single-phase Rectifiers with PFC Functionality

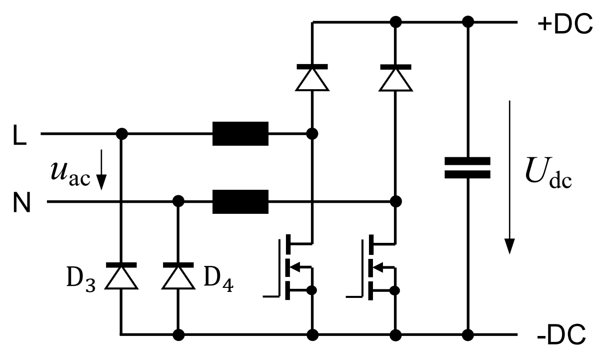
Boost PFC



Advantages
- inexpensive
- simple and low-cost control
- moderate CM noise level (DC - N)

Disadvantages
- moderate efficiency (current has to path three diodes)
- DC grid can not be directly grounded if AC is grounded

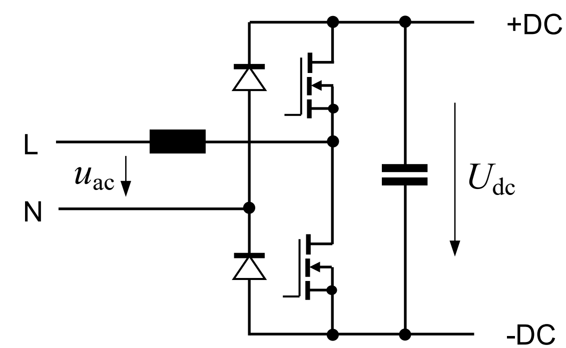
Bridgeless PFC



Advantages
- high efficiency possible
- relatively easy control
- moderate CM noise level (DC - N) when using D_3, D_4

Disadvantages
- two chokes necessary
- DC grid can not be directly grounded if AC is grounded

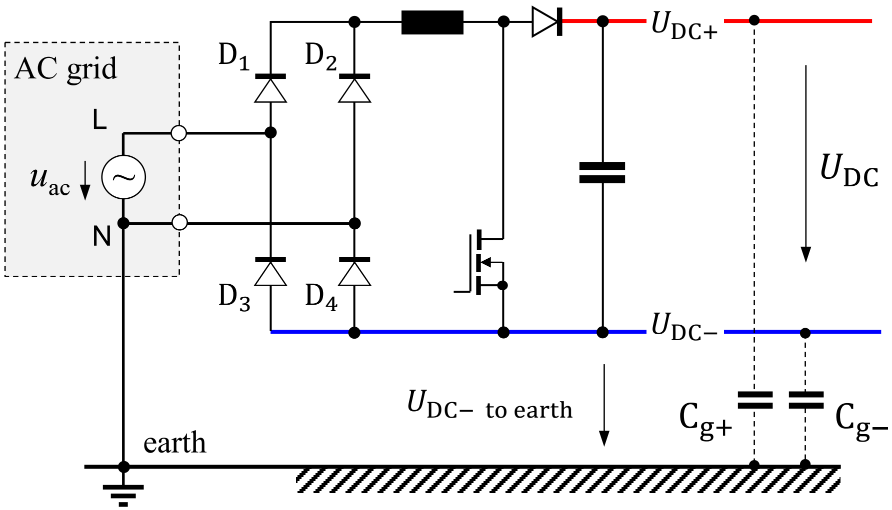
Totem-pole PFC

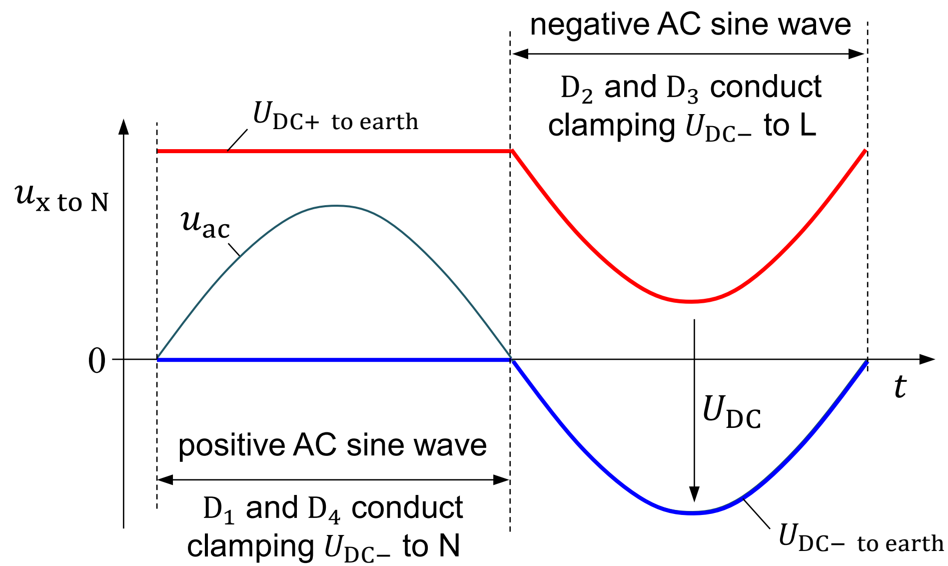


Advantages
- high efficiency possible
- low component count

Disadvantages
- increased CM noise level (DC - N)
- increased control complexity (highside gate driver)
- DC grid can not be directly grounded if AC is grounded

The »Common Mode« (CM) Problem

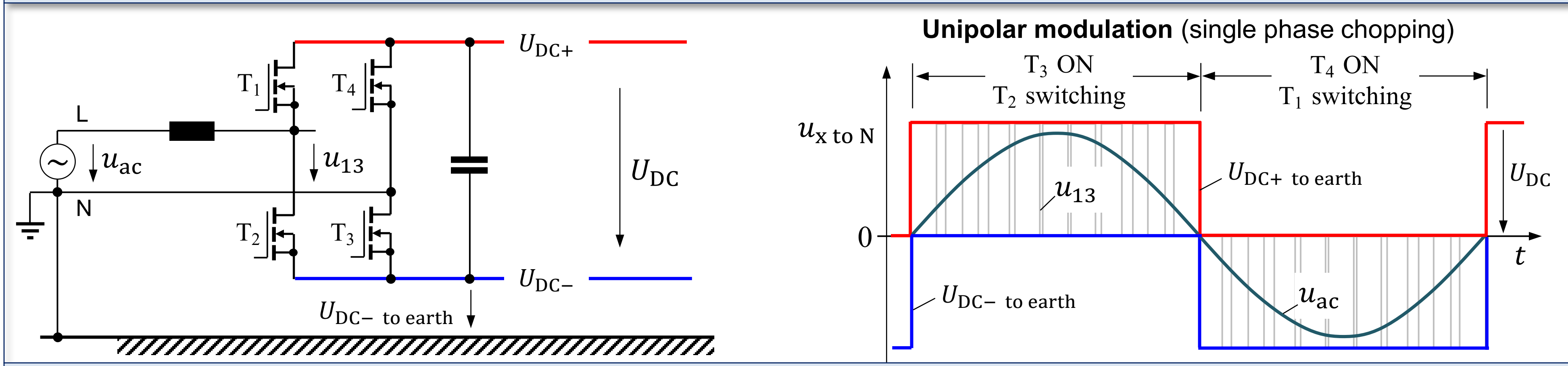




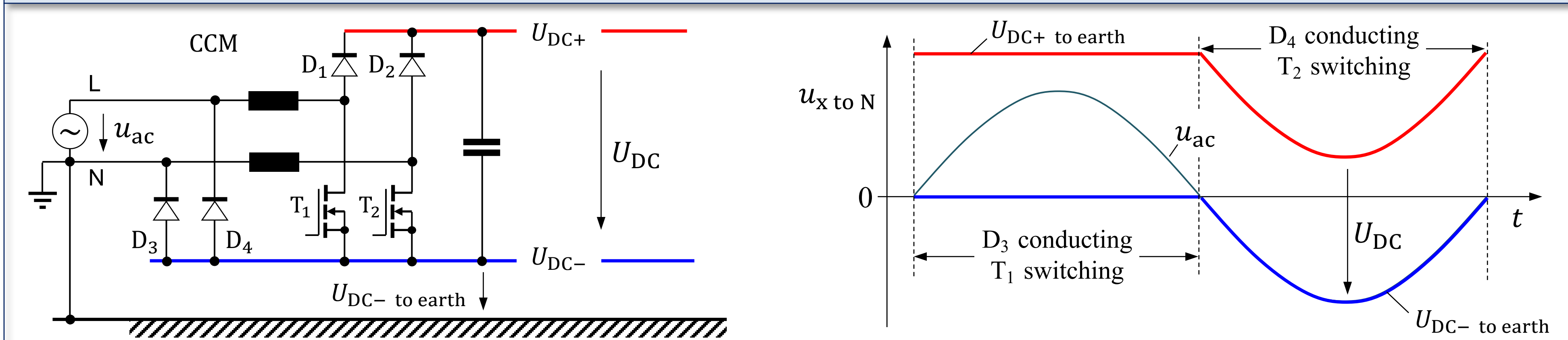
- Depending on the rectifier topology and the modulation method, the potential of the DC grid "jumps" with respect to ground (here with the AC mains frequency)
- Even if no extended grid is connected on the DC side but "only" a battery storage system or a PV system, high leakage/touch currents can result from their parasitic ground capacitances (C_g)!

»Common Mode« Properties of some Single Phase PFC Topologies

Full-bridge PFC

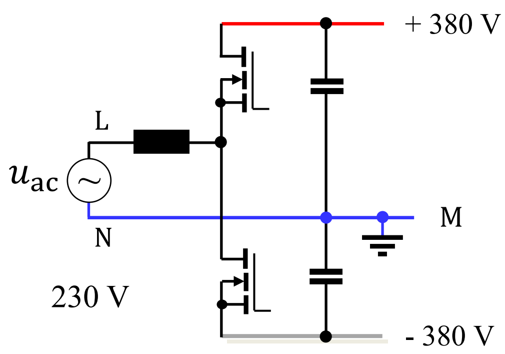


Bridgeless PFC



Single-phase Direct Feed into a Symmetrically Grounded DC Grid

Half-bridge Boost PFC



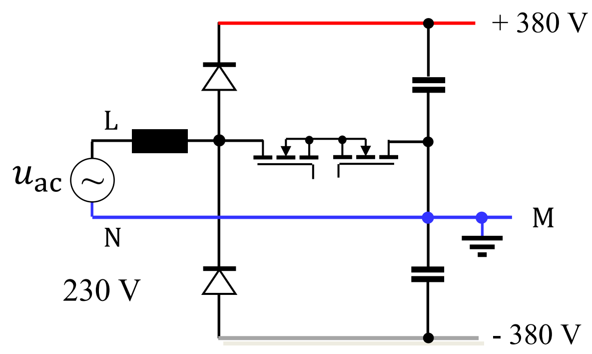
Advantage

- quite simple

Disadvantages

- only suitable for DC grids with line-to-line voltages (line to M) greater than the peak value of the AC voltage
- half-wave operation requires large storage capacitances

T-Type NPC PFC



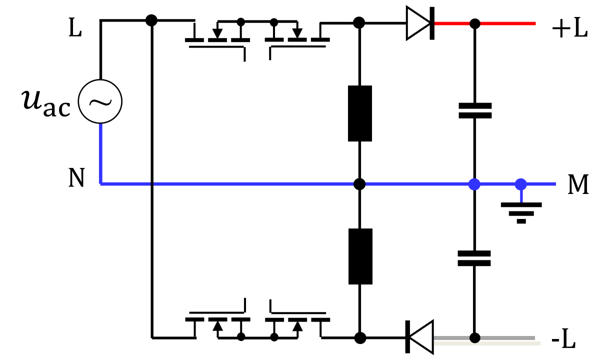
Advantages

- high efficiency
- EMC favorable (3-Level)

Disadvantages

- only suitable for DC grids with line-to-line voltages (line to M) greater than the peak value of the AC voltage
- half-wave operation requires large storage capacitances

Dual Invers PFC



Advantage

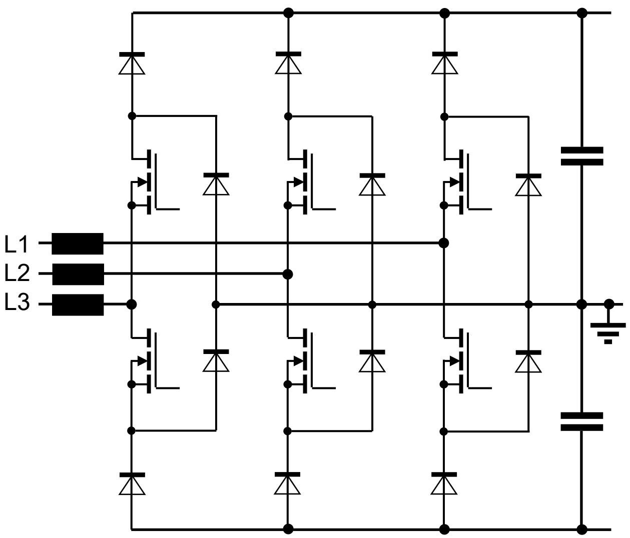
- also DC voltages smaller than the peak value of the AC mains voltage are possible

Disadvantages

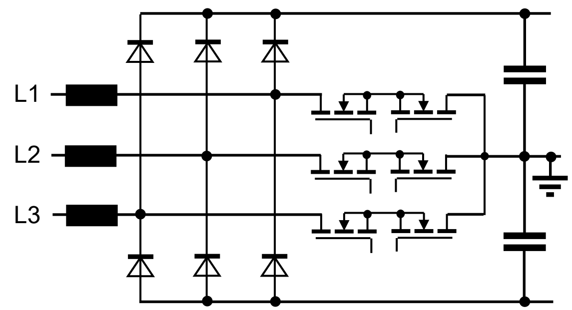
- very high blocking power semiconductors required
- Increased power semiconductor and control effort

Three-phase AC Rectifier Topologies (3-level boost type PFC rectifier)

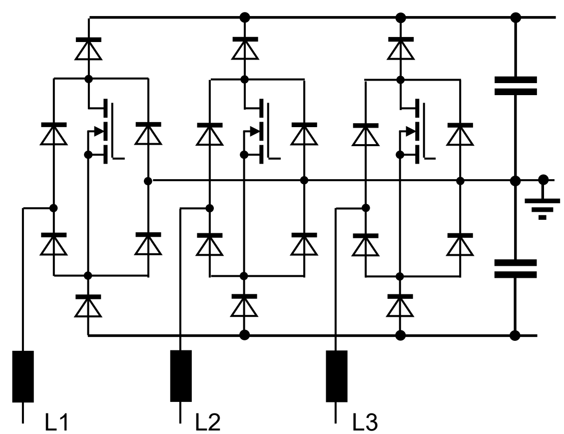
NPC rectifier



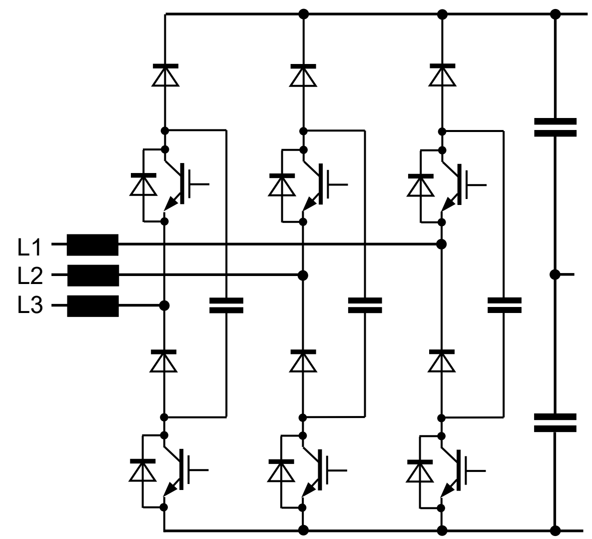
T-Type NPC rectifier



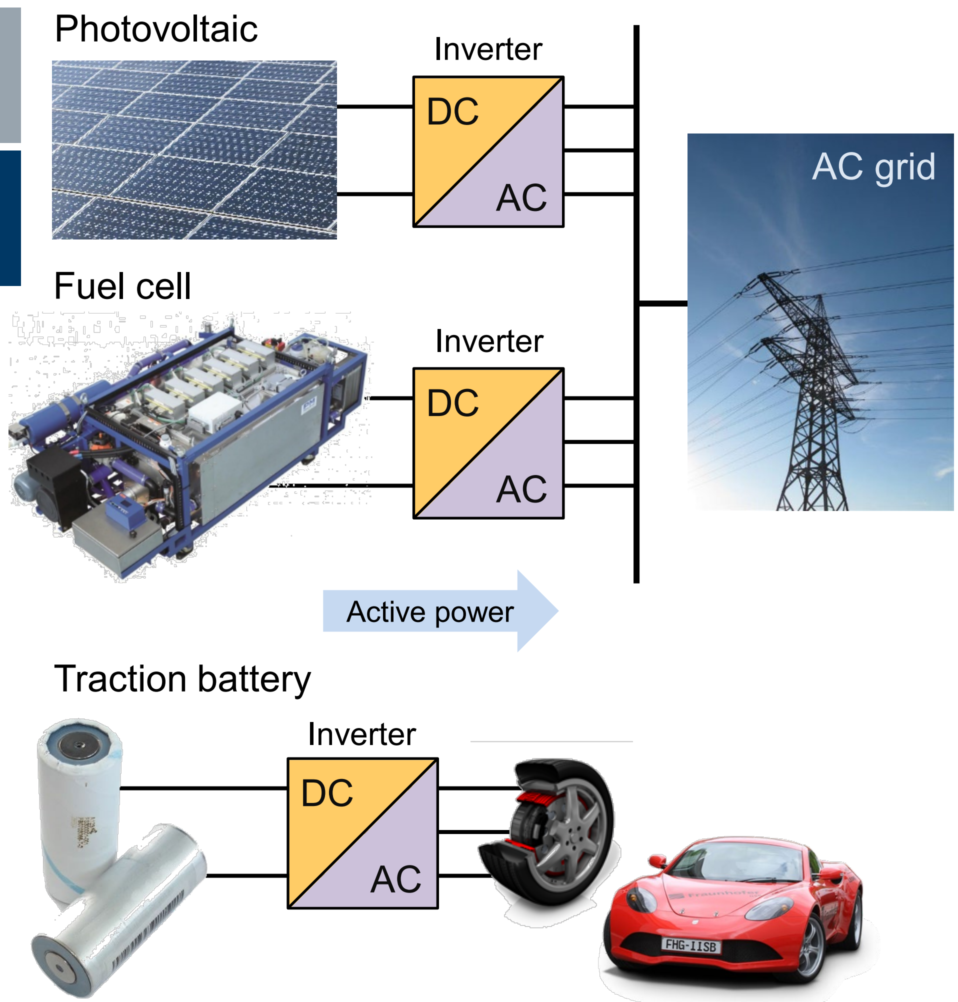
Vienna I rectifier



Flying capacitor rectifier



Inverter

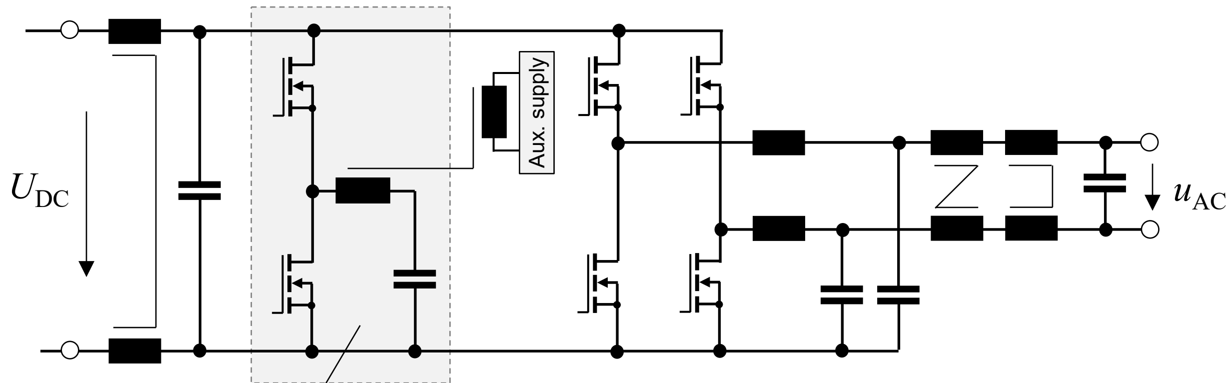


Requirements

- In order to avoid fatal/lethal accidents, the inverter must never feed into a switched-off AC grid section (mains monitoring required)!
- A strict distinction must be made between operation on the public AC grid and a stand-alone (island grid) operation
- The higher the system power, the more demanding the grid connection conditions (grid codes)
- Requirements for high power feed-in inverters:
  - Capability to provide a certain share of inductive or capacitive reactive power for AC grid voltage stabilization
  - Converters must not switch off immediately in the event of a short-term mains voltage drop, in order to prevent a domino effect and thus a large-scale AC mains collapse

Single Phase PV Inverter

Power density at the feasibility limits – Finalist in Google “Little Box Challenge”



Active DC-link capacitor

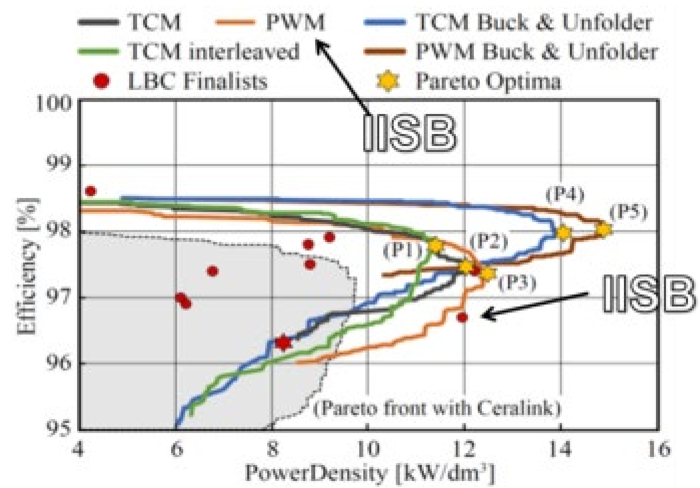


Diagram: Prof. J. Kolar, ETH Zürich:

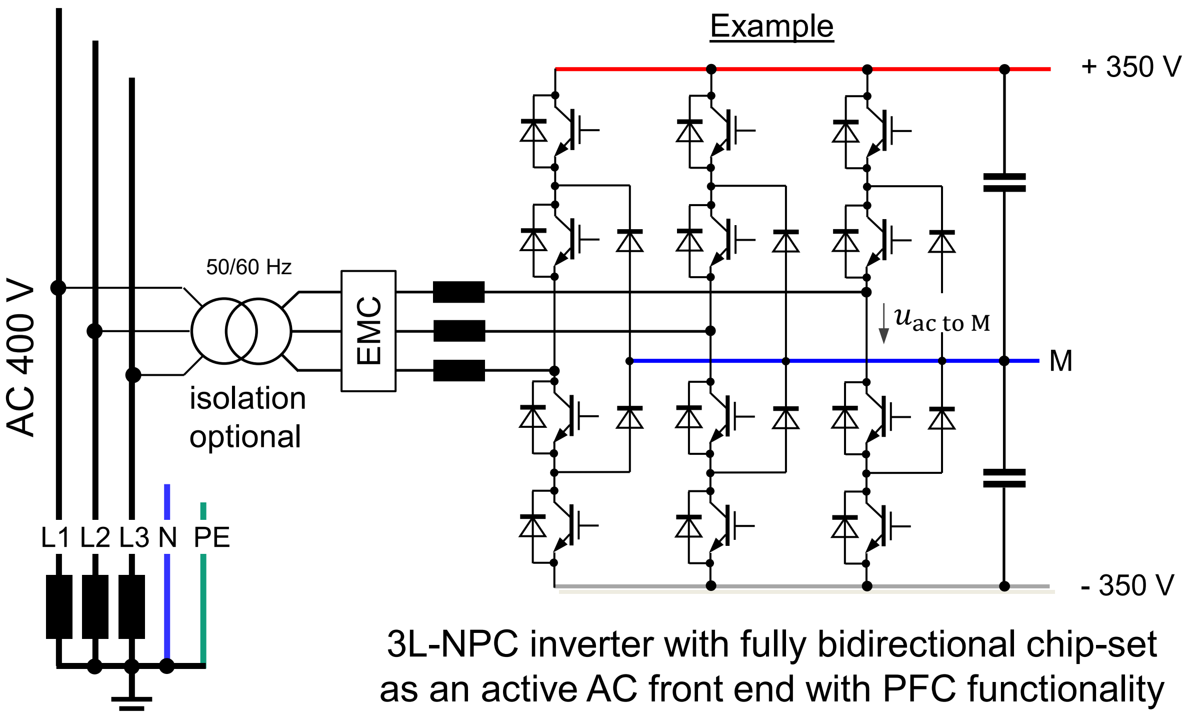
Technical data

Voltage	DC 450 V to AC 240 V
Power (max.)	2 kW
Power density	12 kW/dm^3
Technology	full SiC

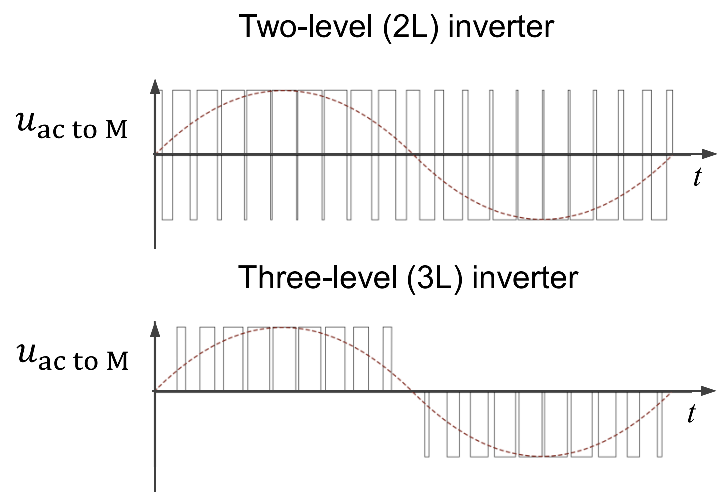
Active Controlled AC Frontends (AFE)

- Allow **bidirectional power flow** (rectifier and inverter operation)
- Ensure a **high power factor** and allow (optional) **capacitive** and **inductive reactive power** to be provided
- Provide a **regulated DC grid voltage**
- Most topologies cannot control or interrupt the current from the AC grid in the event of a DC-side short

Example



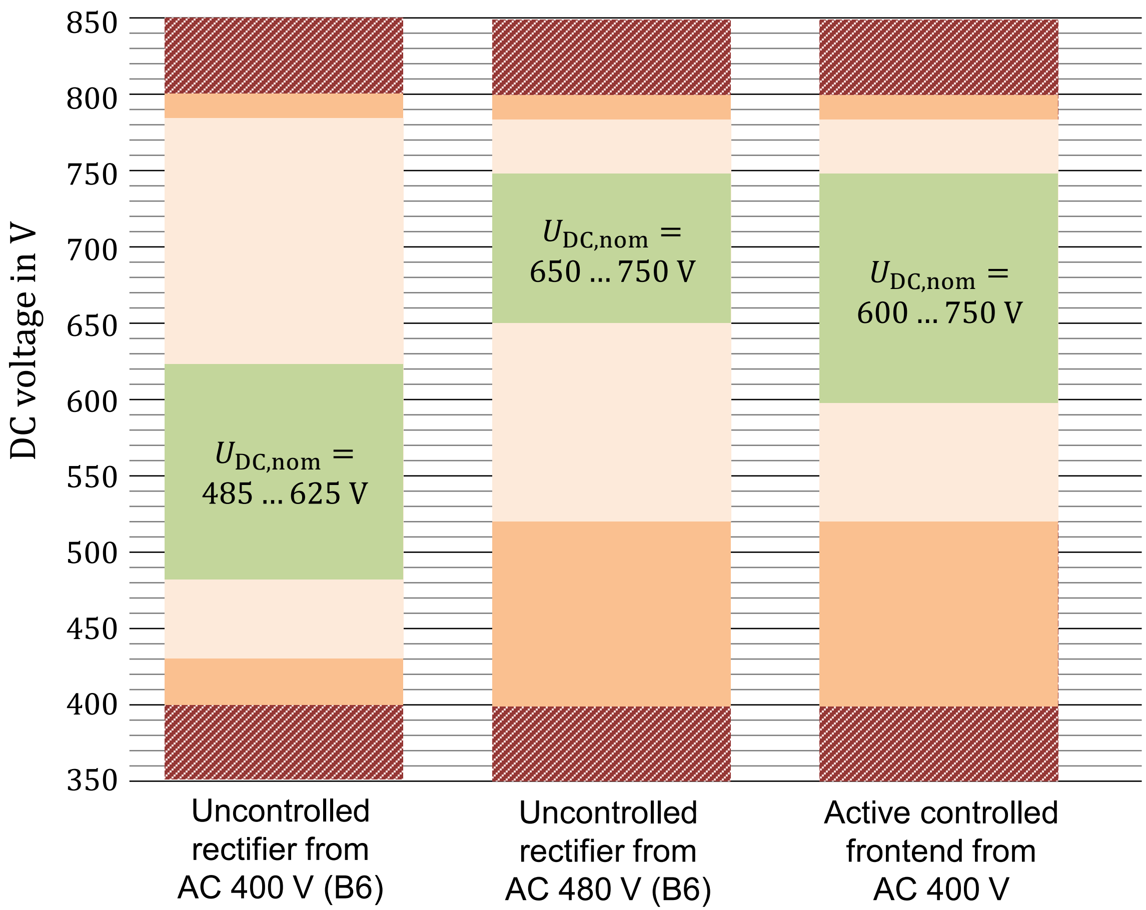
3L-NPC inverter with fully bidirectional chip-set as an active AC front end with PFC functionality



3L inverters allow a considerable reduction in EMC filter effort with regard to AC current harmonics!

Voltage Specifications in Industrial Environments

according to a proposal of the DC-Industrie2 consortium



Nominal operation
- fully functional

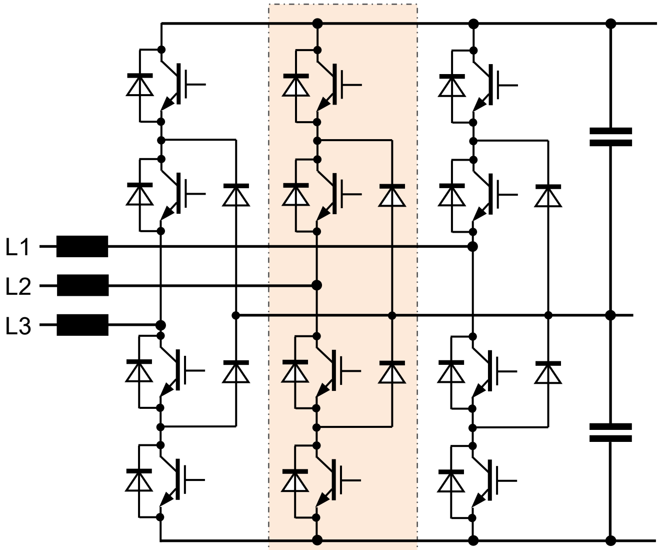
Stationary over-/undervoltage
- continuous operation permitted
- derating permitted
- active grid participants counteract the voltage deviation

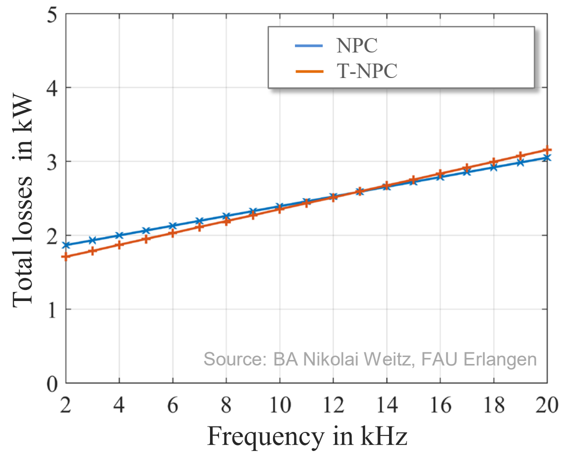
Transient over-/undervoltage
- voltage may be in this range only for a limited time
- functional restrictions are permissible, but must disappear when the nominal voltage range is returned

Shutdown areas
- loss of function, devices switch off permanently for self-protection

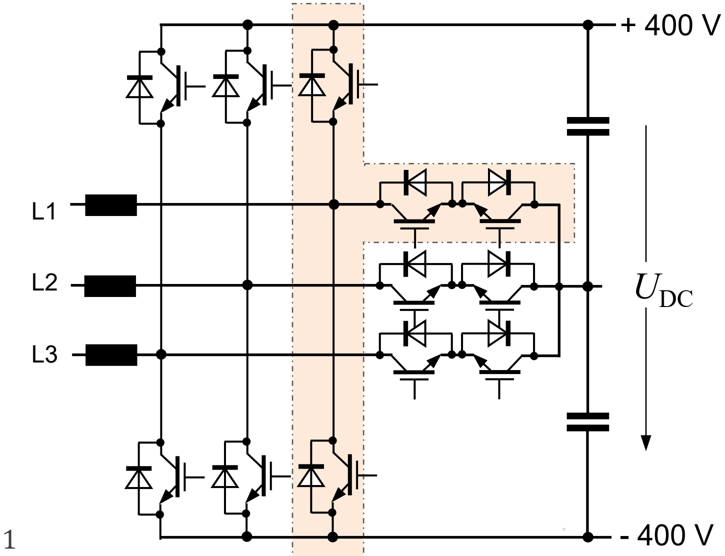
Neutral Point Clamped (NPC)

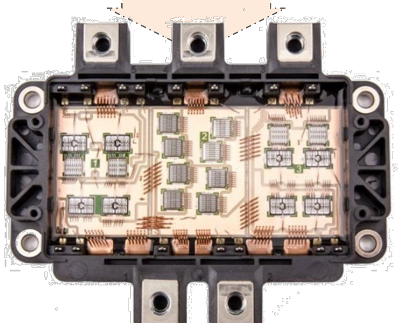
T-Type NPC



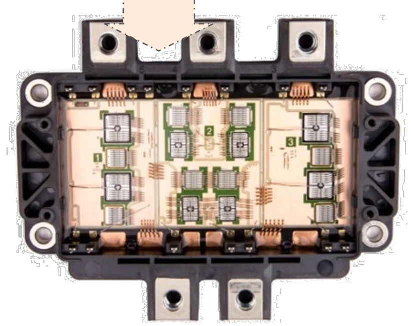


Operating point
$U_{DC} = 800\ V, M = 0{,}8, I_{AC,pk} = 280\ A, \cos\varphi = -1$
(rectifier operation)





Depending on the operating point and engineering focus (costs, efficiency, etc.), there are slight but no substantial advantages for one or the other topology.



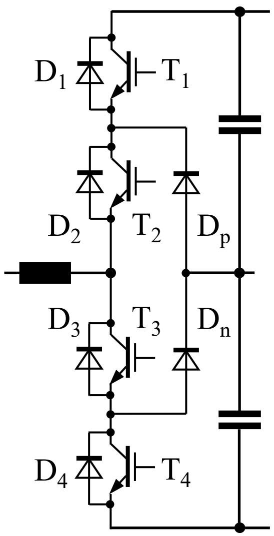
SEMIX 205 MLI 07E4

- Blocking voltage: all semiconductors 650 V ($V_{DC,max}$ = 1300 V)
- Nominal current: 200 A (Price: 166,95 €)

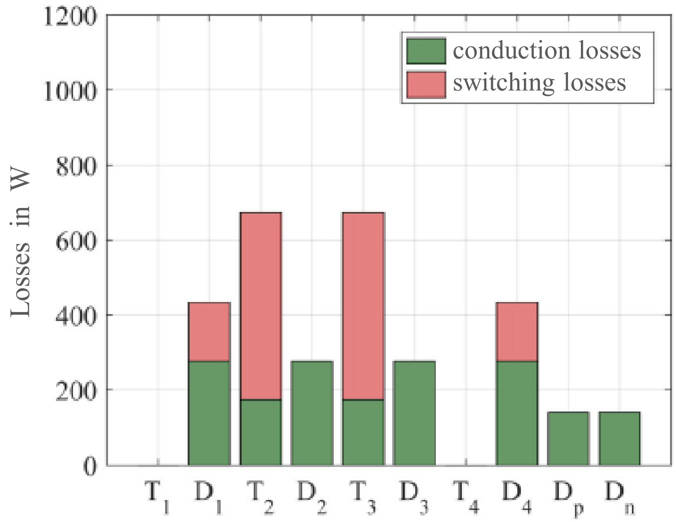
SEMIX 205 TMLI 12E4B

- Blocking voltage: 650/1200 V ($V_{DC,max}$ = 1200 V)
- Nominal current: 200 A (Price: 165,29 €)

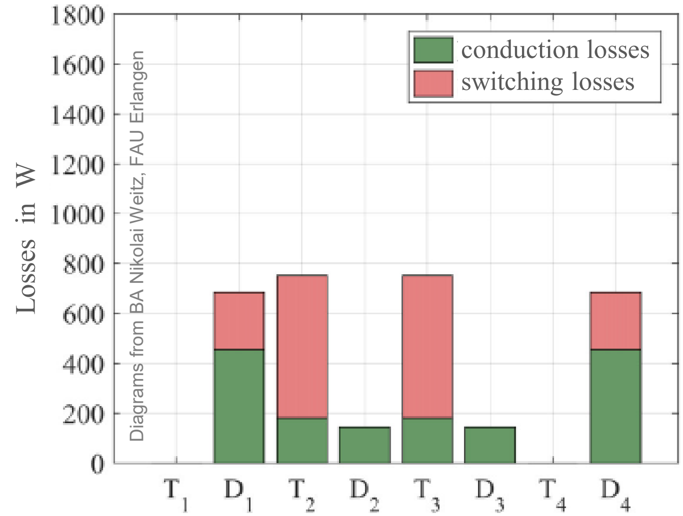
Distribution of Losses in Rectifier Operation (AC to DC)

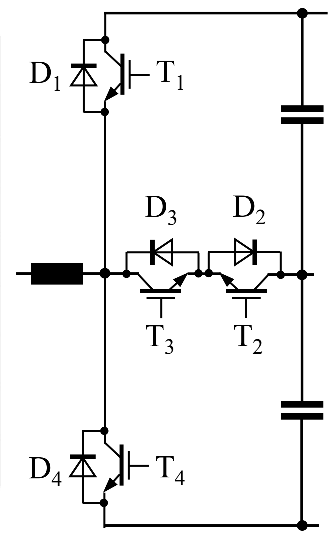


NPC



T-Type NPC





SEMIX 205 MLI 07E4

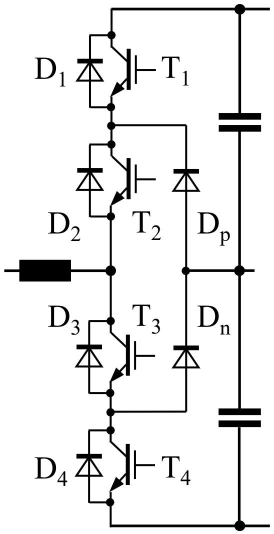
Operating point

$U_{DC} = 800$ V, $I_{AC,pk} = 280$ A, $f_{sw} = 20$ kHz, $\cos\varphi = -1$, $M = 0{,}8$

SEMIX 205 TMLI 12E4B

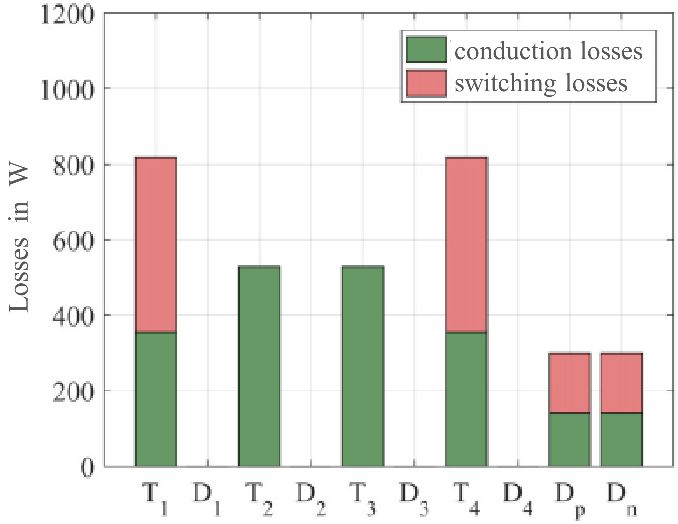
- There are potential savings for pure PFC rectifier operation (inactive switches ($T_{1,4}$) could be replaced by their diodes)
- Already at 20 kHz (just above the audible limit) silicon power semiconductors reach their limits, i.e. the switching losses clearly begin to dominate
- The analysis of the loss distribution shows optimization potential through hybrid assembly (i.e. mixed assembly of Si and SiC components)

Distribution of Losses in Inverter Operation (DC to AC)

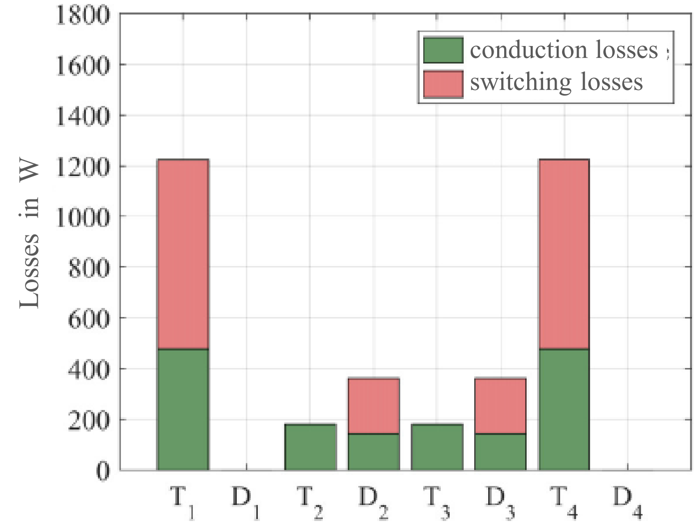


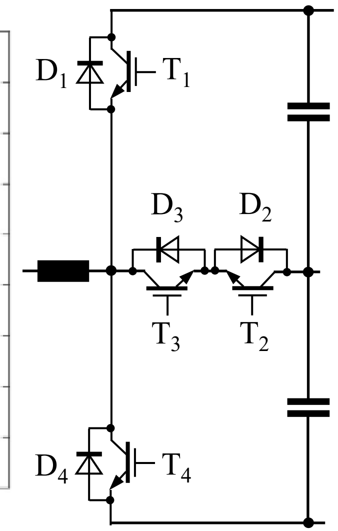
SEMIX 205 MLI 07E4

NPC



T-Type NPC





SEMIX 205 TMLI 12E4B

Operating point

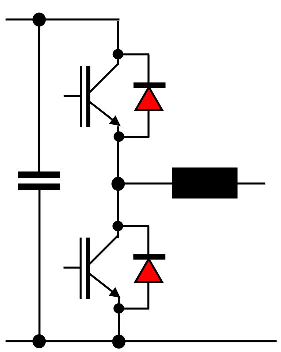
$U_{DC} = 800$ V, $I_{AC,pk} = 280$ A, $f_{sw} = 20$ kHz, $\cos\varphi = +1$, $M = 0{,}8$

- In inverter operation, the outer switches are particularly stressed
- Here, too, one can see that bipolar Si power semiconductors come to their dynamic limits quite soon
- The analysis also shows optimization potential through a mixed assembly of Si and SiC devices

Diagrams from BA Nikolai Weitz, FAU Erlangen

Limits of modern Si power semiconductors

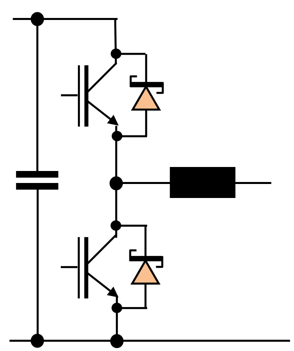
Diode commutation



Si IGBT + Si (p/n) diode

Switch and diode
bipolar

Hard switching

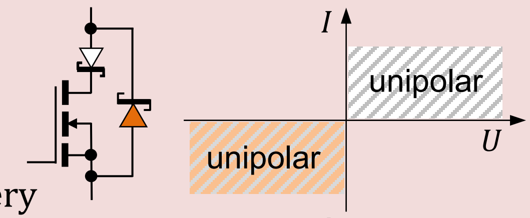


Si IGBT +
SiC Schottky diode (SBD)

Switch **bipolar,**
diode **unipolar**

Soft switching and Si alternatives

Si MOSFET
+ SiC SBD



A semiconductor cemetery
to achieve unipolar behavior in the 1st and 3rd quadrants

Soft switching
But zero current a/o zero voltage switching (ZCS / ZVS)
is not economically viable in any topology

The most interesting Si alternatives today
SiC-MOSFET and **GaN-HEMT**

0	**50 kHz**	**100 kHz**	**with 650 V power semiconductors**
0	**15 kHz**	**30 kHz**	**with 1200 V power semiconductors**

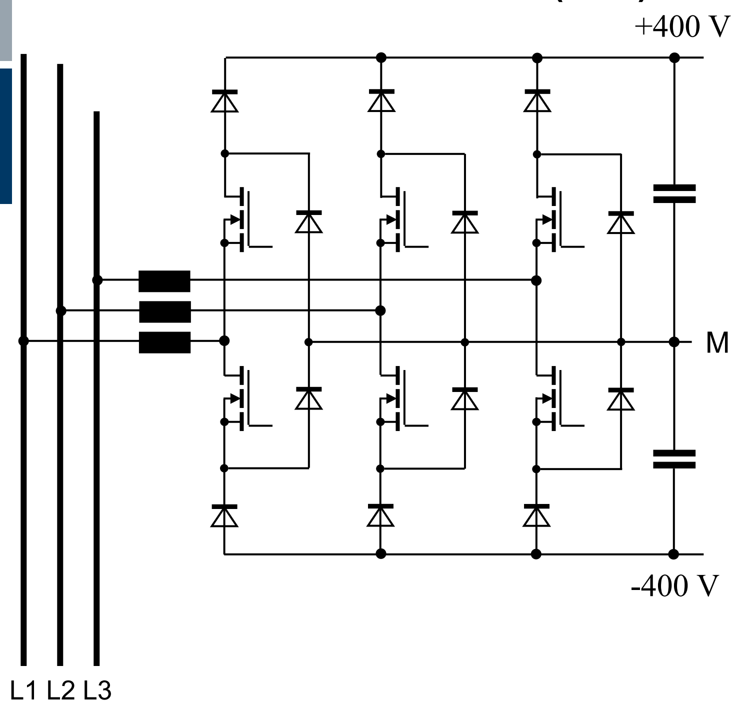
possible switching frequencies →

Switching frequency limits apply when peak efficiencies are required beyond 98%

Rectifier with Galvanic Isolation via a Medium Frequency / RF Transformer

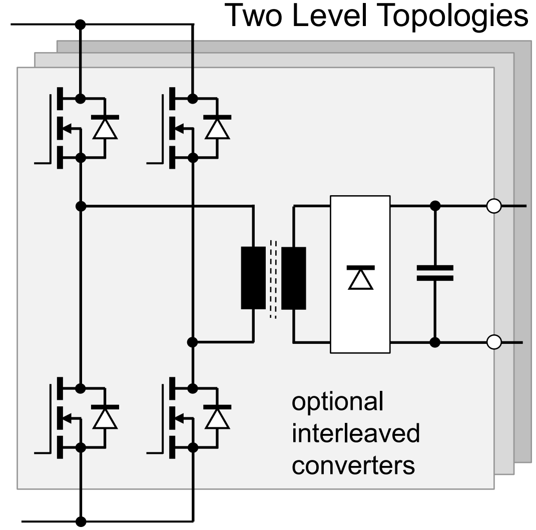
Examples

Active Frontend (AFE)

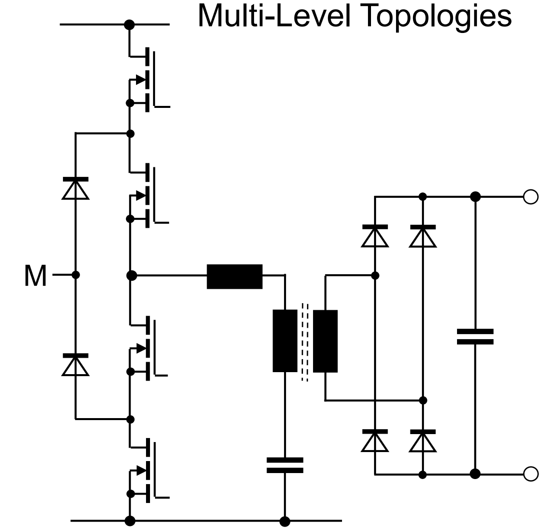


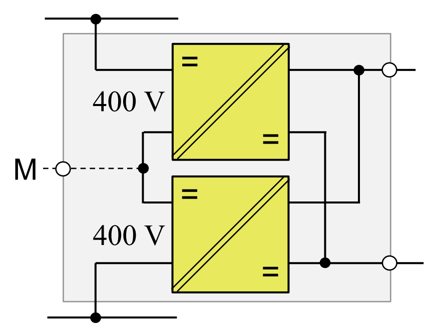
Galvanic Isolating DC/DC

Two Level Topologies



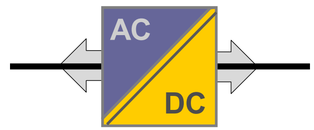
Multi-Level Topologies

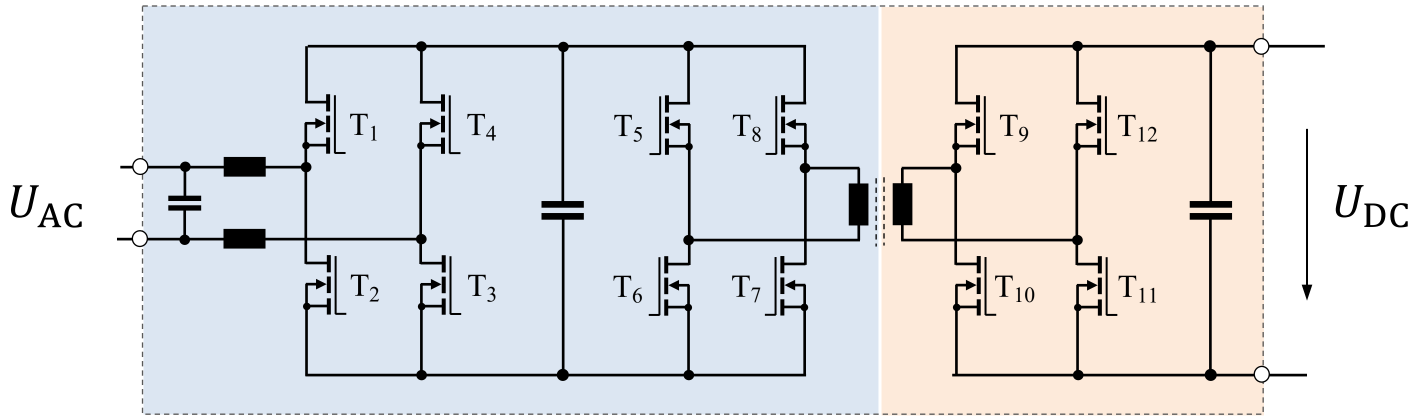




optional
series/parallel connection of
single converters

Bi-directional Coupling of the AC Grid with an IT DC Grid



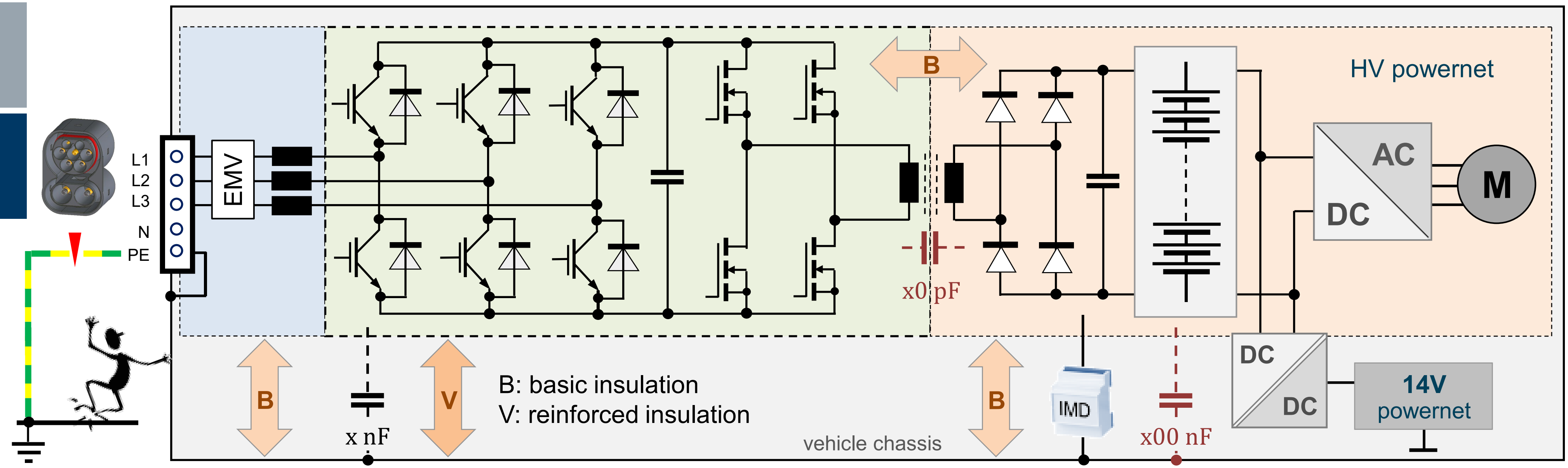


Galvanic Isolation and Bi-directionality

Already for a single phase a very high circuitry effort, therefore

minimize the number of interfaces to the AC grid!

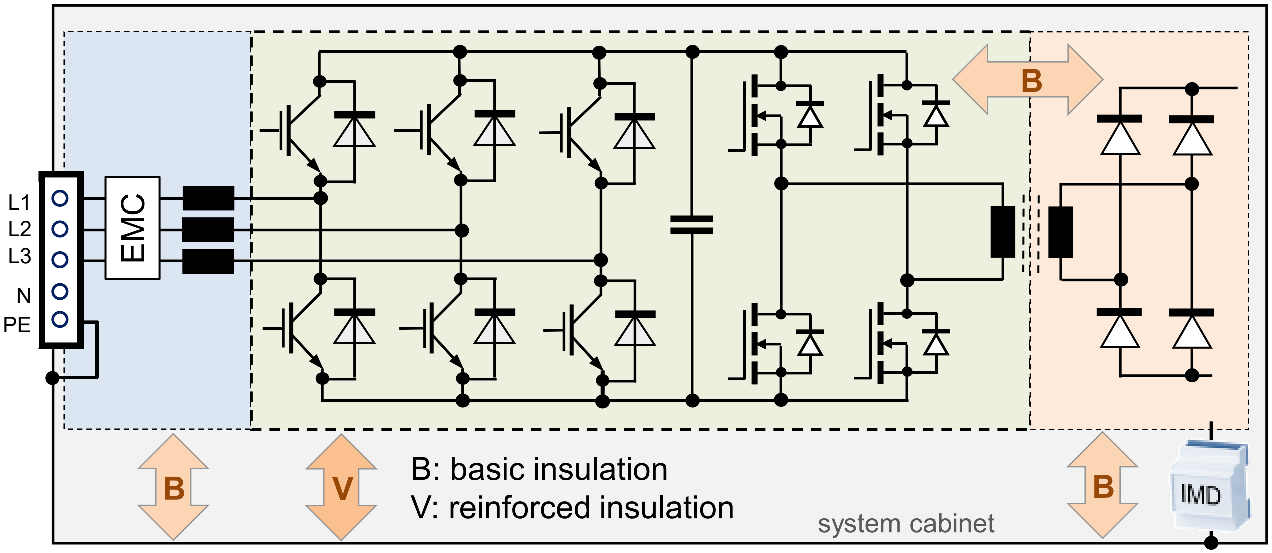
Coupling a DC IT Grid with the Grounded AC Grid (e.g. when charging an EV)



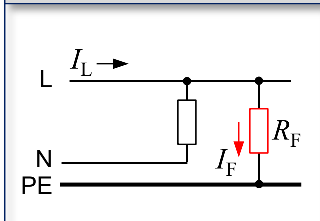
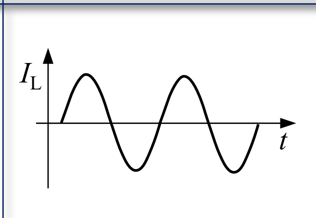
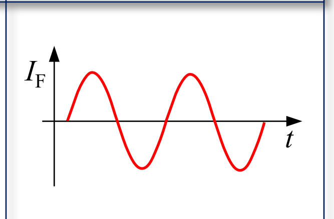
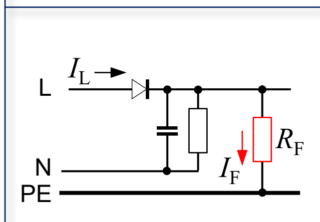
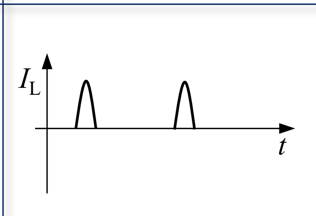
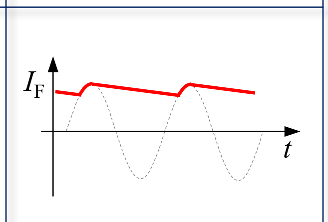
An isolating AC/DC converter has to fulfill two main normative requirements (⇨ measures to do so)

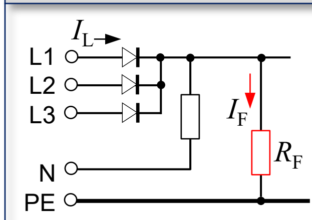
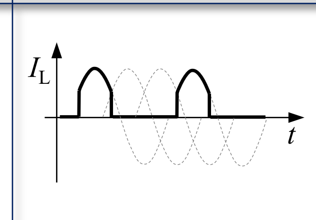
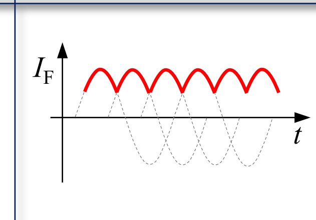
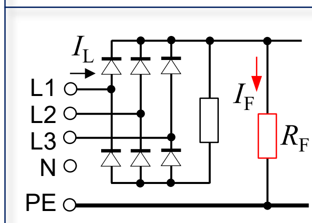
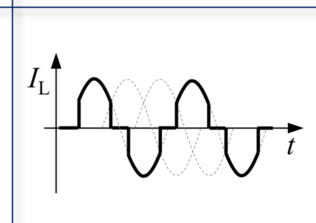
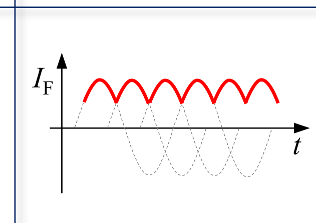
- **Limit leakage currents**, which in the event of a fault (interruption of the protective conductor PE) could as a touch current endanger people!
  ⇨ Decoupling the high "earth capacitance" of the entire HV vehicle electrical system (IT) through galvanic isolation
- **Avoid DC residual currents** on the AC power lines in order not to blind residual current devices (RCD-A) in the AC grid infrastructure!
  ⇨ Reinforced isolation of the circuit part between the AC rectifier and galvanic isolation (transformer)

Components of Decentral Energy Systems

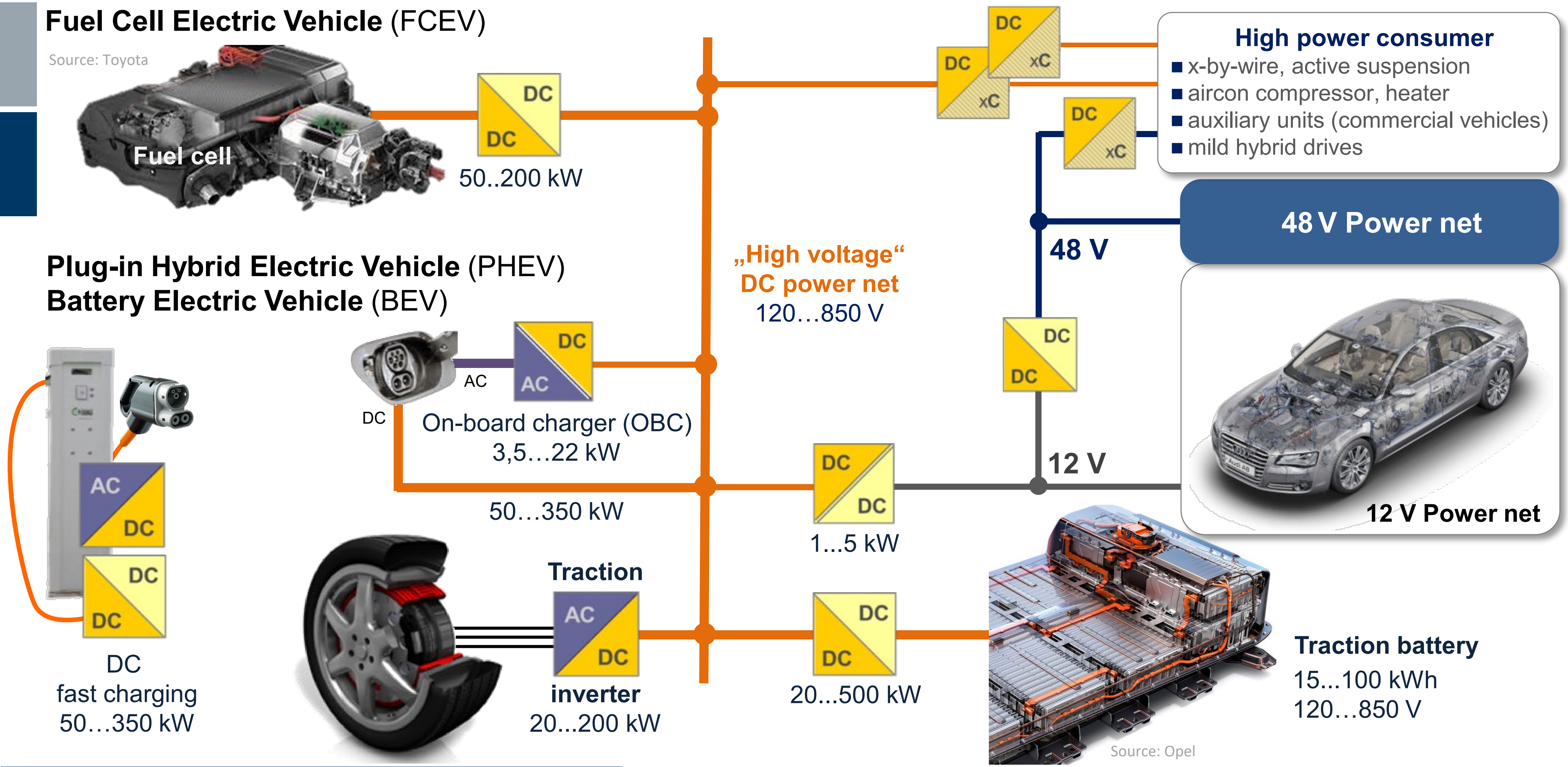


- Faults behind diode structures can lead to a DC component in the mains current
- A single error in these circuit parts must not lead to a hazard
  ➲ reinforced insulation required
- Behind the internal transformer there is an IT grid with insulation monitoring (IMD) ➲ basic insulation sufficient

Fault case	Load current	Fault current
		
		

Fault case	Load current	Fault current
		
		

Power Electronics in Electric Vehicles´ Power Net



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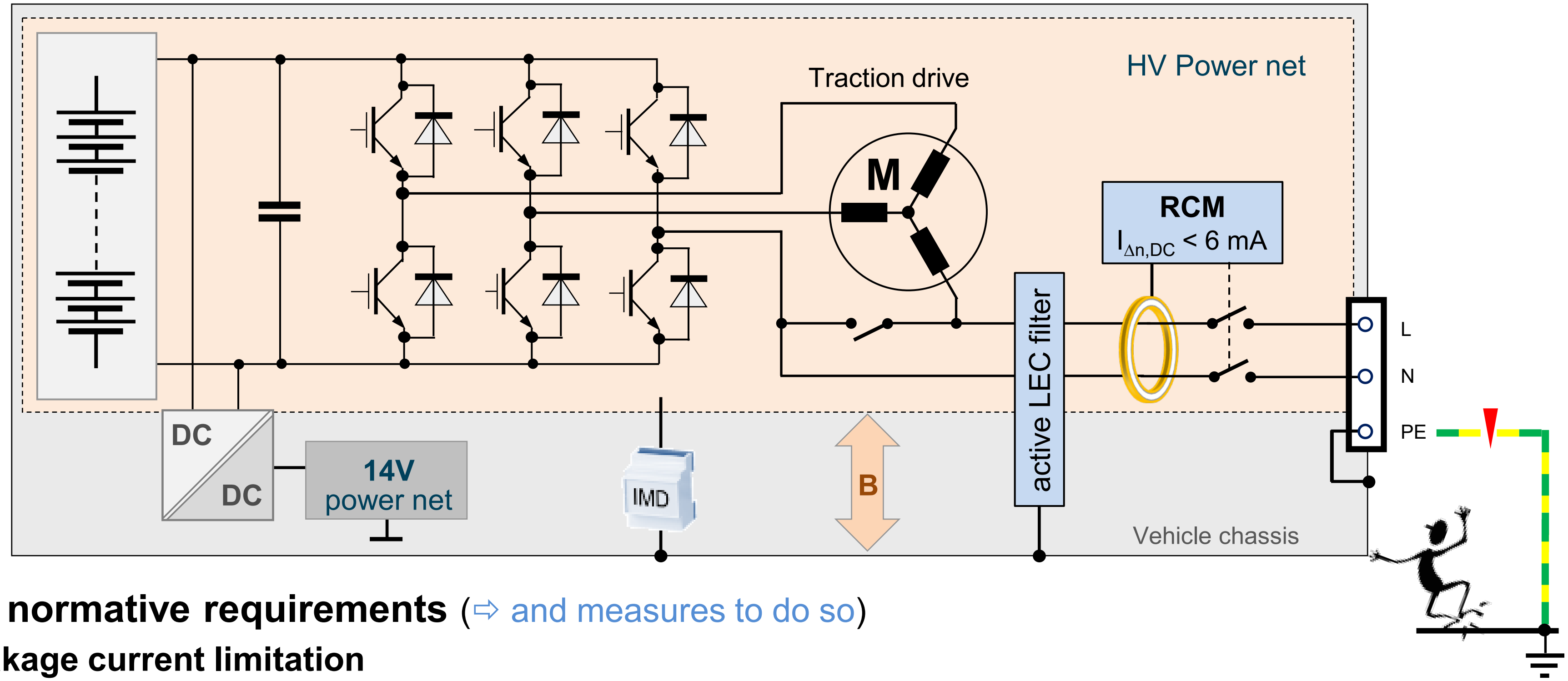
Coupling a DC Grid with the Public AC Grid Without Galvanic Isolation

(at the example of a high voltage vehicle power net)



Basic normative requirements (⇨ and measures to do so)

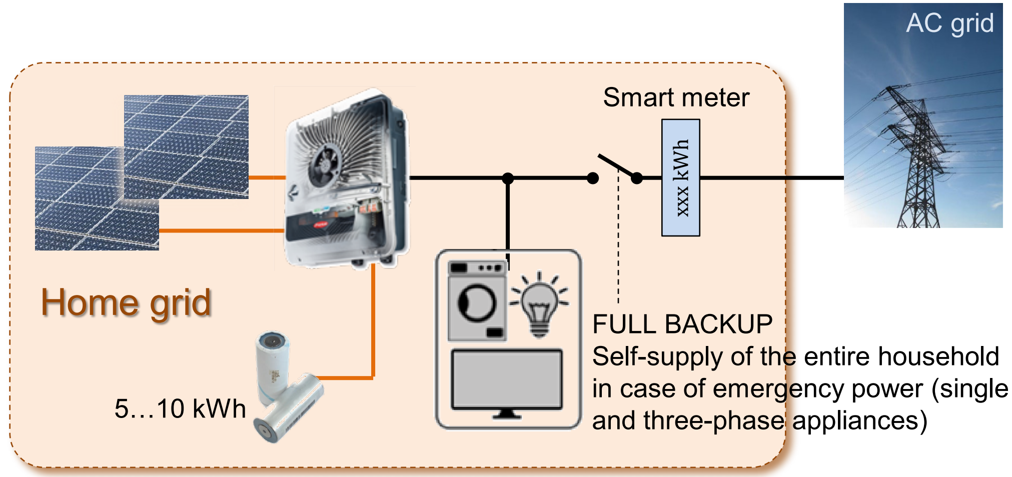
- **Leakage current limitation**
  - ⇨ Here by using an active leakage earth current filter (LEC filter)
- **Avoid DC residual currents on the AC power lines**
  - ⇨ DC-compatible residual current monitoring (Residual Current Monitoring – RCM) and mains disconnector

Components of Decentral Energy Systems

Power Electronics for a Decentral Home Energy System

Example
FRONIUS SYMO GEN24 PLUS

SiC technology inside



Technical data

PV converter

- 2x MPP Tracker: (80)278…800 V, 12.5 A (each)
- Max. DC input voltage: 1000 V
- Max. PV peak power: 15 kW

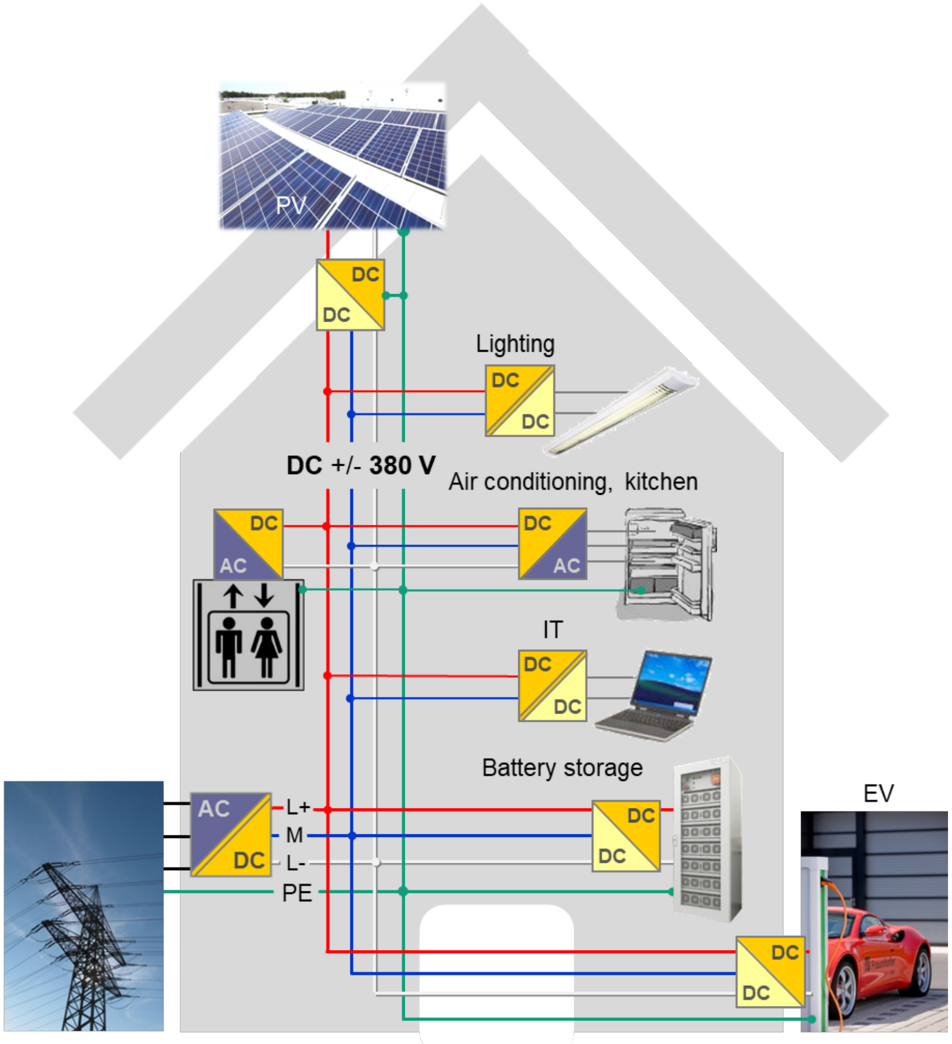
Inverter

- Non isolating
- Efficiency PV to AC: 97.9%

Battery converter

- Battery voltage range: 160…531 V
- Max. charge/discharge power: 10 kW

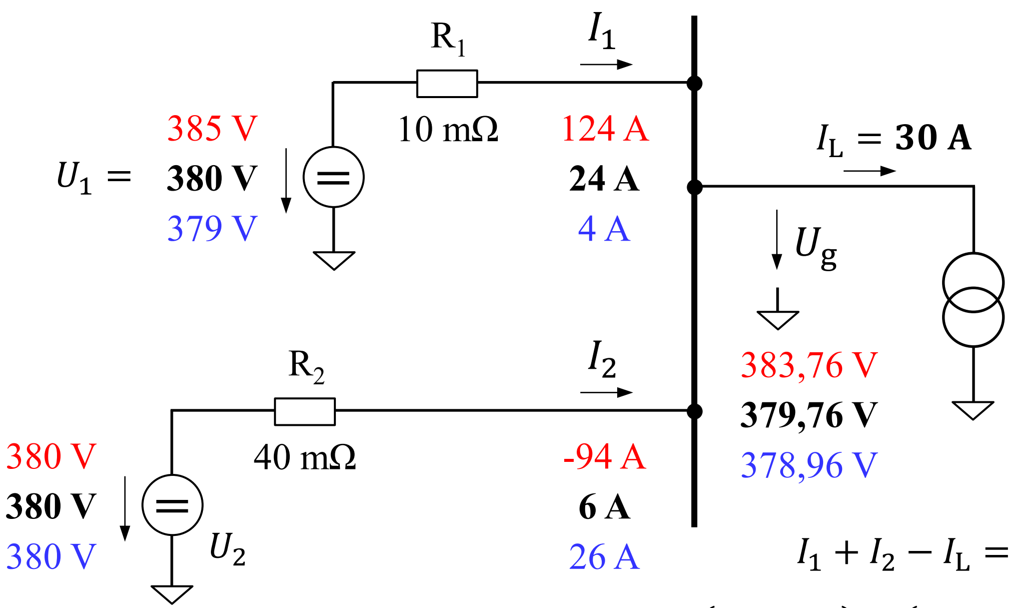
DC Grids for Decentral Energy Systems



Controlling Local DC-Grids

Never Connect Voltage Sources in Parallel!

Three case studies in three colours



$$I_1 + I_2 - I_L = 0$$

$$\frac{(U_1 - U_g)}{R_1} + \frac{(U_2 - U_g)}{R_2} = I_L$$

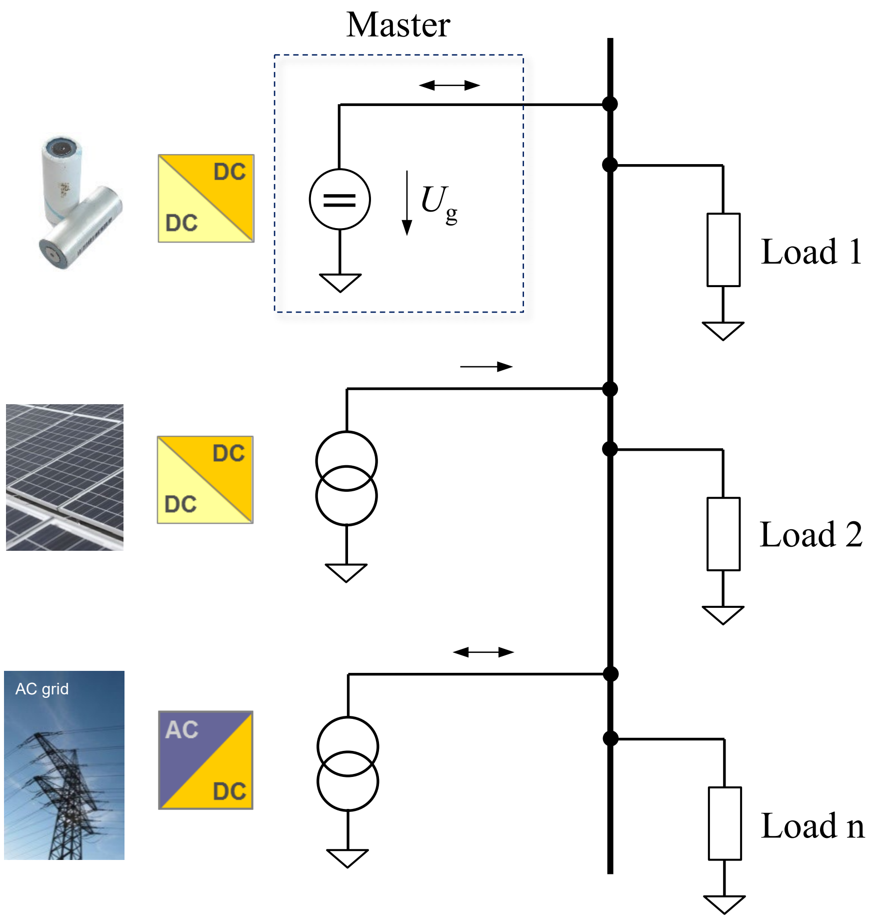
- Even with exactly the same source voltages, there can be significant shifts in the current distribution - e.g. due to different cable lengths or internal resistances
- Small differences in the source voltages can result in very high equalizing currents or even circulating currents!

Note: 5 Volt deviation means only **1.3%** at 380 V
(cf. tolerance of voltage dividers, temperature drift of measuring amplifiers, etc.)

Conclusion

- Not more than one feed-in converter must work with output voltage regulation!
- Caution also with several battery storage systems in a grid: extreme equalizing currents possible!

Grid Voltage Control based on a Master-Slave Principle



Principle

- One source (the **master**) takes over the grid **voltage regulation**, **all** other feeding converters work current-regulated

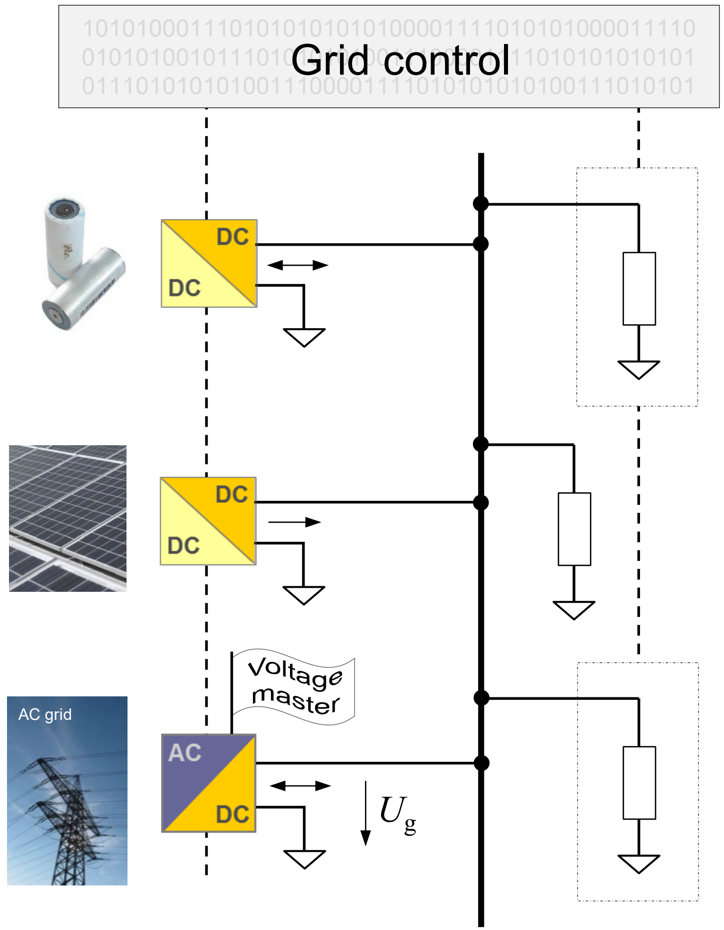
Problem

- The master must be able to work bidirectionally and, if necessary, supply the entire grid load or absorb the entire excess power on its own
- Grid breakdown or leaving the grid voltage window if the master fails (remedy: voltage limitation in all other power sources)

Application example

- The 12 V / 24 V electrical system in vehicles in which the lead acid battery acts as the master

Superordinate Grid Control (Smart-Grid)



Advantages

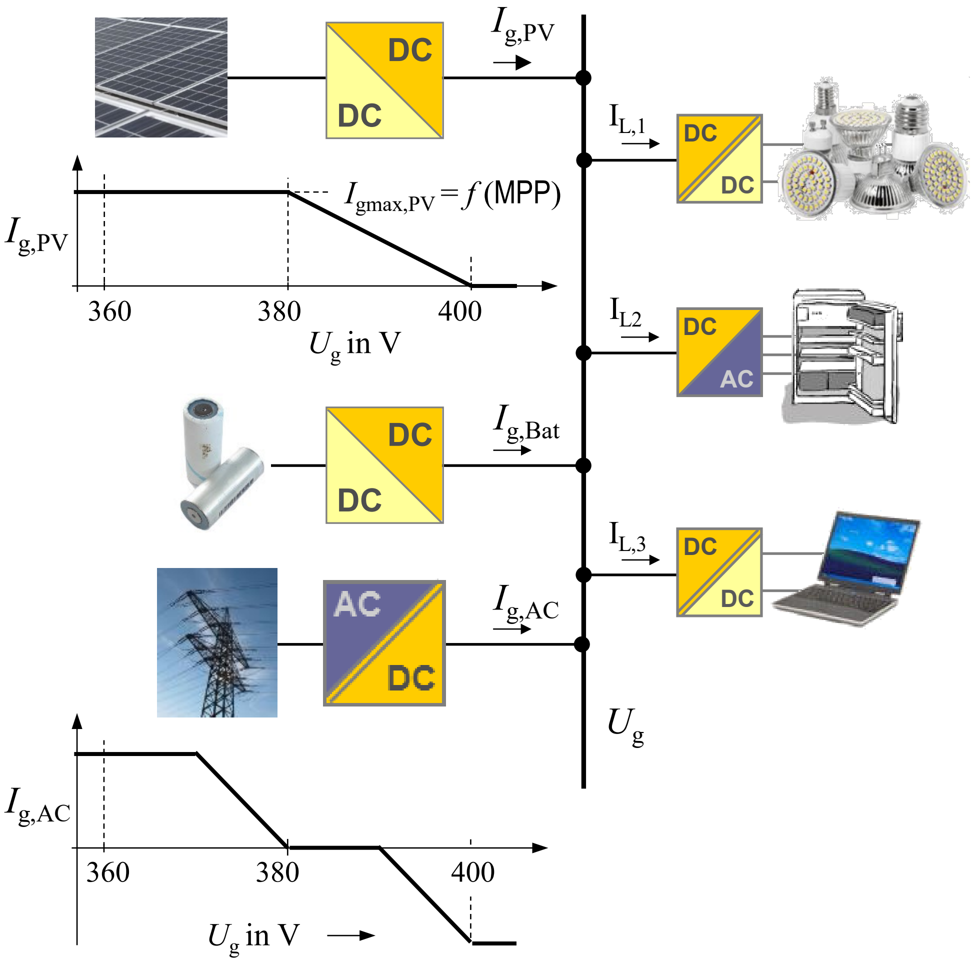
- "Voltage master" function can be passed on through dynamic reconfiguration of the feed-in converters
- Power flows can be flexibly adjusted
- Controllable loads allow demand-side management

Problems

- Additional communication channel required
- Safety functions are real-time critical
- Successful hacker attacks can have fatal consequences

Control of Local DC Grids

Droop Control



Idea

- Use the **grid voltage** as the central control variable (similar to frequency in the AC grid)
- In terms of control, all feeding converters work as voltage sources with internal resistance respectively voltage-regulated current sources

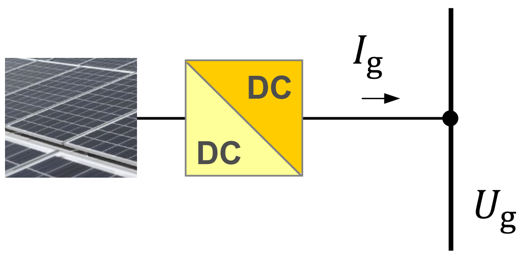
Advantages

- No higher-level communication infrastructure required
- Very high robustness and availability
- High-level functions (e.g. for energy management) can be implemented by online adaption of the control characteristics

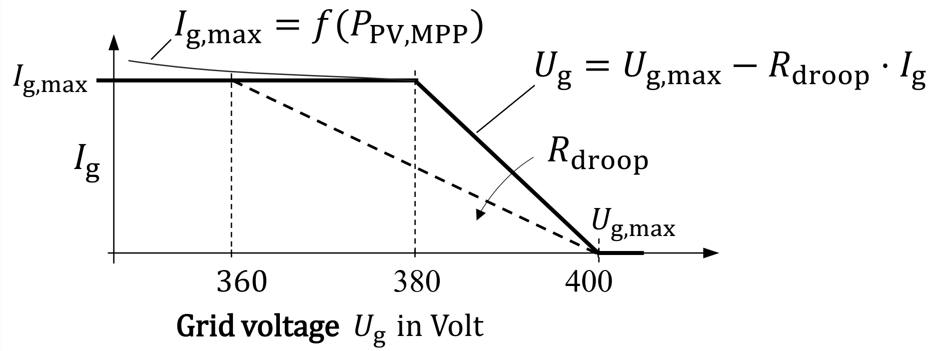
Droop Control

Exemplary control characteristic for a unidirectional source

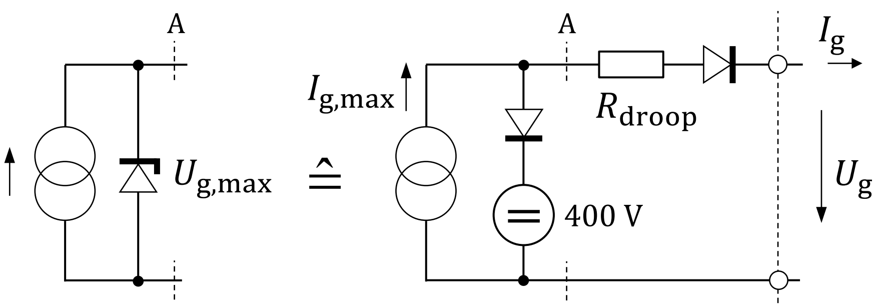
Feed-in converter



Control characteristic of the converter



Equivalent circuit



Droop resistance

$$R_{droop} = -\frac{dU_g}{dI_g}$$

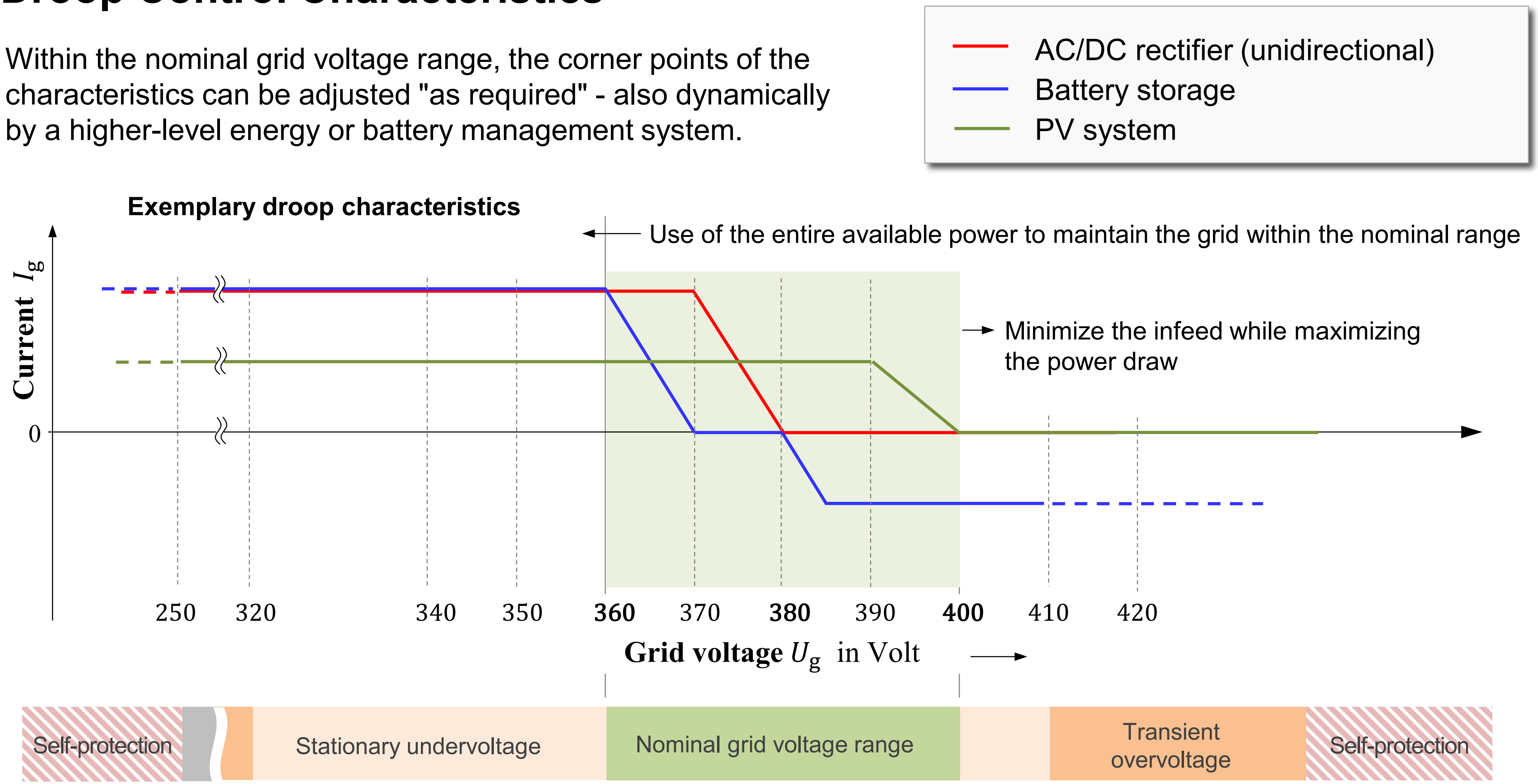
If $\Delta I_g = +20\text{ A}$ at $\Delta U_g = -20\text{ V}$ ⇨ $R_{droop} = 1\ \Omega$

If $\Delta I_g = +20\text{ A}$ at $\Delta U_g = -40\text{ V}$ ⇨ $R_{droop} = 2\ \Omega$

Control of Local DC Grids

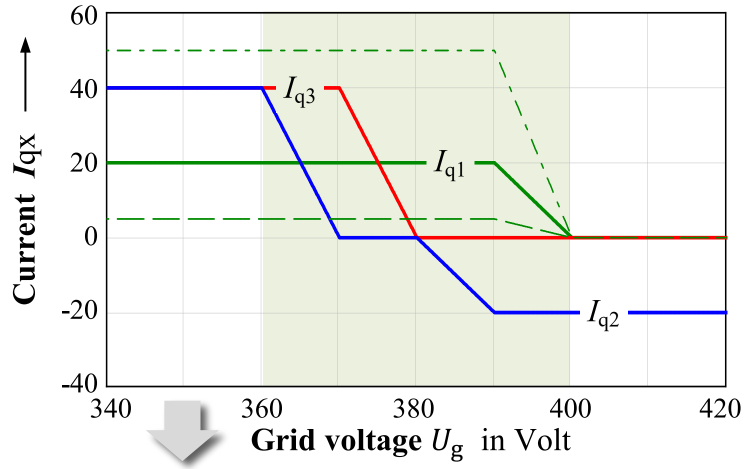
Droop Control Characteristics

Within the nominal grid voltage range, the corner points of the characteristics can be adjusted "as required" - also dynamically by a higher-level energy or battery management system.

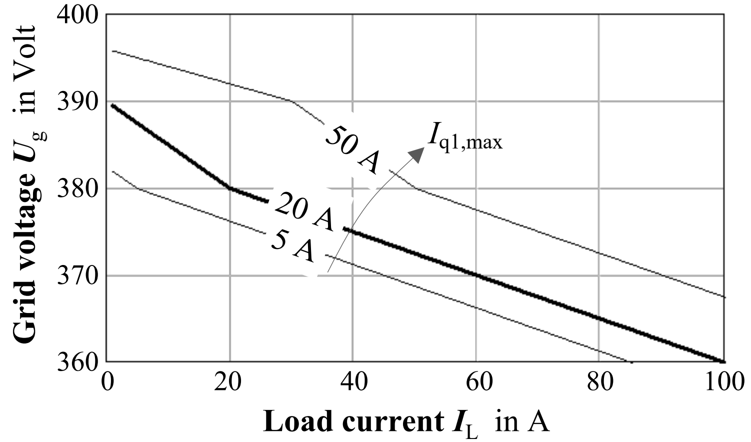


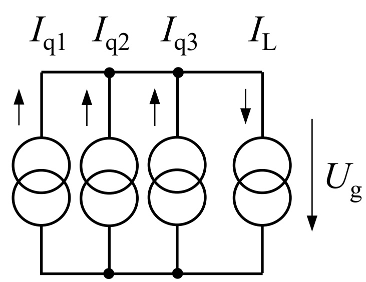
Effect of the droop characteristics on the steady-state grid voltage

Droop characteristics of the sources in a grid



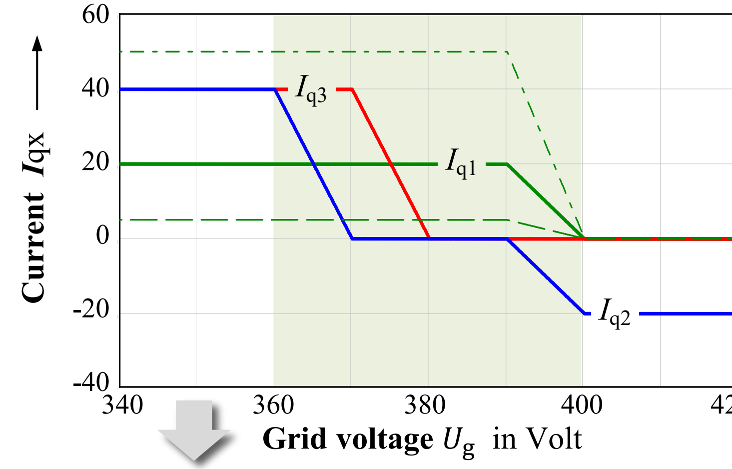
Resulting grid voltage depending on grid load



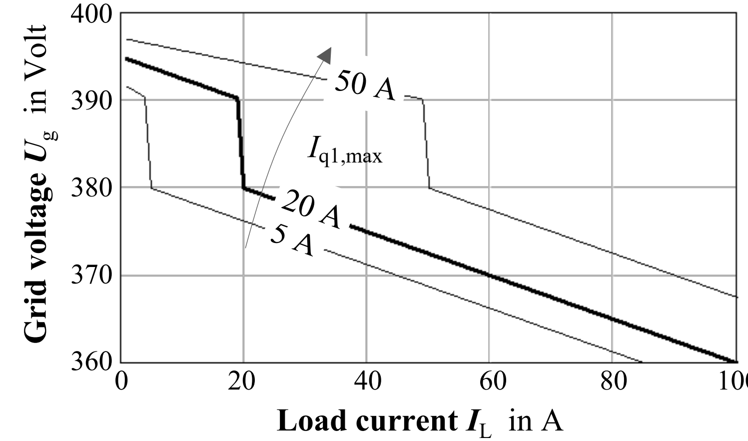


Do not allow any "undefined" voltage ranges!
(i.e., never provide all sources in the grid simultaneously with a horizontal characteristic (= ideal current sources), as shown on the right between 380 V and 390 V!) ⇨

Droop characteristics of the sources in a grid



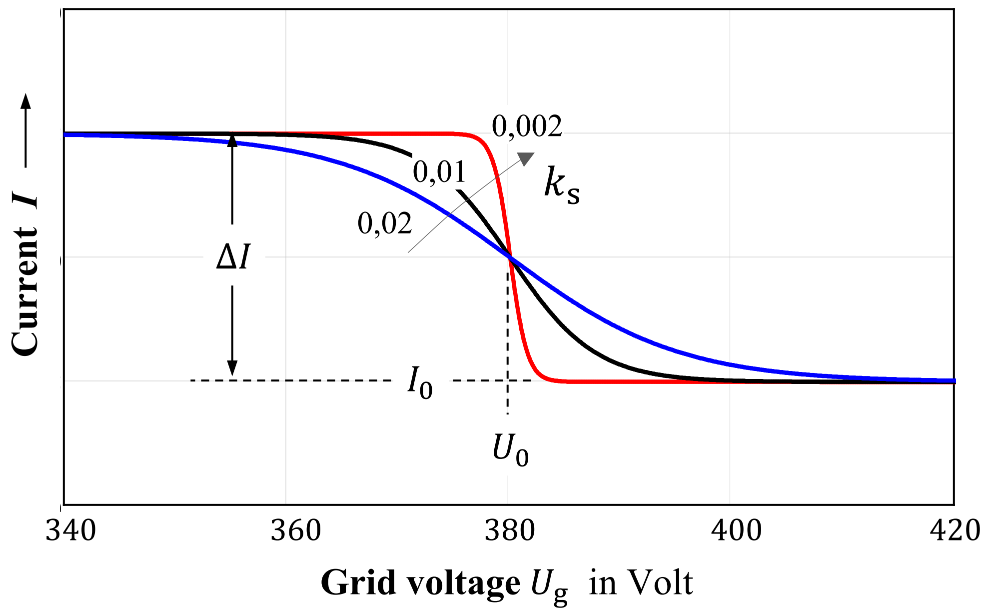
Resulting grid voltage depending on grid load



Droop Control Characteristics

Droop characteristics must be monotonous but not piecewise linear!

The “**Fermi function**” (or Sigmoid function) as an example of a very variable, monotonous and everywhere differentiable droop characteristic



$$I(U_g) = \Delta I \left(\frac{1}{1 + e^{\frac{1}{k_s}\left(\frac{U_g}{U_0} - 1\right)}} \right) + I_0$$

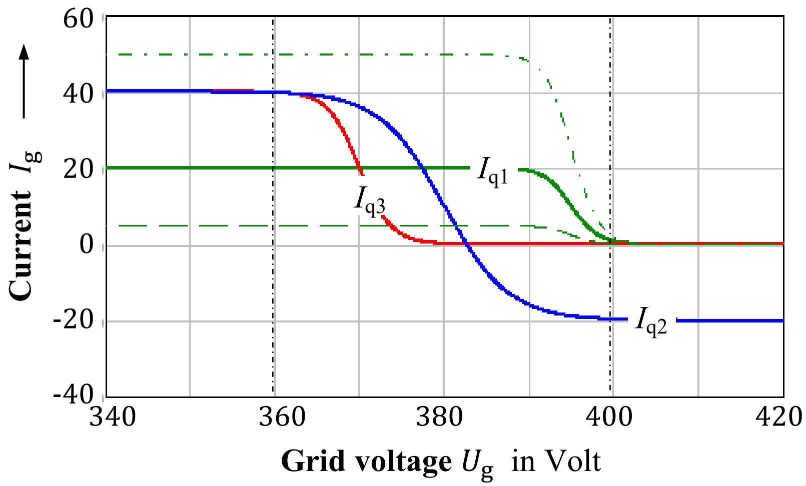
The steepest slope, i.e. the **minimum droop resistance** occurs at the turning point at U_0:

$$R_{\text{droop\_min}} = \left(\frac{-dI(U_g)}{dU_g} \right)^{-1} \Bigg|_{U_g = U_0} = \frac{4\, U_0 k_s}{\Delta I}$$

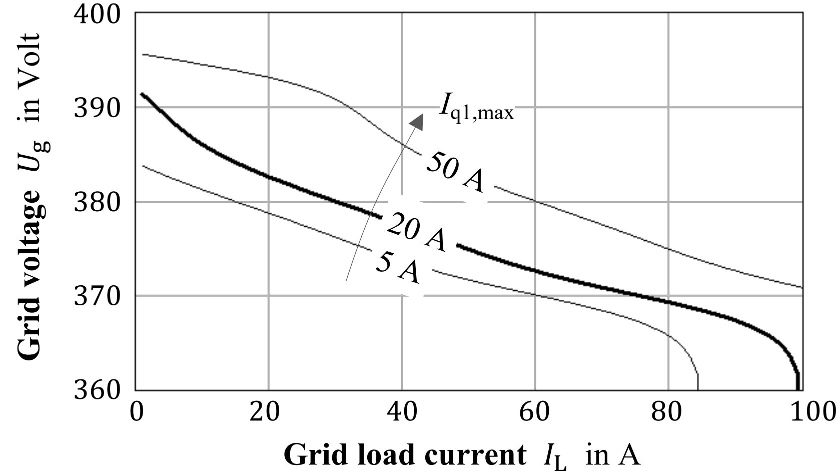
A great advantage of this function: All parameters are completely independent of each other!

Effect of the droop characteristics on the steady-state line voltage behavior

Droop characteristics of the sources in a grid

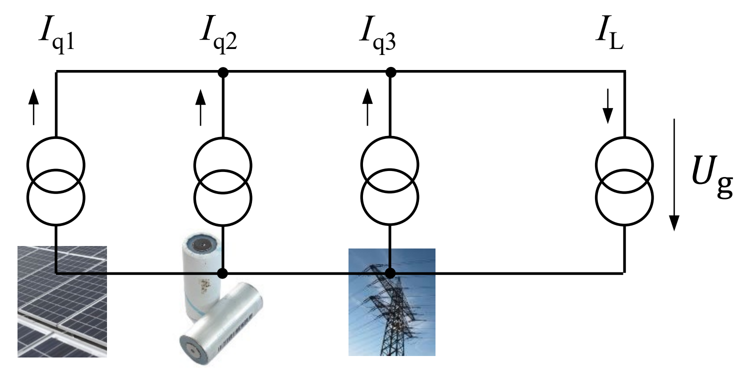


Resulting line voltage as a function of the grid load

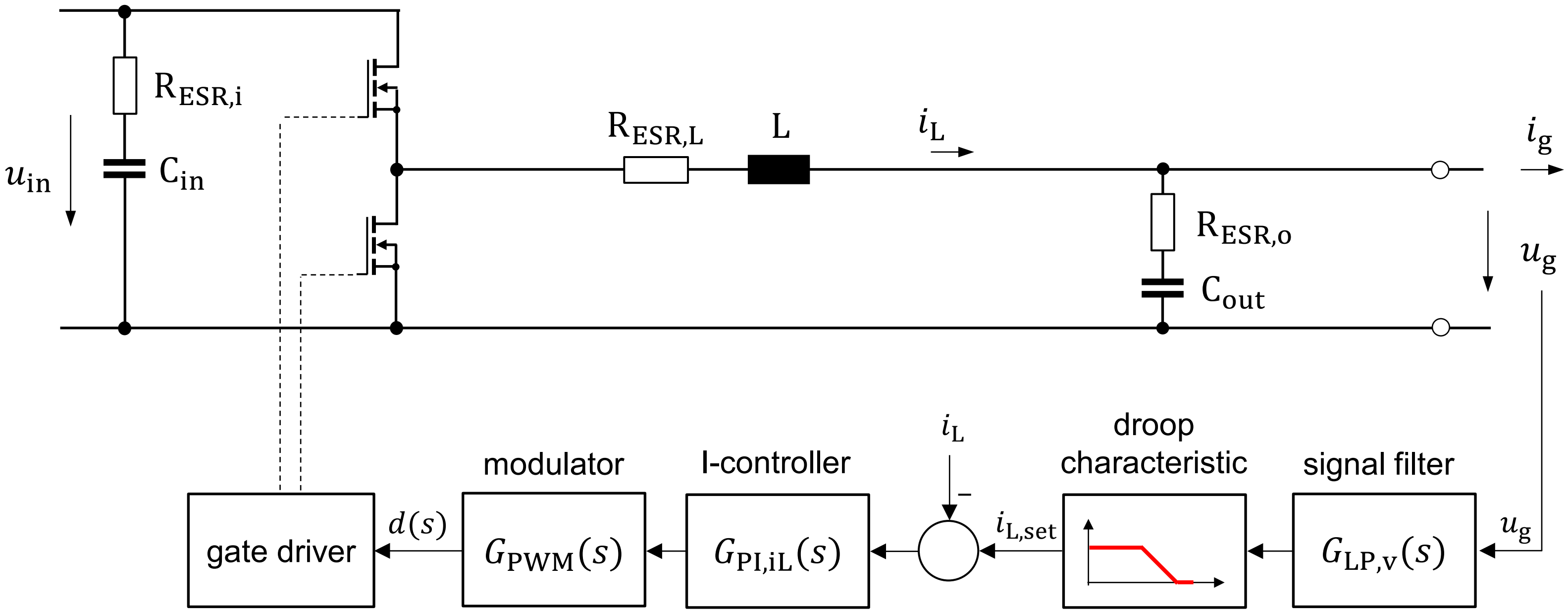


$$I_q(U_g) = \Delta I \left(\frac{1}{1 + e^{\frac{1}{k_S}\left(\frac{U_g}{U_0} - 1\right)}} \right) + I_0$$

Parameters	I_{q1}	I_{q2}	I_{q3}
I_0 in A	0	-20	0
ΔI in A	20	60	40
U_0 in V	395	380	370
k_S	0,004	0,01	0,005

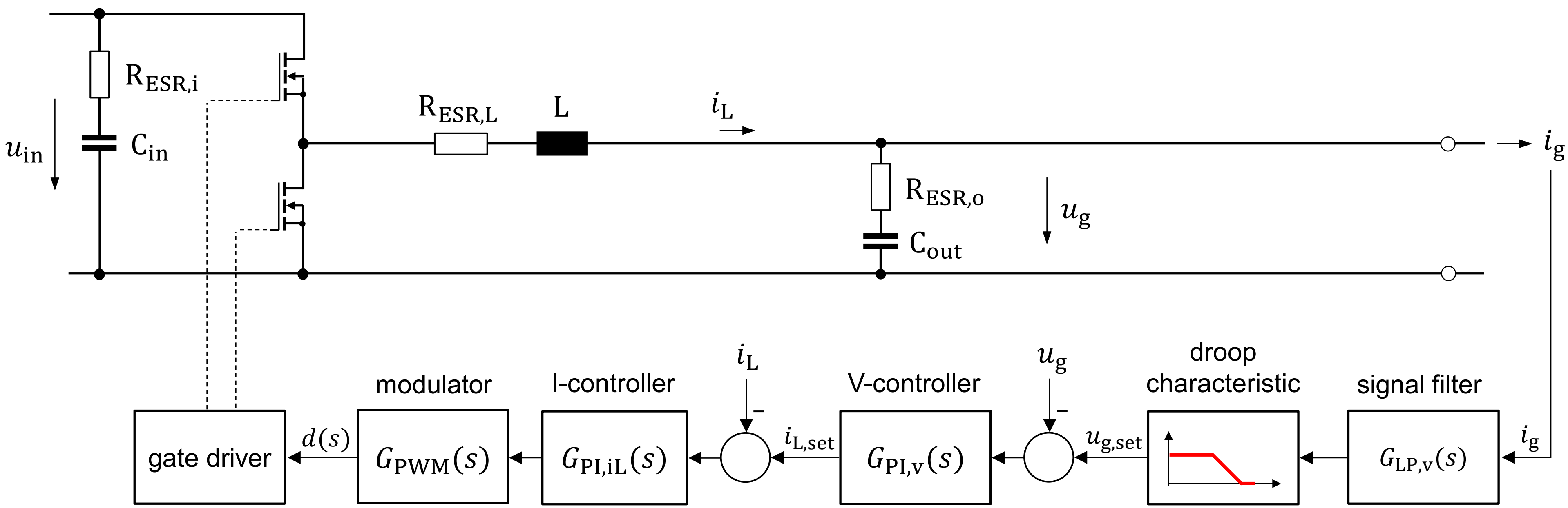


Implementation of a Droop Controller



Description of the control task:
"Feed a current into the grid whose magnitude depends on the grid voltage (converter terminal voltage) according to a specified characteristic (droop characteristic)!" ⇨ **Grid voltage-controlled current source**

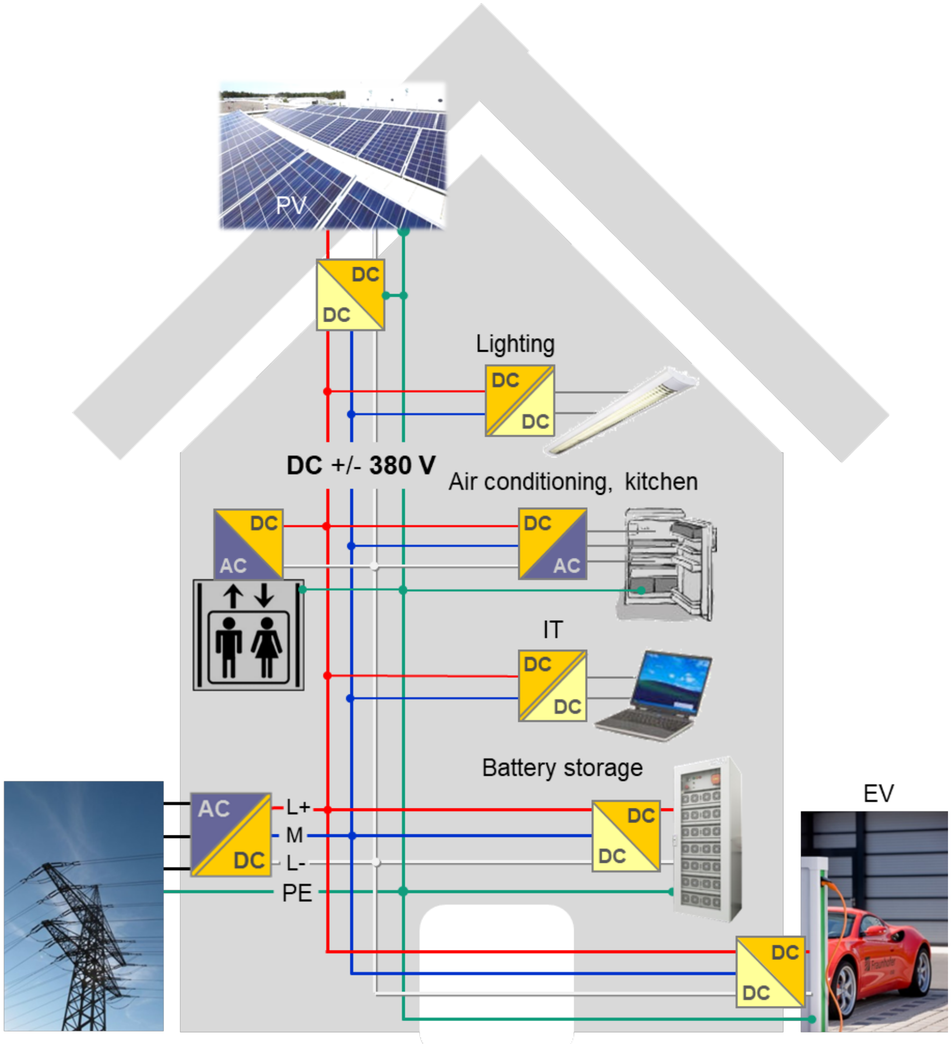
Alternative Implementation of a Droop Controller



Description

„Adjust to an output voltage whose value depends on the current fed into the grid according to a specified characteristic (invers droop characteristic)!" ⇨ **Voltage source with an internal resistance**

DC Grids for Decentral Energy Systems



Stability Analysis in DC Grids

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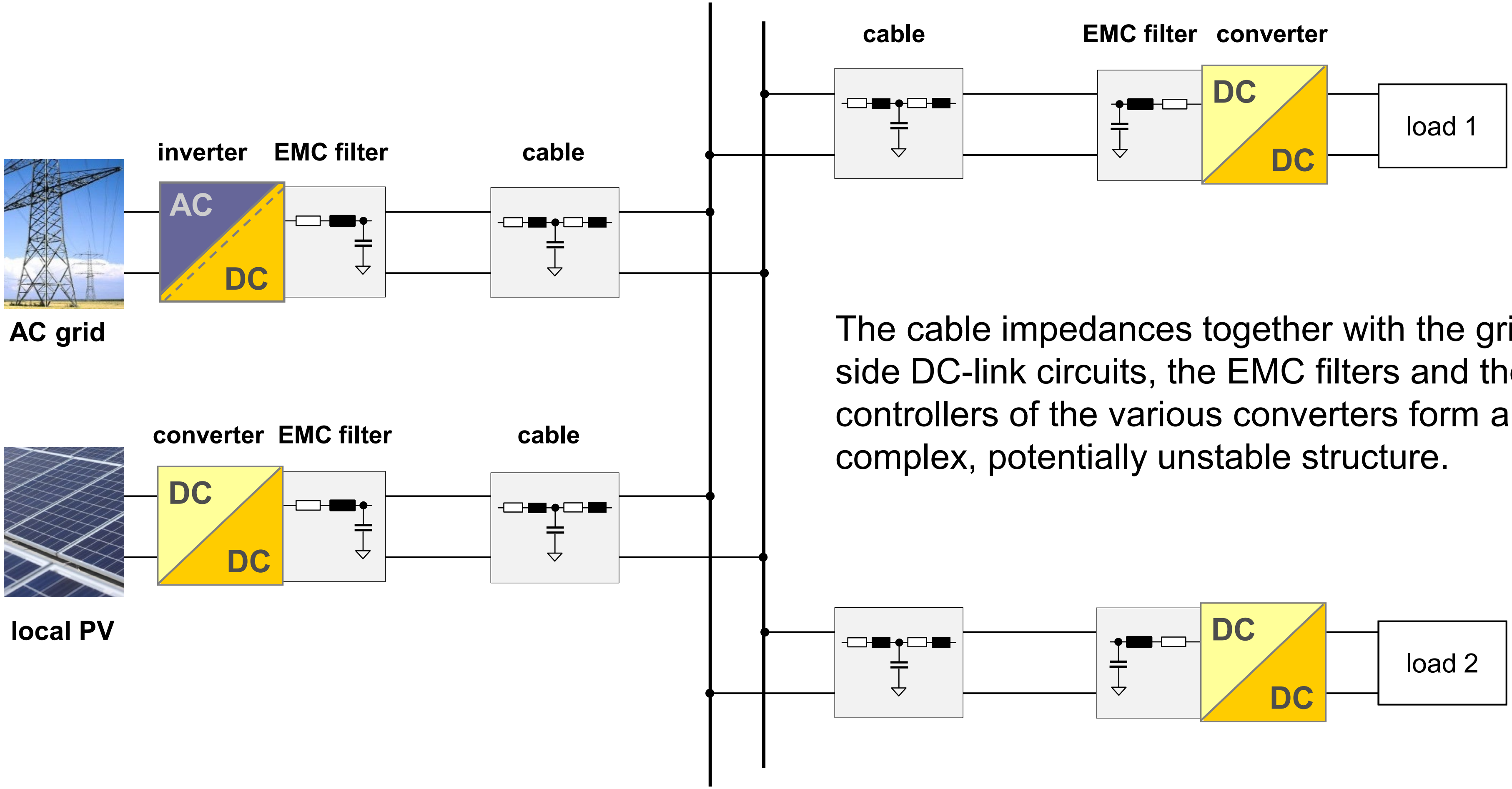
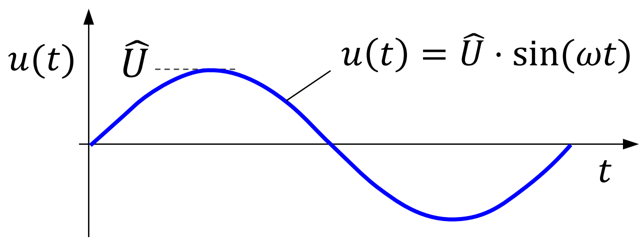
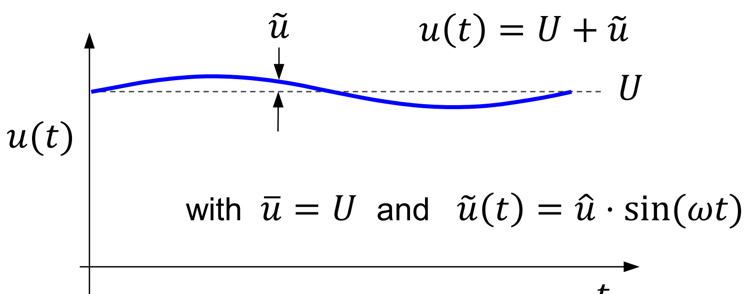
Stability Analysis in DC Grids

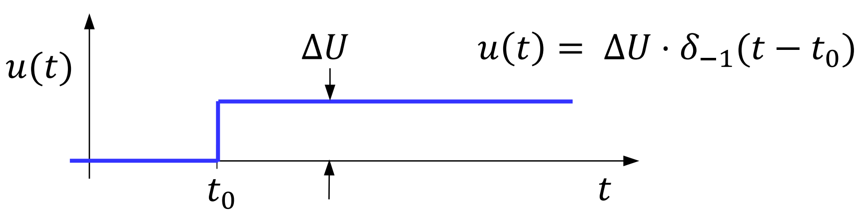


The cable impedances together with the grid-side DC-link circuits, the EMC filters and the controllers of the various converters form a complex, potentially unstable structure.

Notation Conventions

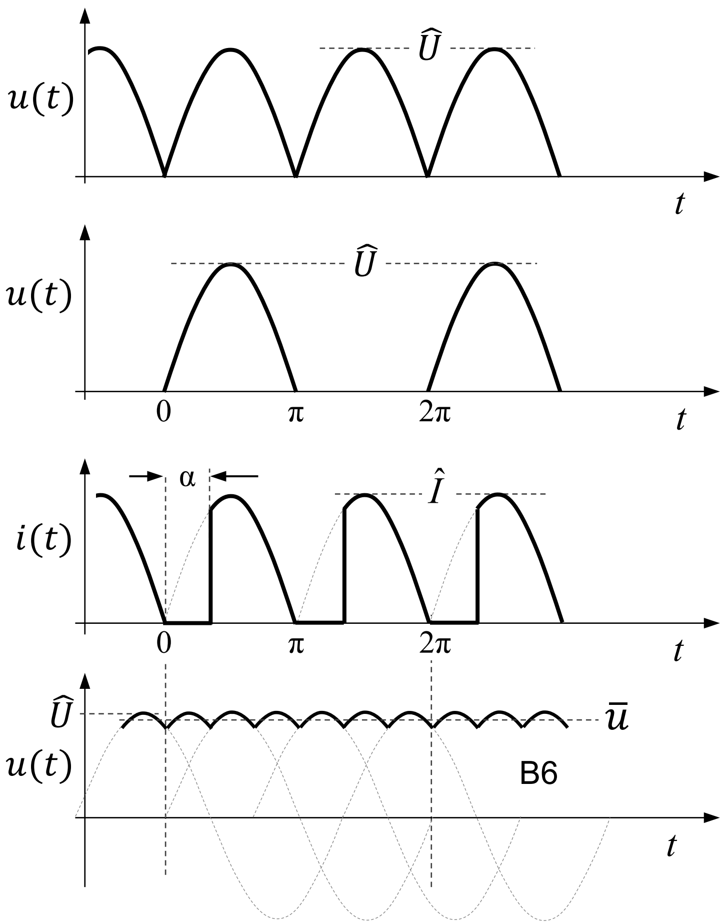






$u(t)$, u	(Total) instantaneous value of a time-dependent signal (lower case)
$\hat{U}$, $\hat{u}$	Amplitude (or peak value) of a signal
U, $\bar{u}$	Static part respectively the mean value of a variable, RMS value of an AC signal
$\tilde{u}$	Superimposed small-signal component of a quantity
ΔU, Δu	Deflection or deviation of a signal

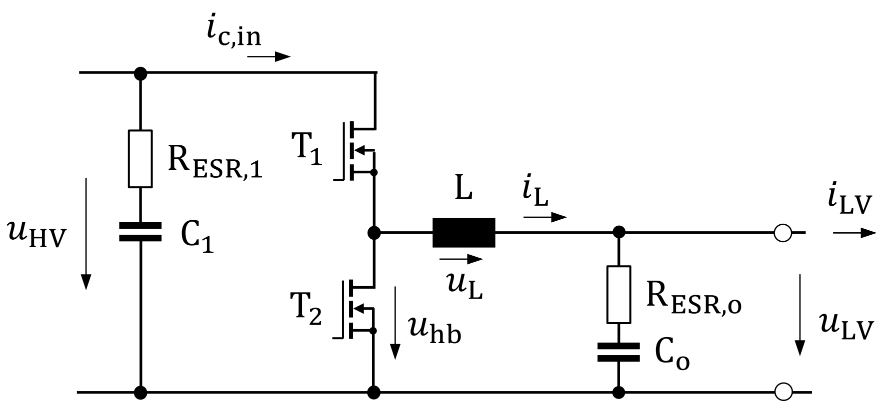
Mean and RMS values of common AC waveforms

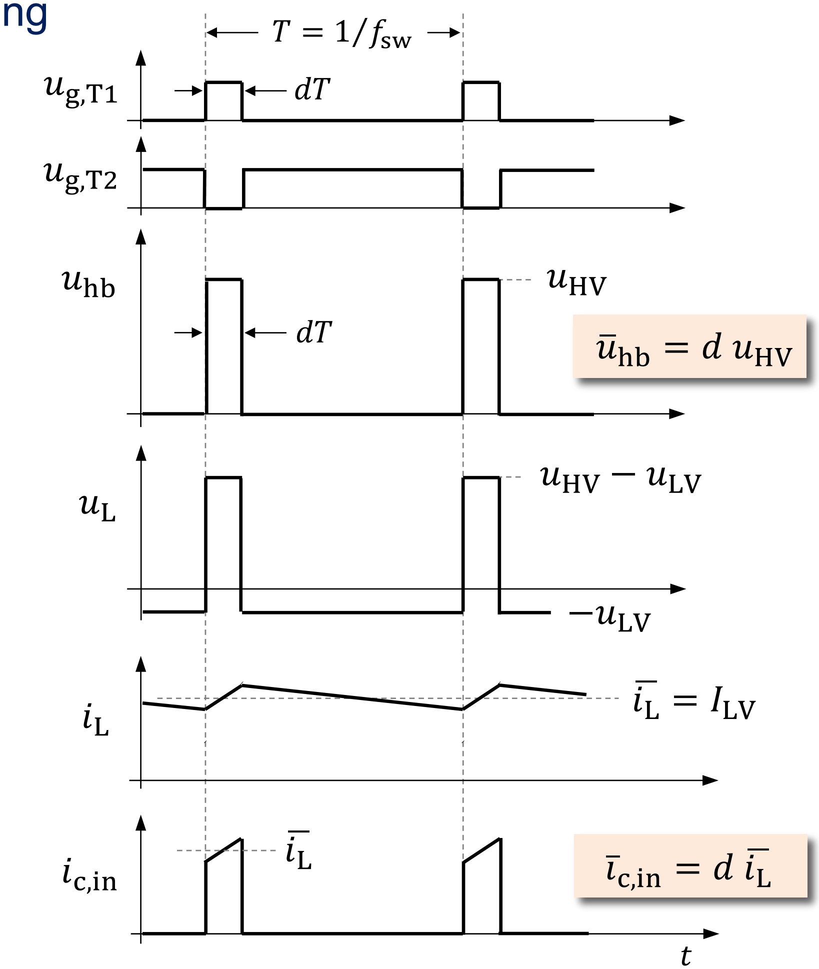


Mean value	RMS value
$\bar{u} = \frac{2}{\pi}\,\hat{U}$	$u_{\mathrm{rms}} = \frac{\hat{U}}{\sqrt{2}}$
$\bar{u} = \frac{\hat{U}}{\pi}$	$u_{\mathrm{rms}} = \frac{\hat{U}}{2}$
$\bar{i} = \frac{\hat{I}}{\pi}\,(1 + \cos\alpha)$	$i_{\mathrm{rms}} = \frac{\hat{I}}{2}\sqrt{\frac{1}{\pi}\,[2(\pi - \alpha) + \sin(2\alpha)]}$
$\bar{u} = \frac{3}{\pi}\,\hat{U} = 0{,}955 \cdot \hat{U}$	$u_{\mathrm{rms}} = \hat{U}\sqrt{\frac{1}{2} + \frac{3\sqrt{3}}{4\pi}} = 0{,}956 \cdot \hat{U}$

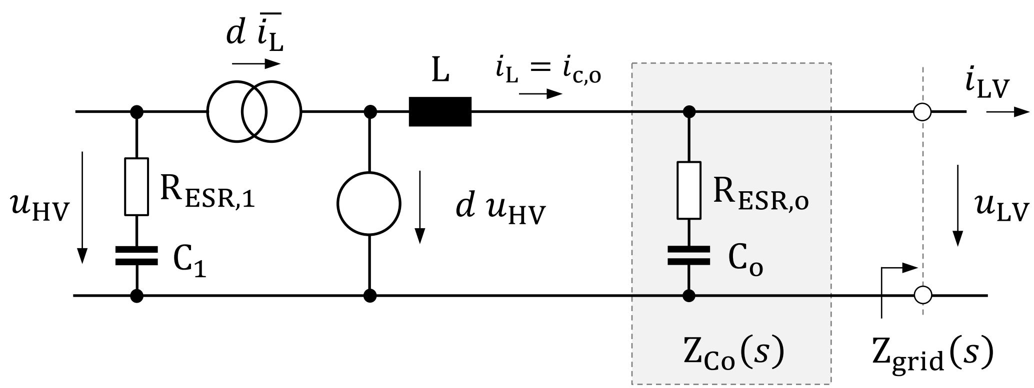
Modeling Switch-mode Converters ■ Average Model

Example: **Step-down converter** with complementary switching





Average model



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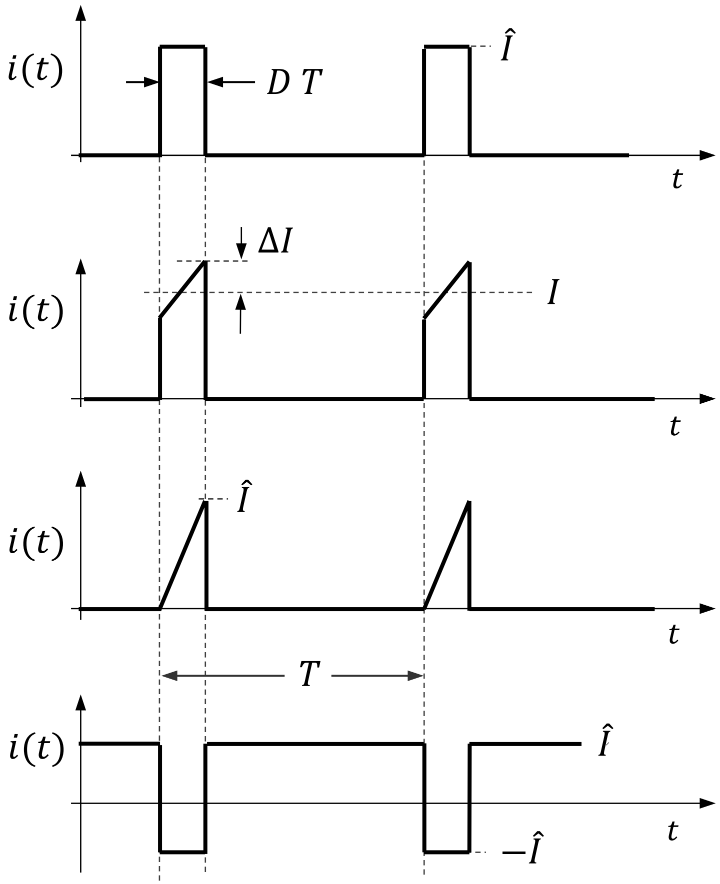
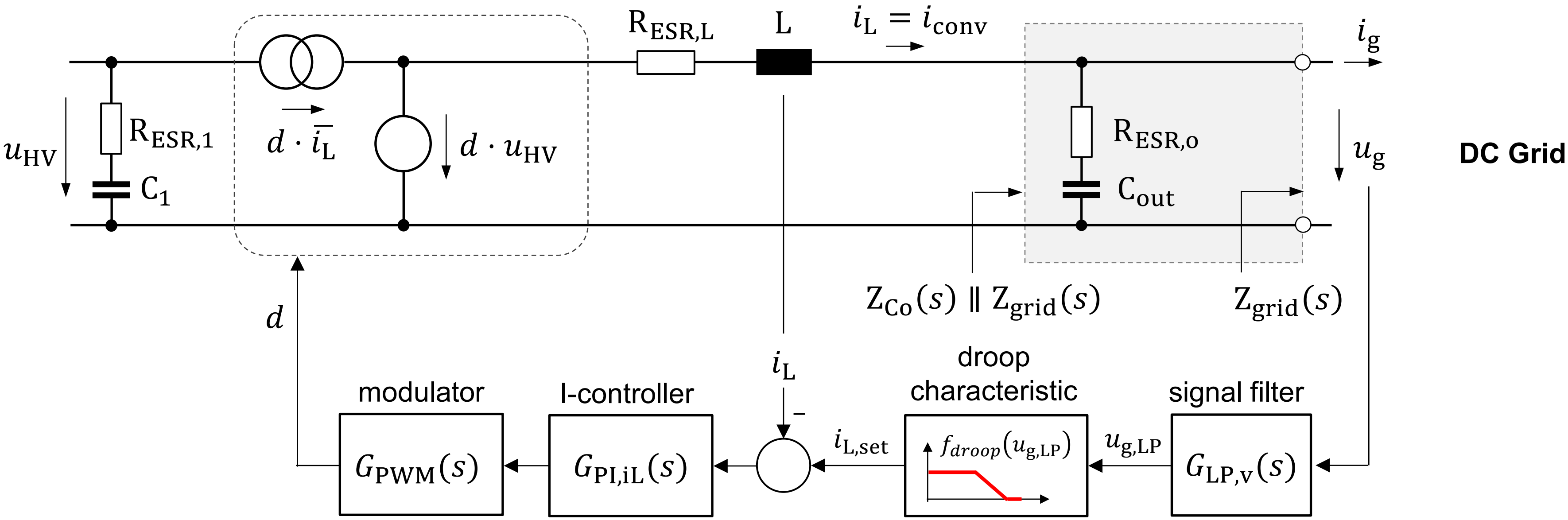
Common Waveforms



Mean value	RMS value
$\bar{i} = \hat{I}\, D$	$i_{rms} = \hat{I}\,\sqrt{D}$
$\bar{i} = I\; D$	$i_{rms} = I\,\sqrt{D}\,\sqrt{1+\frac{1}{3}\left(\frac{\Delta I}{I}\right)^2}$
$\bar{i} = \hat{I}\,\frac{D}{2}$	$i_{rms} = \hat{I}\,\sqrt{\frac{D}{3}}$
$\bar{i} = \hat{I}\,(1-2D)$	$i_{rms} = \hat{I}$

Integration of Average Model and Controller Model

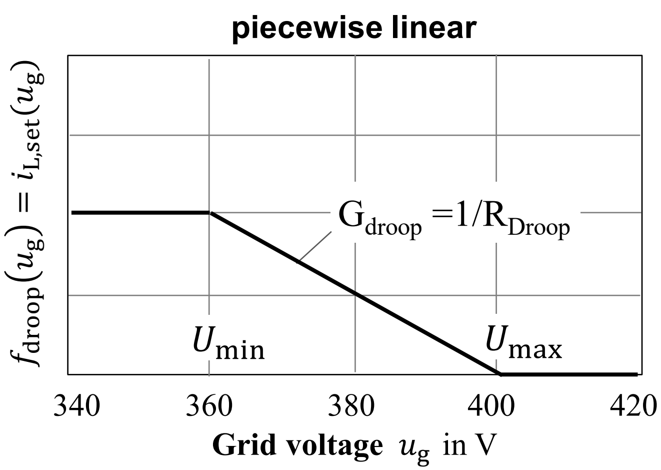
Example: **Step-down converter** with complementary switching

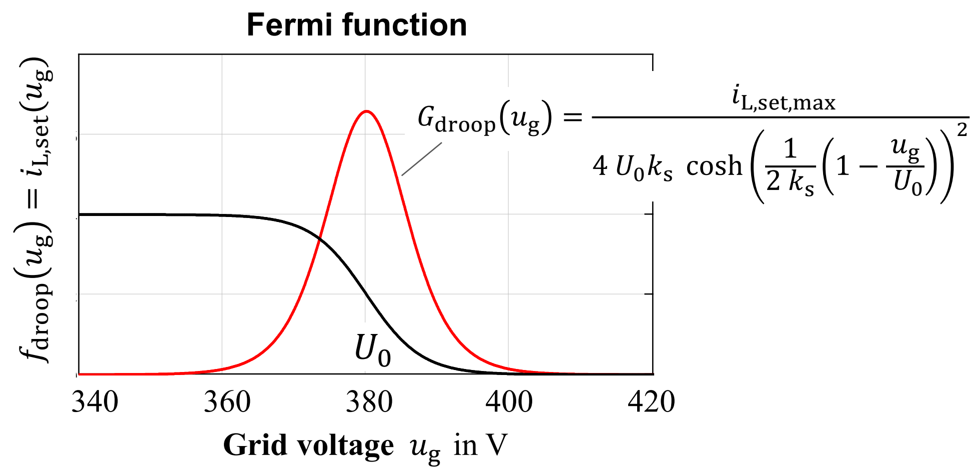


- The switching stage impresses an output current i_{conv} (corresponding to the inductor current i_L in the case of a step-down converter) in the parallel connection of output capacitance and grid impedance. The resulting voltage across this parallel connection corresponds to the terminal voltage of the converter.
- In the general case of a droop characteristic, the control loop is dependent on the operating point (u_g), i.e. non-linear.

Stability Analysis in DC Grids

Droop Characteristics





$$i_{L,set}(u_g) = \begin{cases} i_{L,set,max} & u_g \leq U_{min} \\ i_{L,set,max} - G_{droop}\,(u_g - U_{min}) & U_{min} < u_g < U_{max} \\ 0 & u_g \geq U_{max} \end{cases}$$

$$i_{L,set}(u_g) = i_{L,set,max}\left(1 + e^{\frac{1}{k_s}\left(\frac{u_g}{U_0}-1\right)}\right)^{-1}$$

Small signal transfer function: $\frac{di_{L,set}}{du_g} = -G_{droop}$

$$\tilde{i}_{L,set} \leftarrow \boxed{-G_{droop}} \leftarrow \tilde{u}_g$$

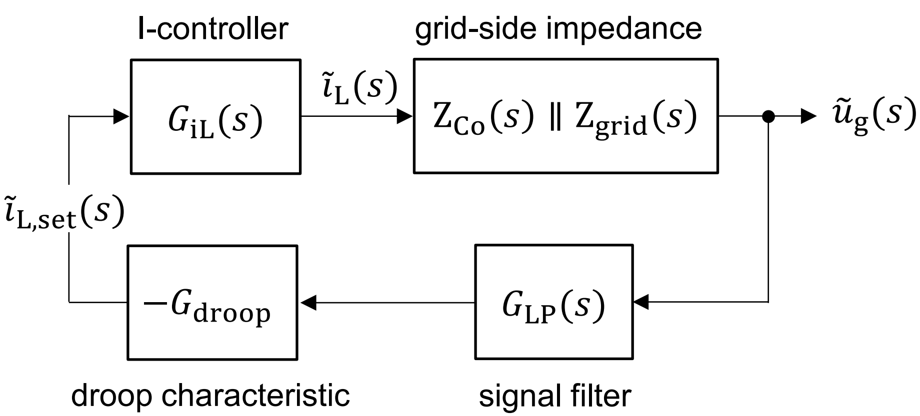
Small signal transfer function: $\frac{di_{L,set}}{du_g} = -G_{droop}(u_g)$

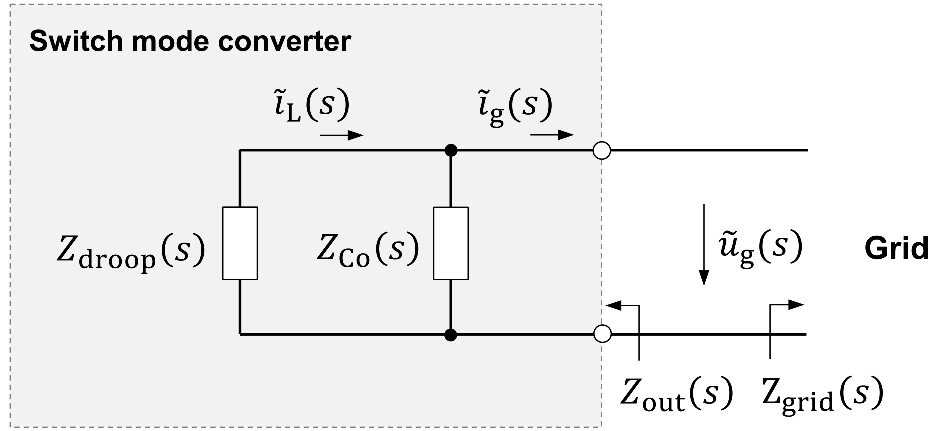
$$\tilde{i}_{L,set} \leftarrow \boxed{-G_{droop}(u_g)} \leftarrow \tilde{u}_g$$

The behavior within the linear section can be described by a constant droop resistance (droop conductance)

In this case, the behavior depends on the operating point (u_g) and is therefore non-linear

Small Signal Model of a Feeding Converter





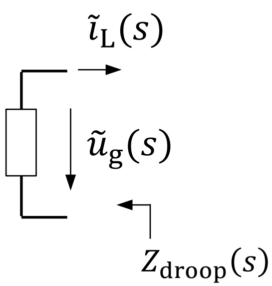
Inductor current

$$\tilde{i}_L(s) = \tilde{u}_g(s) \cdot \left[G_{LP}(s) \cdot (-G_{droop}) \cdot G_{iL}(s)\right]$$

Small signal output impedance of the converter

$$Z_{out}(s) = \frac{\tilde{u}_g(s)}{-\tilde{i}_g(s)} = \frac{Z_{droop}(s) \cdot Z_{Co}(s)}{Z_{droop}(s) + Z_{Co}(s)}$$

Droop Impedance (definition)



$$Z_{droop}(s) = \frac{\tilde{u}_g(s)}{-\tilde{i}_L(s)} = \frac{1}{G_{LP}(s) \cdot G_{droop} \cdot G_{iL}(s)}$$

Small Signal Model of a Feeding Converter

at the example of a buck converter with complementary switching and droop control

The small signal output impedance of the converter is: $Z_{\mathrm{out}}(s) = \frac{\tilde{u}_{\mathrm{g}}(s)}{-\tilde{\imath}_{\mathrm{g}}(s)} = \frac{Z_{\mathrm{droop}}(s) \cdot Z_{\mathrm{Co}}(s)}{Z_{\mathrm{droop}}(s) + Z_{\mathrm{Co}}(s)}$

Neglecting the ESR of the output capacitor leads to: $Z_{\mathrm{Co}}(s) = \frac{1}{sC_{\mathrm{o}}}$

If the cutoff frequency of the signal filter is chosen much lower than the corner frequency of the current control loop, i.e.

$\omega_{\mathrm{c,LP}} \ll \omega_{\mathrm{c,iL}}$, then the current control loop transfer function becomes $G_{\mathrm{iL}}(s) \approx 1$ and the droop impedance simplifies:

$$Z_{\mathrm{droop}}(s) = \frac{1}{G_{\mathrm{LP}}(s) \cdot G_{\mathrm{droop}} \cdot G_{\mathrm{iL}}(s)} \approx \frac{R_{\mathrm{droop}}}{G_{\mathrm{LP}}(s)}$$

Using a simple RC low-pass for grid voltage signal filtering results in a first-order transfer function: $G_{\mathrm{LP}}(s) = \frac{1}{1+\frac{s}{\omega_{\mathrm{c,LP}}}}$

and in the following expression for the output impedance:

$$Z_{\mathrm{out}}(s) = \frac{R_{\mathrm{droop}} \cdot \left(1 + \frac{s}{\omega_{\mathrm{c,LP}}}\right)}{1 + s\,R_{\mathrm{droop}} C_{\mathrm{o}} + s^2 \frac{R_{\mathrm{droop}} C_{\mathrm{o}}}{\omega_{\mathrm{c,LP}}}}$$

Small Signal Model of a Feeding Converter

We can now define a **droop corner frequency**: $\boxed{\omega_{\mathrm{drp}} = \frac{1}{R_{\mathrm{droop}}\, C_{\mathrm{o}}}}$

Inserted into the expression for the converter output impedance provides:

$$Z_{\mathrm{out}}(s) = R_{\mathrm{droop}} \cdot \frac{\left(1 + \frac{s}{\omega_{\mathrm{c,LP}}}\right)}{s^2 \frac{1}{\omega_{\mathrm{drp}}\, \omega_{\mathrm{c,LP}}} + s \frac{1}{\omega_{\mathrm{drp}}} + 1}$$

For very low frequencies, the output impedance approaches the droop resistance: $\lim_{s \to 0} Z_{\mathrm{out}}(s) = R_{\mathrm{droop}}$

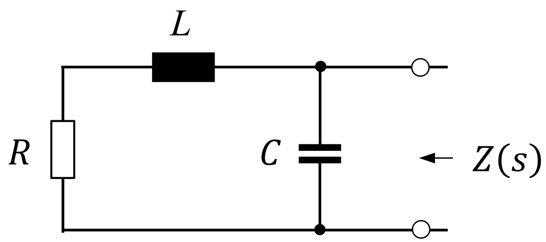
A coefficient comparison with the impedance description on the next slide provides $\omega_0{}^2 = \omega_{\mathrm{drp}}\, \omega_{\mathrm{c,LP}}$

and for the quality factor: $\boxed{Q = \sqrt{\frac{\omega_{\mathrm{drp}}}{\omega_{\mathrm{c,LP}}}}} = \sqrt{\frac{1}{\omega_{\mathrm{c,LP}} \cdot R_{\mathrm{droop}}\, C_{\mathrm{o}}}}$

The smaller the output capacitance and the steeper the droop characteristic the higher the droop corner frequency and the quality factor – resulting in an increasing risk of instabilities!

Nevertheless, with an ideal current controller (cutoff frequency of $G_{\mathrm{iL}}(s)$ infinite), Z_{out} would be unconditional stable.

Parallel Resonant Circuit - Basics



Impedance

$$Z(s) = R \cdot \frac{\left(1+s\frac{L}{R}\right)}{s^2LC+sRC+1}$$

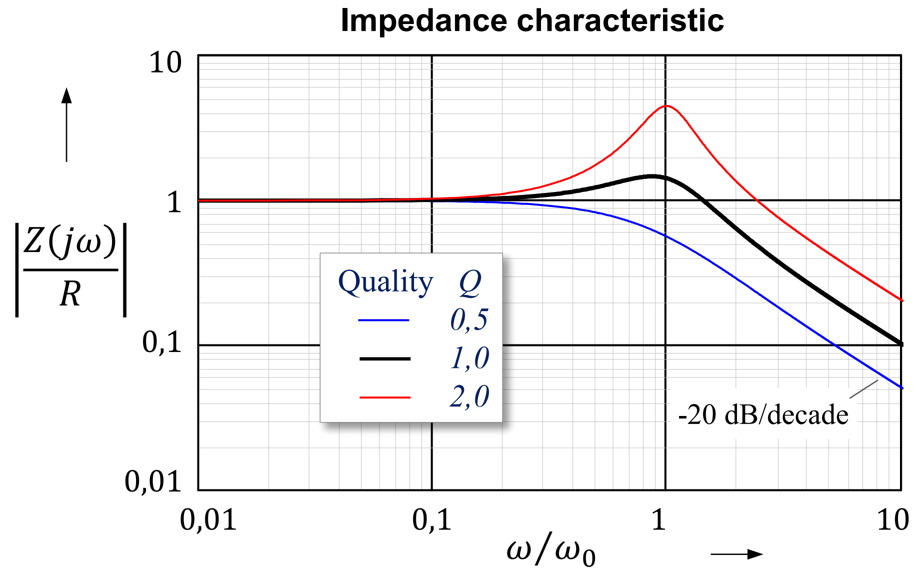
Using the following relationships

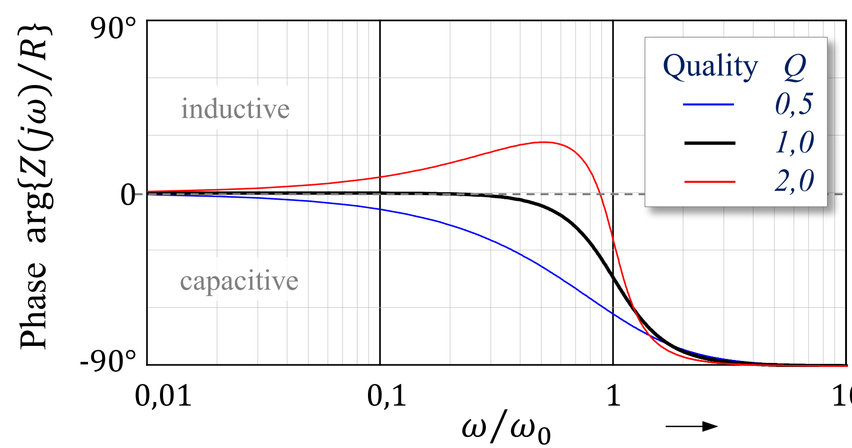
$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad Z_0 = \sqrt{\frac{L}{C}} \quad \text{and} \quad Q = \frac{Z_0}{R}$$

the impedance equation can be rewritten as

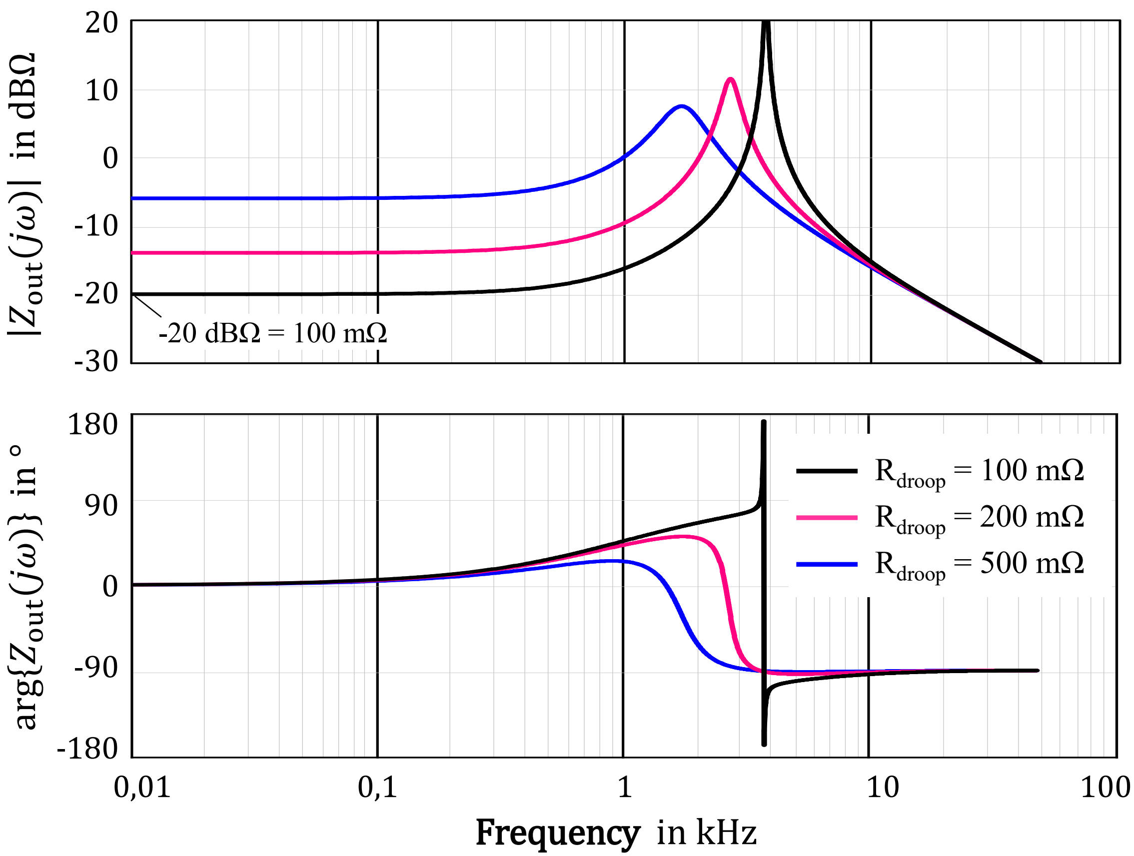
$$Z(s) = R \cdot \frac{\left(1+s\frac{Q}{\omega_0}\right)}{\left(\frac{s}{\omega_0}\right)^2+s\frac{1}{Q\omega_0}+1}$$

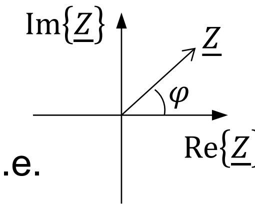
an equation of the same structure as the output impedance $Z_{out}(s)$ found before.





Output Impedance of a Buck Converter (CCM) with Droop Control





- If the real part of the output impedance remains positive, i.e.

$$\mathrm{Re}\{Z_{\mathrm{out}}(j\omega)\} > 0 \quad \forall\, \omega$$

and thus the phase φ within the range from -90° to +90°, the converter behaves passively.

Global Passivity Criterion

- If all converters in a grid behave passively, then the entire grid is also passive, i.e. stable!

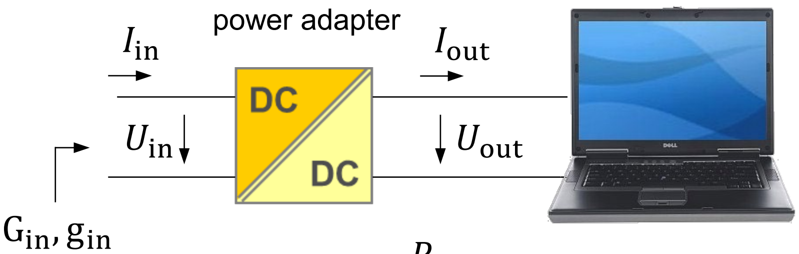
Rule of Thumb

- The steeper the droop characteristic and the smaller the output capacitance, the greater the tendency to oscillate

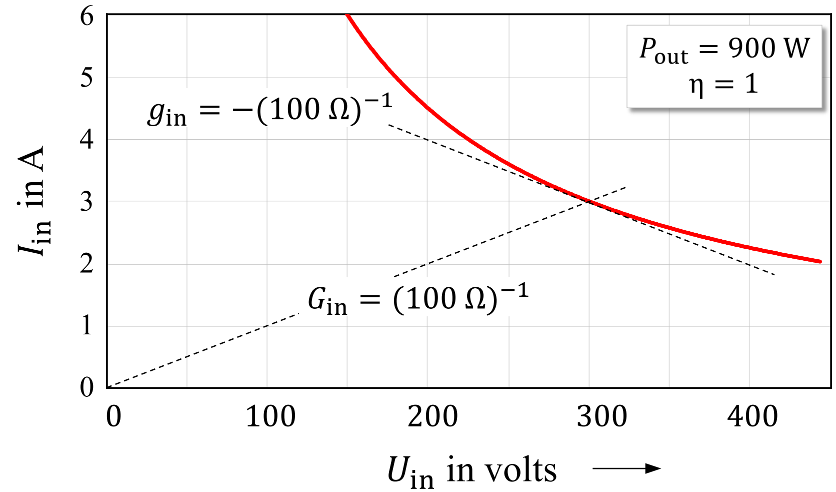
Data: $f_{\mathrm{cLP}} = 1$ kHz, $f_{\mathrm{cIL}} = 14$ kHz (non-ideal current control loop), $C_{\mathrm{o}} = 100$ µF

Stability Analysis in DC Grids

Constant Power Loads (CPL)



$$P_{in} = U_{in} \cdot I_{in} = \frac{P_{out}}{\eta}$$



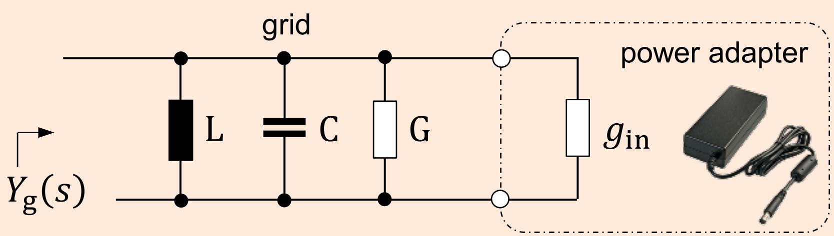
The input power is determined only by the load and is kept constant even when the input voltage changes.

Under quasi-static conditions (i.e. $f \to 0$) it follows for the **absolute conductance**

$$G_{in} = \frac{I_{in}}{U_{in}} = \frac{P_{out}}{\eta\, U_{in}^2}$$

and for the **differential conductance**

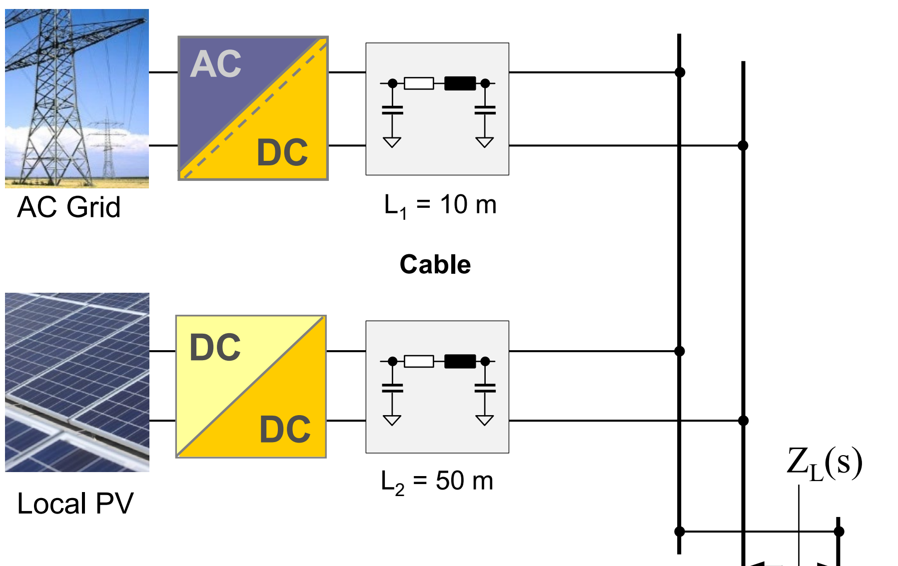
$$g_{in} = \frac{dI_{in}}{dU_{in}} = \frac{d}{dU_{in}}\left(\frac{P_{out}}{\eta\, U_{in}}\right) = \frac{P_{out}}{\eta}\frac{d}{dU_{in}}\left(U_{in}^{-1}\right) = -\frac{P_{out}}{\eta\, U_{in}^2}$$

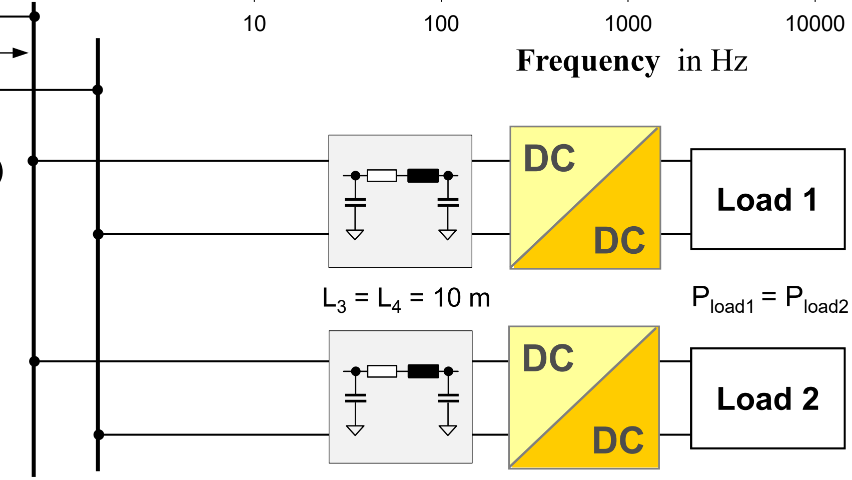


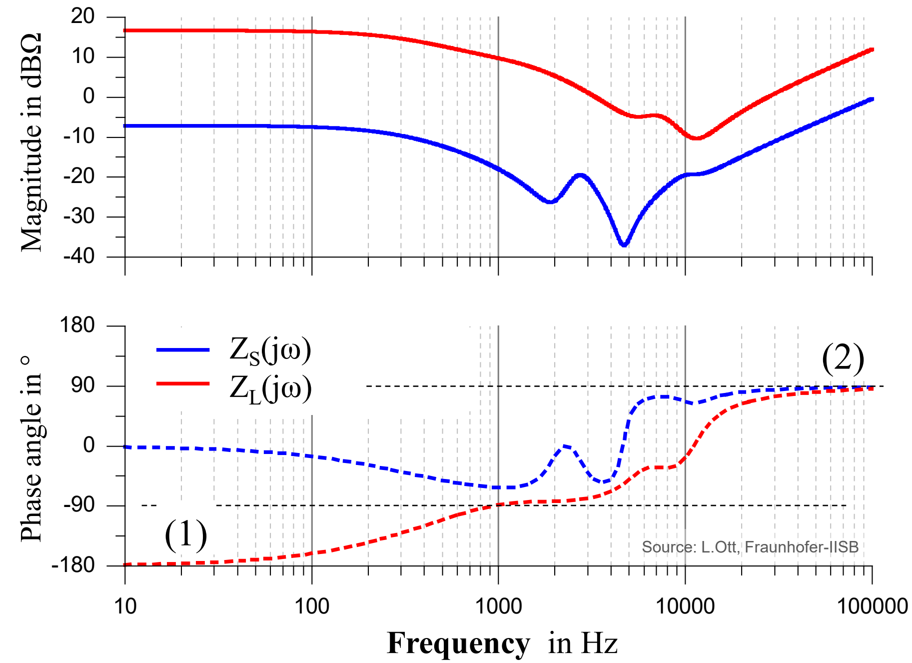
$$Y_g(s) = sC + \frac{1}{sL} + \left(G - \frac{P_{out}}{\eta\, U_{in}^2}\right)$$

A negative differential conductance can de-attenuate a (lossy) passive structure and thus lead to instabilities!

Grid Level Considerations







Observations

(1) Constant power loads show a negative differential input impedance (phase -180°) for frequencies approaching zero!

(2) For high frequencies, the impedances of the long cables dominate here at the observation point (⇨ phase +90°, i.e. inductive)

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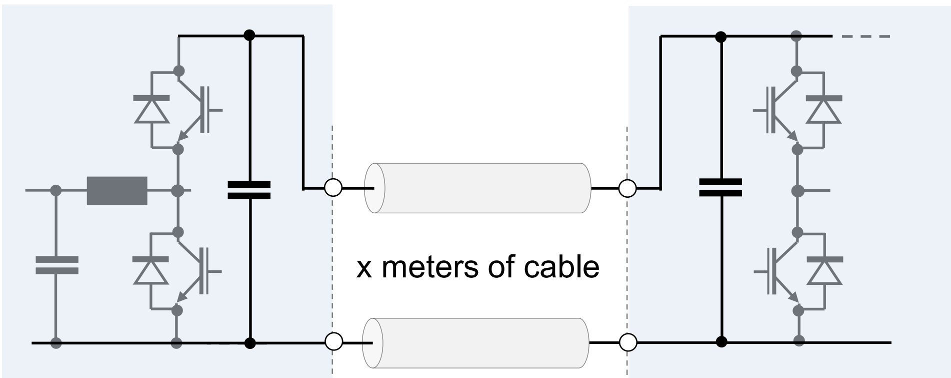
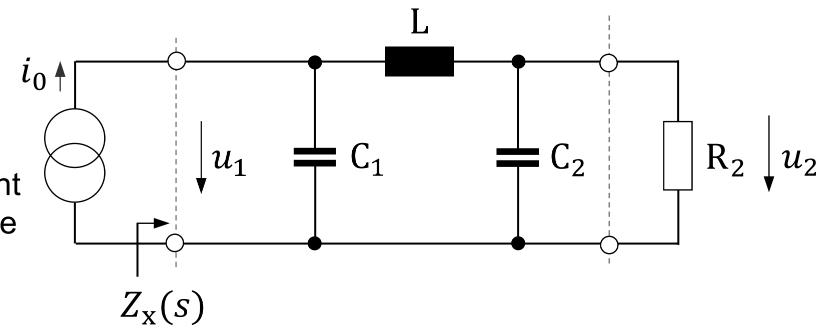
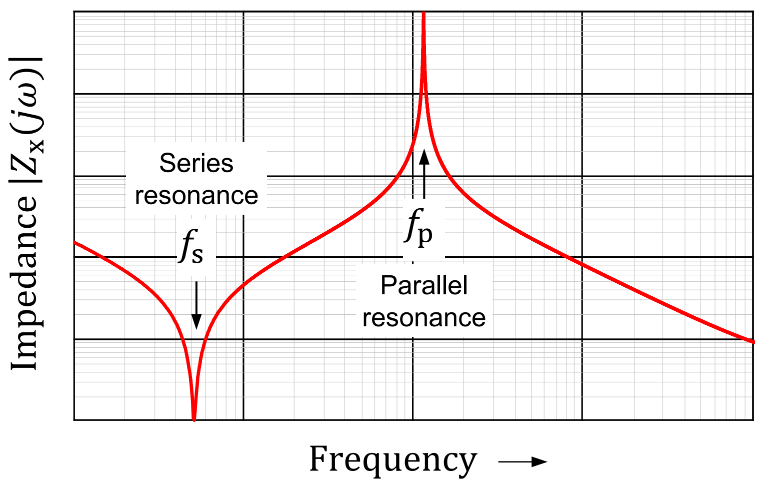
Parasitic Resonances in a DC Grid



Equivalent circuit





The **impedance** Z_x seen by the noise current source

shows a **zero** at: $f_s = \dfrac{1}{2\pi\sqrt{LC_2}}$

and a **pole** at: $f_p = \dfrac{1}{2\pi\sqrt{LC_S}}$ with $C_s = \dfrac{C_1 \cdot C_2}{C_1 + C_2}$

Since the series connection of the two capacitances C_s is always smaller than C_2 ($C_s < C_2$), the pole is always above the zero!

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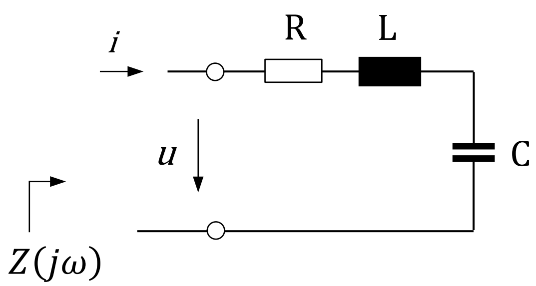
Series Resonant Circuit in the frequency domain



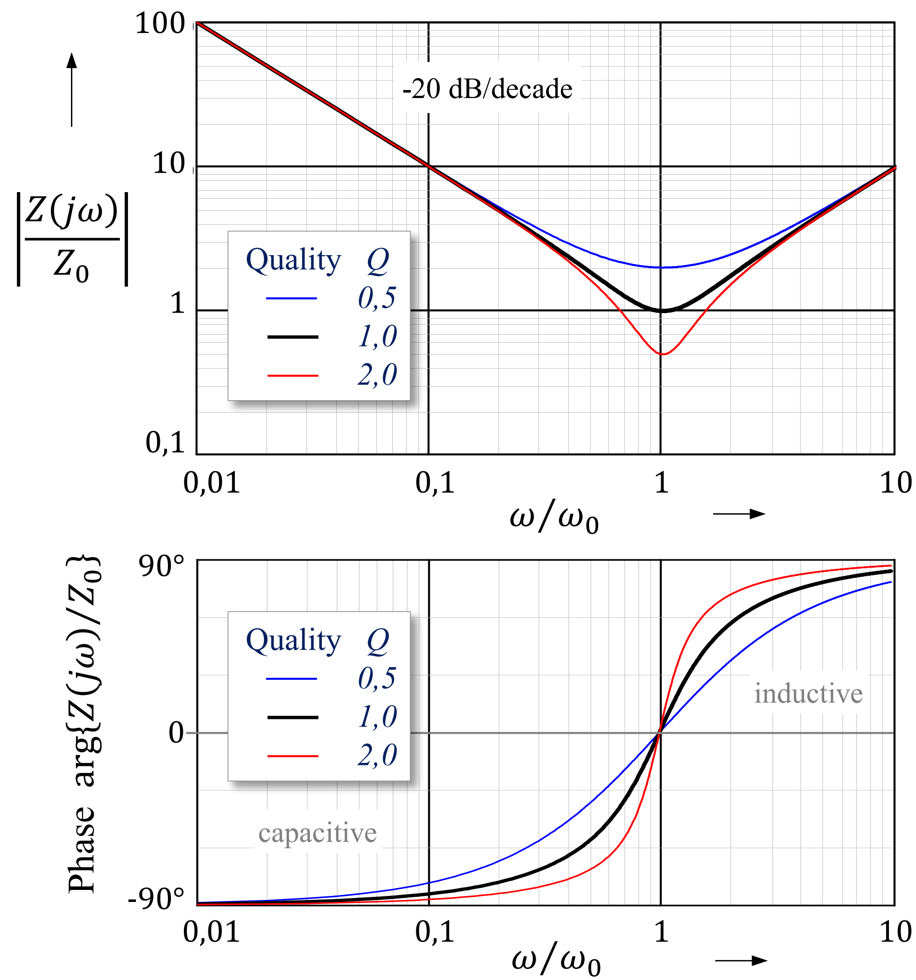
Resonance frequency: $\omega_0 = \frac{1}{\sqrt{L\,C}}$

Resonant circuit impedance:

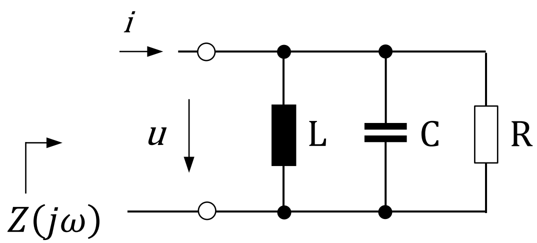
$$Z(s) = \frac{u(s)}{i(s)} = \frac{s^2LC + sRC + 1}{sC}$$

$$Z(s) = Z_0 \frac{\left(\frac{s}{\omega_0}\right)^2 + \frac{1}{Q}\left(\frac{s}{\omega_0}\right) + 1}{\left(\frac{s}{\omega_0}\right)}$$

Impedance characteristic



Parallel Resonant Circuit in the frequency domain



Quality factor: $Q = \frac{R}{Z_0}$

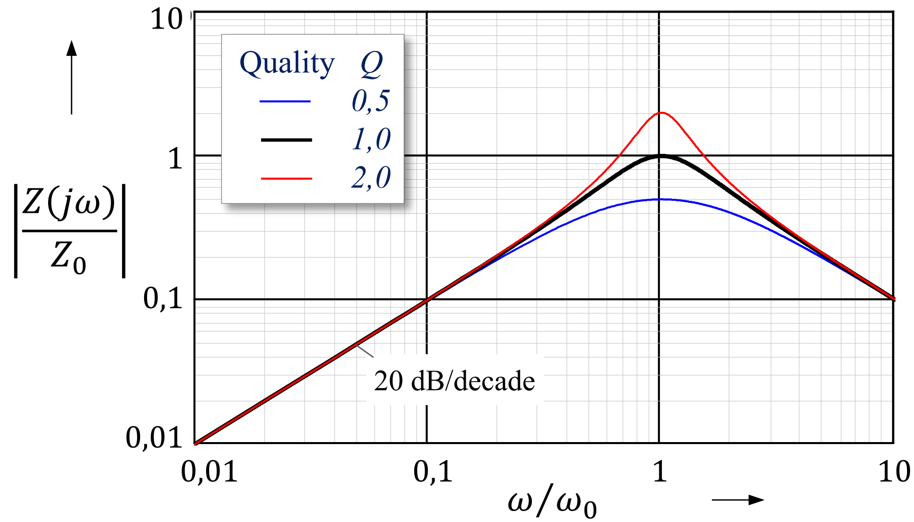
Characteristic impedance: $Z_0 = \sqrt{\frac{L}{C}}$

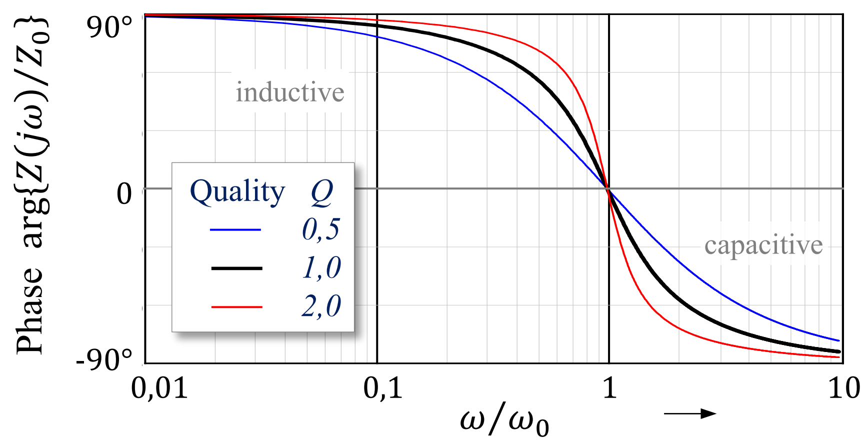
Resonant circuit impedance:

$$Z(s) = \frac{u(s)}{i(s)} = \frac{sL}{s^2LC + s\frac{L}{R} + 1}$$

$$Z(s) = \frac{u(s)}{i(s)} = Z_0 \frac{\left(\frac{s}{\omega_0}\right)}{\left(\frac{s}{\omega_0}\right)^2 + \frac{1}{Q}\left(\frac{s}{\omega_0}\right) + 1}$$

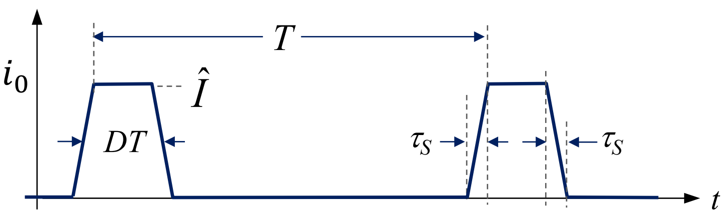
Impedance characteristic





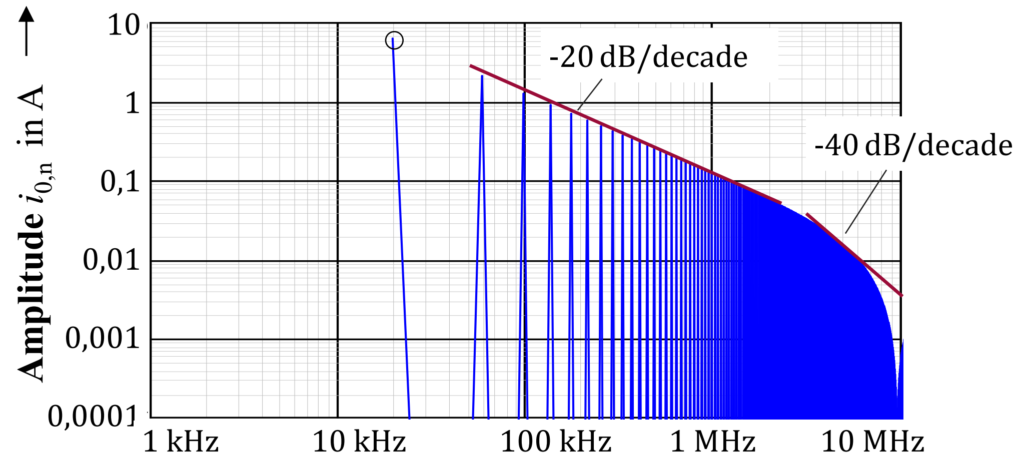
Excitation of Ringing by Harmonics of the Switching Frequency

EM noise current source (block currents assumed)

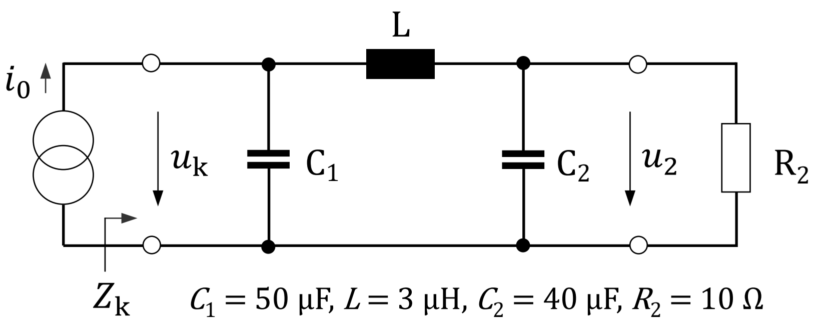


Fourier transformation

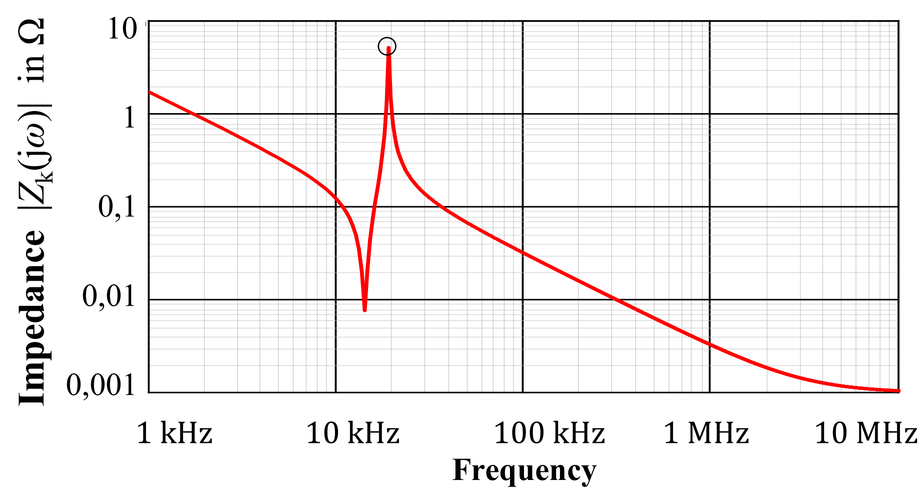
Noise spectrum for : $1/T = 20$ kHz, D = 50%, $\hat{I} = 10$ A, $\tau_s = 100$ ns



Transfer function: $Z_k(s) = \dfrac{u_k(s)}{i_0(s)}$



$C_1 = 50$ µF, $L = 3$ µH, $C_2 = 40$ µF, $R_2 = 10\ \Omega$

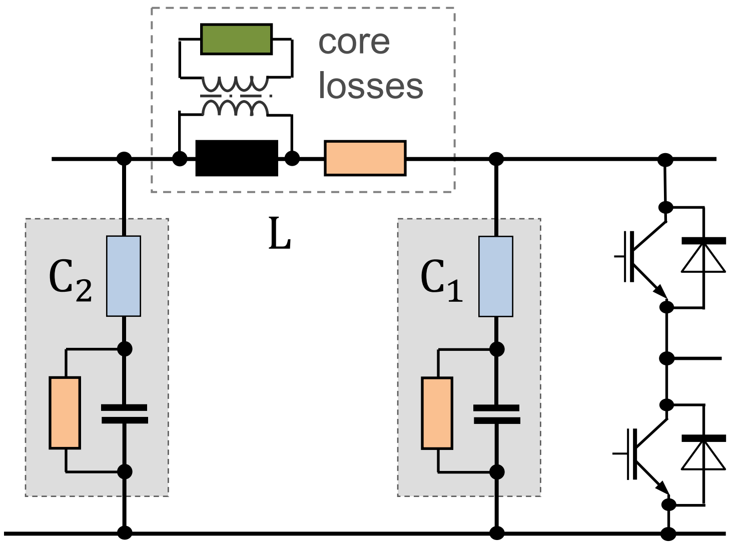


System response: $u_k(s) = Z_k(s) \cdot i_0(s)$

Oscillations at the switching edges with an amplitude of over 30 V would be expected here on the DC link voltage u_k ⇨

How to Damp Oscillating Circuits (e.g. poles in an impedance characteristic)

Example: π filter



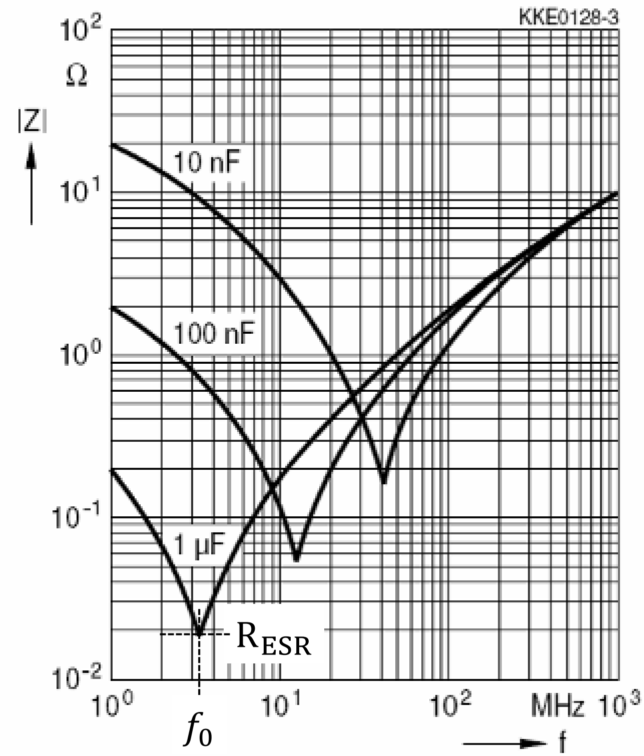
There are a variety of damping options with more or less "side effects"

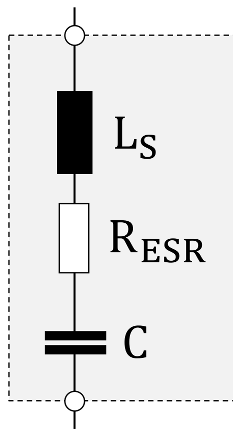
- (orange): High permanent operating losses (due to the DC component of operating voltage or current) 
- (blue): High AC losses and deterioration of the EMI filter characteristic. Deliberately using lossy capacitors is generally not a solution, as this also impairs the desired properties such as high AC load capacity and effective filtering! 
- (green): **No DC** and (with appropriate magnetic core selection) low operating frequent losses; filter properties can be adjusted to some extend via the loss vs. frequency characteristic of the core material. 

Impedance Characteristic of Real Capacitors

Film or ceramic capacitors

i.a. high quality factor Q or low damping D





Resonant frequency

$$f_0 = \frac{1}{2\pi\sqrt{L_S C}}$$

Damping

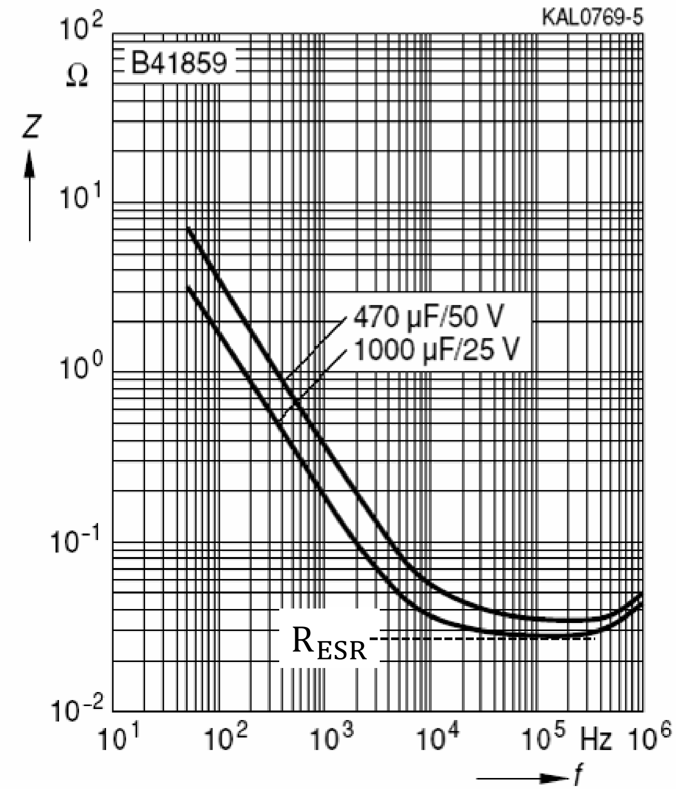
$$D = \frac{R_{ESR}}{2}\sqrt{\frac{C}{L_S}} = \frac{1}{2\,Q}$$

Impedance magnitude

$$|Z(f)| = R_{ESR}\sqrt{1 + Q^2\left(\frac{f}{f_0} - \frac{f_0}{f}\right)^2}$$

Al electrolytic capacitors

(high damping, low quality factor)



Source: EPCOS Data books

Root Causes for Instabilities and EMI Problems in DC Grids

Constant power loads
Low frequency oscillations caused by the negative differential input impedance

Control loops in switch mode power converters / inverters
droop controller, inner current controller

Poorly damped poles in the grid impedance
excited by harmonics of the switching frequency

Differential Mode (DM) noise
Common Mode (CM) noise
Radiated emissions

1 Hz | 10 Hz | 100 Hz | 1 kHz | 10 kHz | 100 kHz | 1 MHz | 10 MHz | 100 MHz

Frequency

EMC Regulations

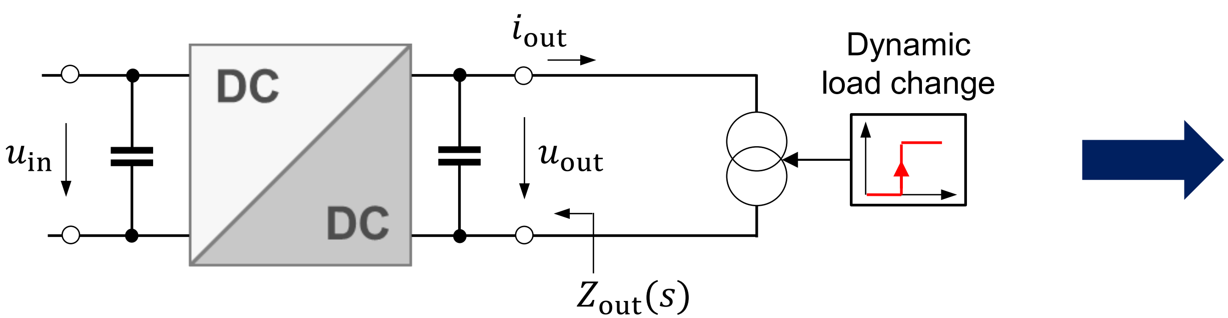
Grid harmonics
(e.g. EN 61000-x-x)

150 kHz → EMC standards
(e.g. CISPR 11, 12, 14, 22, 25)

Impedance Measurement

The complex impedance provides information

- about the dynamic behavior of individual grid components (source and load converters, cable harness, etc.)
  - bandwidth of control loops
  - quality factor of passive structures (input/output filters, etc.)
  - changes in dynamic behavior depending on the operating point (e.g. CCM/DCM)
- to identify stability-critical system designs (unfavorably parameterized controllers, resonances between grid components, etc.)



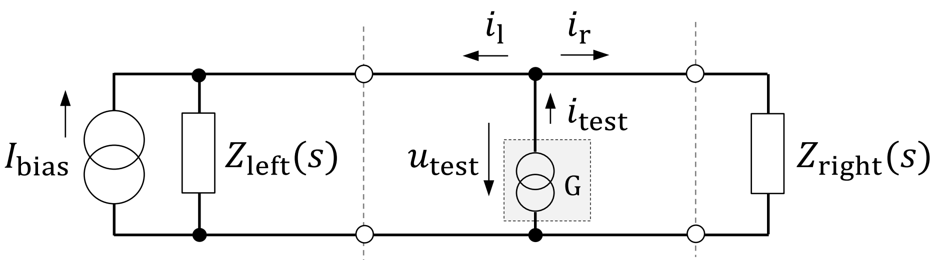
$$Z_{out}(s) = -\frac{u_{out}(s)}{i_{out}(s)}$$

However, **the impedance characterization must be performed under load**, i.e. in the presence of high voltages and currents

How to Perform Impedance Measurements „under load“?

Parallel test signal coupling

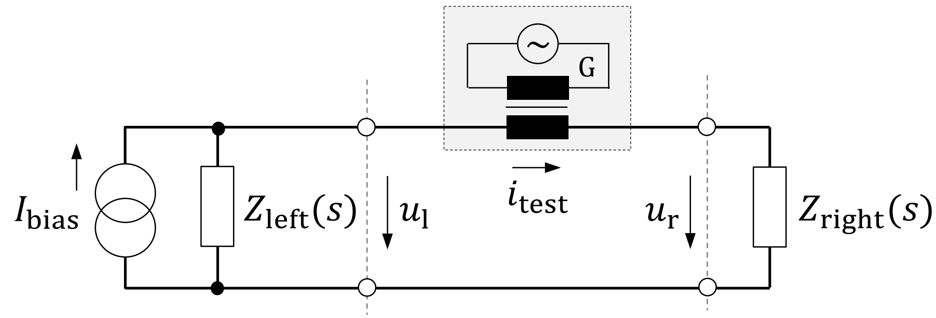
(high voltage stress on the coupling network)



$$Z_{left}(s) = \frac{u_{test}(s)}{i_l(s)} \qquad Z_{right}(s) = \frac{u_{test}(s)}{i_r(s)}$$

Serial test signal coupling

(high DC current load on the coupling transformer)

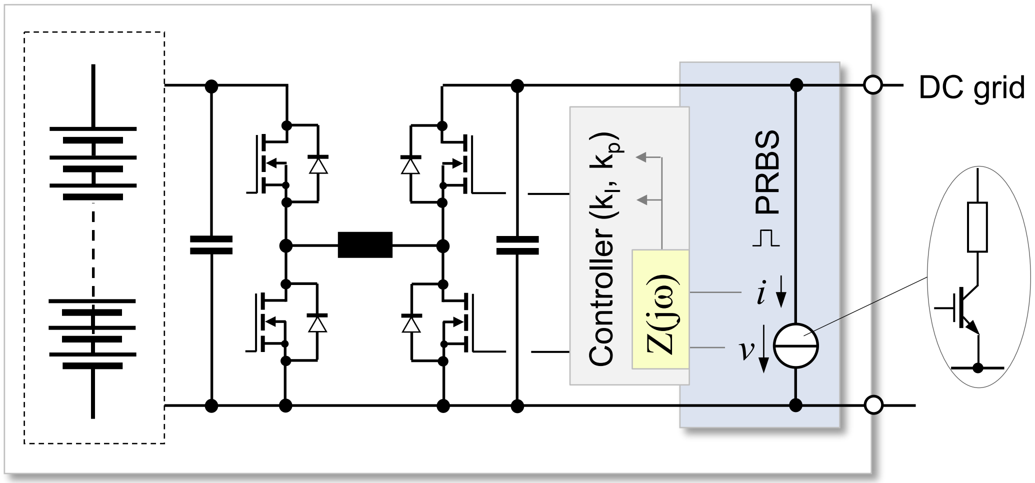


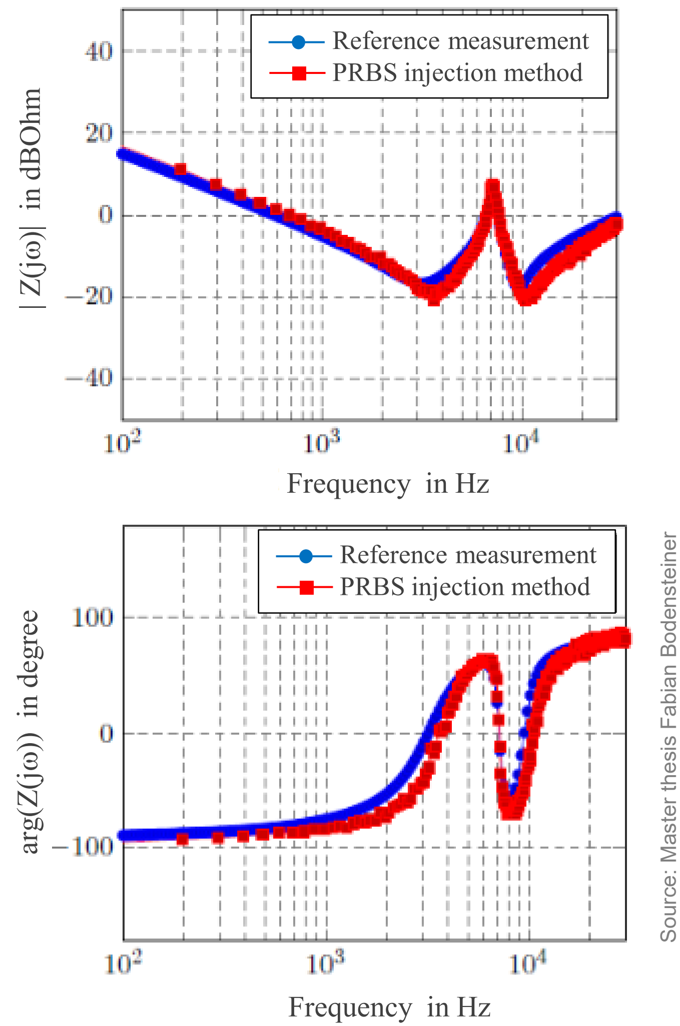
$$Z_{left}(s) = -\frac{u_l(s)}{i_{test}(s)} \qquad Z_{right}(s) = \frac{u_r(s)}{i_{test}(s)}$$

- The system must be in a stationary operating point "under load", with application-specific very high voltages, currents and EM noise levels!
- The measurement can either be carried out by **sweeping an AC test signal** over the measurement frequency range (sweep generator) or by coupling in "**white noise**"
- The test signal can be fed in in parallel or in series (the latter, however, requires the circuit to be opened and is therefore invasive and cannot be implemented without interrupting system operation)
- The test signals must have enough power to achieve a usable signal-to-noise ratio
- The in-coupling network has a significant influence on the frequency range that can be measured

Stability Analysis in DC Grids

Impedance Measurements using „Pseudo-Random-Binary-Sequence (PRBS)“ injection

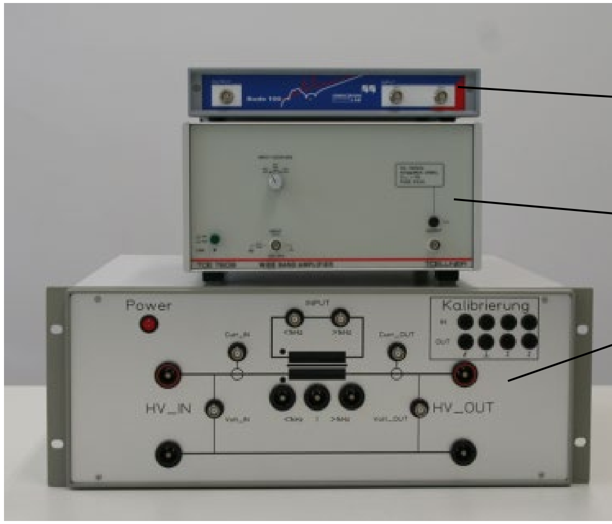




The relatively easy implementability of the PRBS method enables direct integration into power electronic converters for:

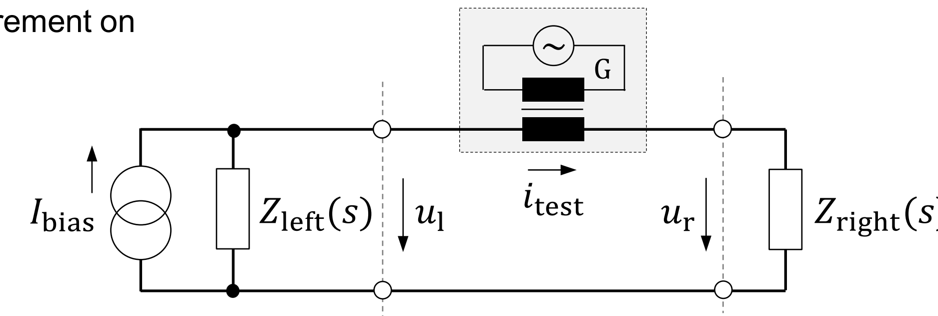
- stability monitoring
- self-parameterizing adaptive control
- fault monitoring

Impedance Measurement using Frequency Sweep Method



- Vector Network Analyzer (sweep signal generator)
- AC amplifier
- Coupling network with current and voltage measurement on both sides

Injection transformer: $I_{\mathrm{DCmax}} = 50\ \mathrm{A}$,
Bandwidth: $10\ \mathrm{Hz}$ to $500\ \mathrm{kHz}$

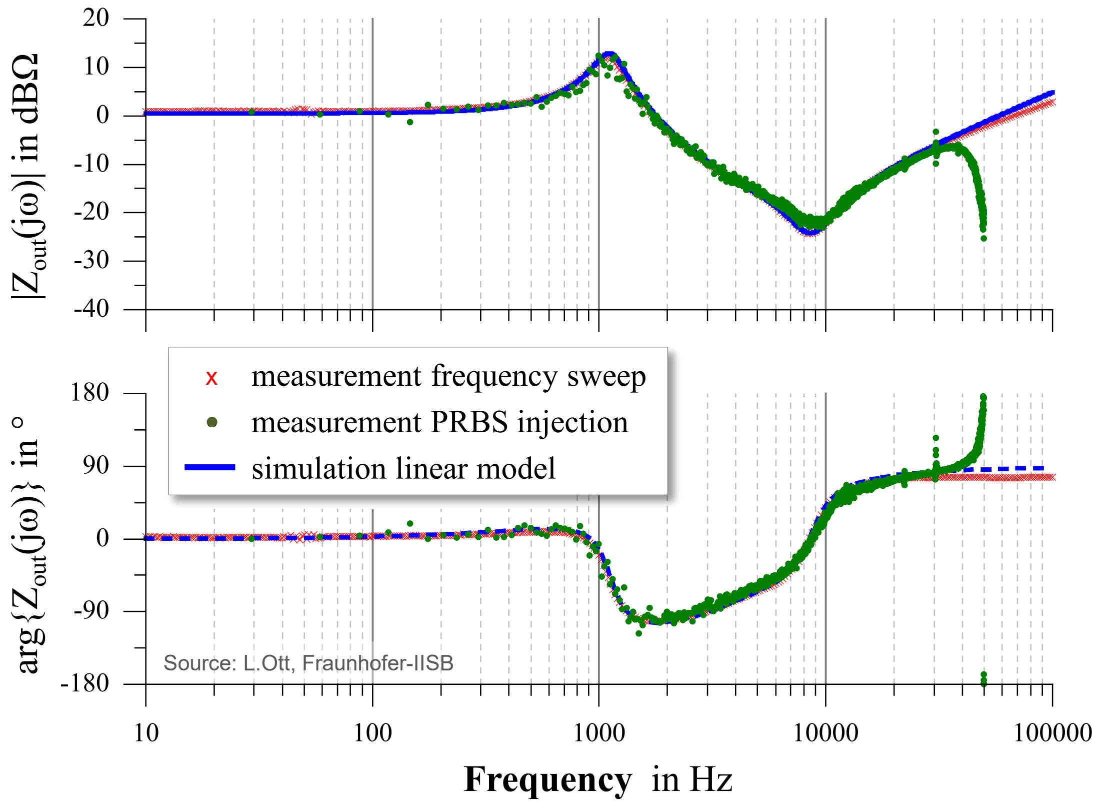


Properties of this Measurement Method

- Very cleanly resolved measurement results, well suited for the verification of simulation models
- High hardware expense and necessity of looping into the measurement setup
- Measurement duration for one run (sweep) in the range of several minutes especially when considering also very low frequencies (no "online monitoring" possible)

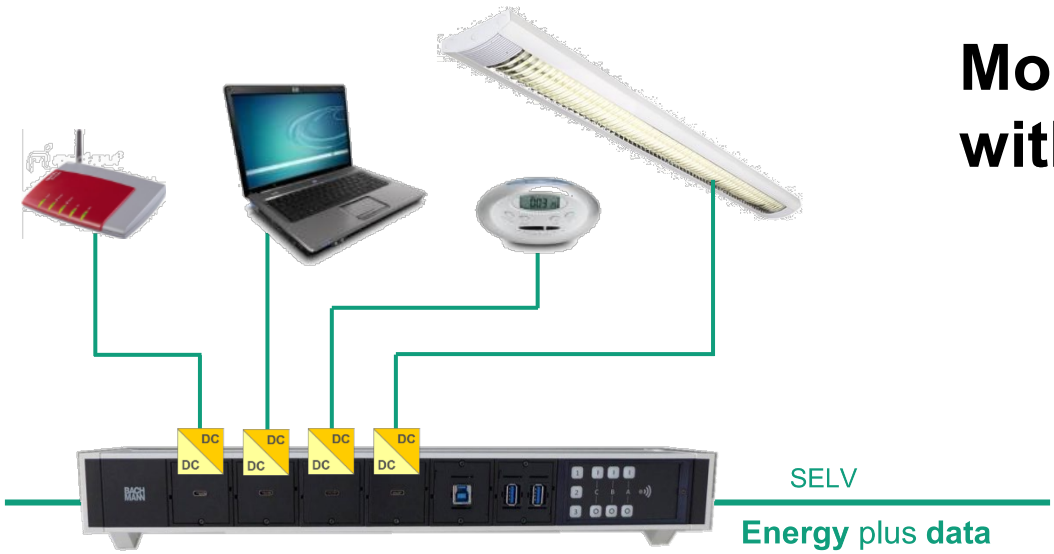
Impedance Characterization Methods

Comparison of the two measurement methods with the result of a linear model (LTSpice)



Output impedance characteristic of a step-down converter with droop control ($U_{\mathrm{HV}} = 400\ \mathrm{V}; U_{\mathrm{LV}} = 375\ \mathrm{V};\ I_{\mathrm{LV}} = 5\ \mathrm{A}$)

Room for Notes



Modern Device Power Supply with Safety **E**xtra-**L**ow **V**oltage

Modern Power Supply with Safety Extra-low Voltage

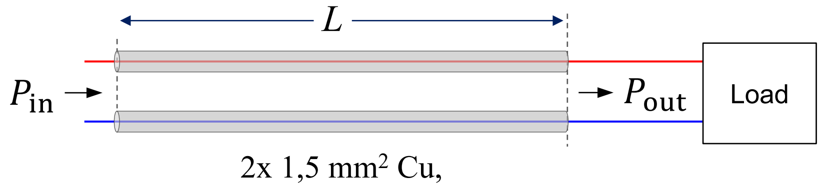
Extra Low Voltage

DC voltage	Description	
75 V to 1500 V	Validity of the Low Voltage Directive (2014/35/EU)	
≤ 120 V	**Extra Low Voltage**: Limit of the permanent permissible touch voltage for adult humans and normal applications	
	Extra-low voltage with **safe** galvanic isolation when fed from higher-voltage circuits	
	Ungrounded (Safety Extra Low Voltage, **SELV**)	**Grounded** (Protective Extra Low Voltage, **PELV**)
60 V to 120 V	Protection against direct contact by cover, casing or insulation	Protection against direct contact by cover, casing or insulation
≤ 60 V	no protection against direct contact required	No protection against direct contact required when used in dry locations and when no large-scale contact with human bodies or livestock is to be expected.
≤ 15 V	no protection against direct contact required	no protection against direct contact required
≤ 30 V	Appliances in showers, bathtubs, whirlpools (VDE 0100-701)	
≤ 24 V	Maximum voltage for children's toys (EU directive 2009/48/EG)	

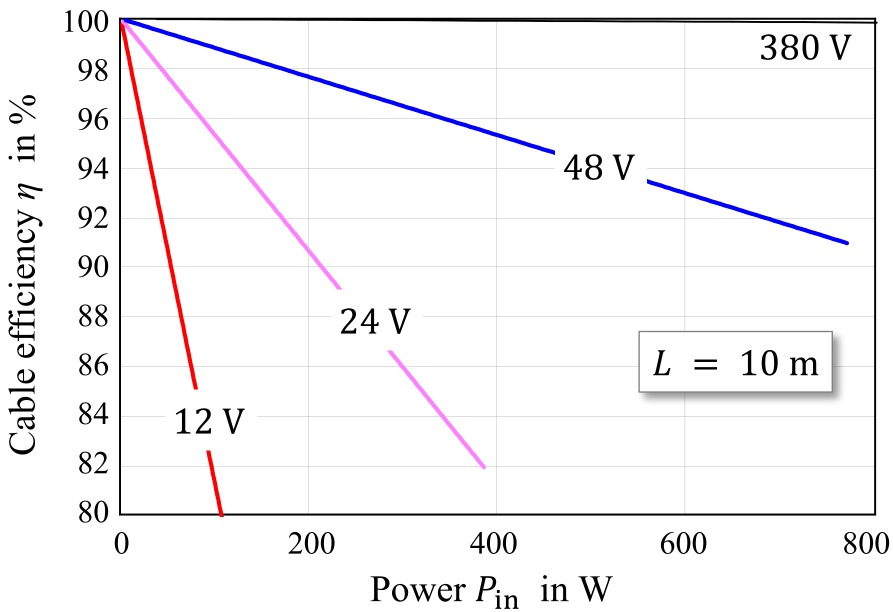
Deviating from the standards, "safety extra-low voltage" is used below as a generic term for SELV and PELV.

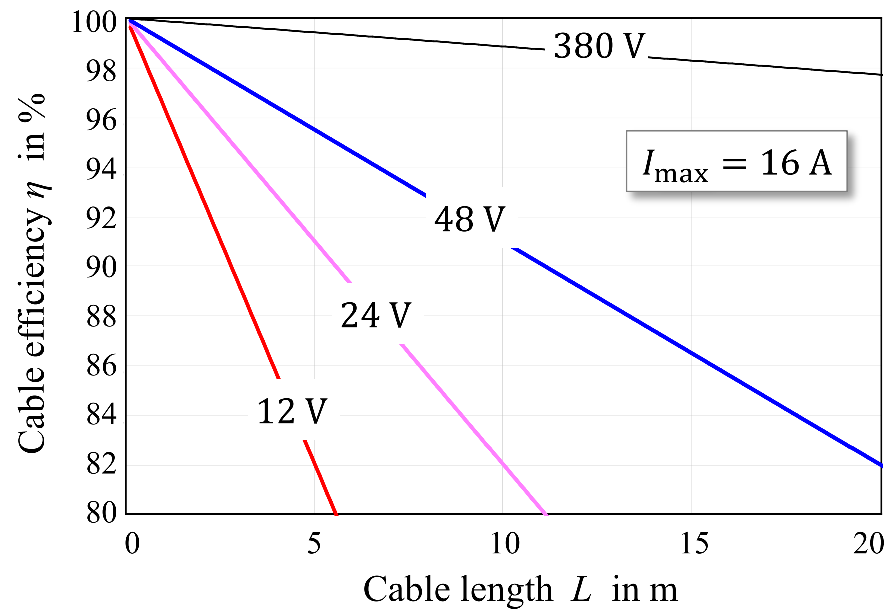
Modern Power Supply with Safety Extra-low Voltage

Cable Losses



$$\eta = \frac{P_{out}}{P_{in}}$$





↳ Electric power in the three-digit watt range can be transmitted economically and energy-efficiently over just a few meters with extra-low voltage!

Modern Power Supply with Safety Extra-low Voltage

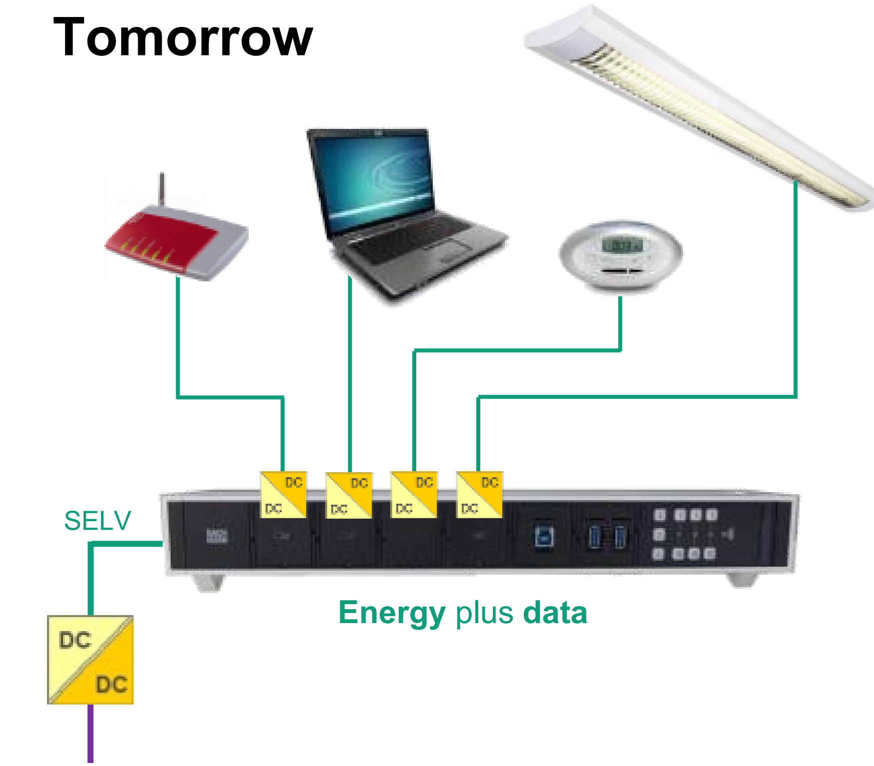
Situation Today: **A Proliferation of Voltages and Incompatible Plugs**

Modern Power Supply with Safety Extra-low Voltage

Today

The power adapters become part of the infrastructure and intelligent sockets individually supply the voltage required by the application.

Tomorrow



Modern Power Supply with Safety Extra-low Voltage

Power plus data over one cable (with a single unified plug)

USB 3.1 Typ-C – PD

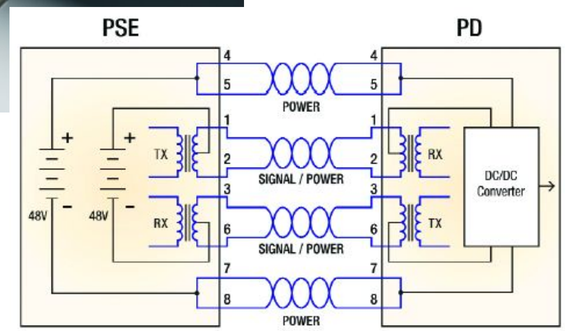
- Voltages: 5 V, 12 V or 20 V (up to 5 A)
- Power: 100 W (Power Delivery 2.0 Spec.)
- For short distances only (up to 3 m)
- Bidirectional power flow possible without changing cable or connector

USB Type C connector

A12	A11	A10	A9	A8	A7	A6	A5	A4	A3	A2	A1
GND	RX2+	RX2-	VBUS	SBU1	D-	D+	CC	VBUS	TX1-	TX1+	GND
GND	TX2+	TX2-	VBUS	VCON			SBU2	VBUS	RX1-	RX1+	GND
B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12

Power-over-Ethernet (PoE)

- IEEE 802.3 (4-pair Power-over-Ethernet)
- Power: 25.5 W (IEEE 802.3at-2009, PoE+)
- Voltage: 44 V to 57 V (in supply mode)
- Power flow from “Power Sourcing Equipment” (PSE) to the “Powered Device” (PD)

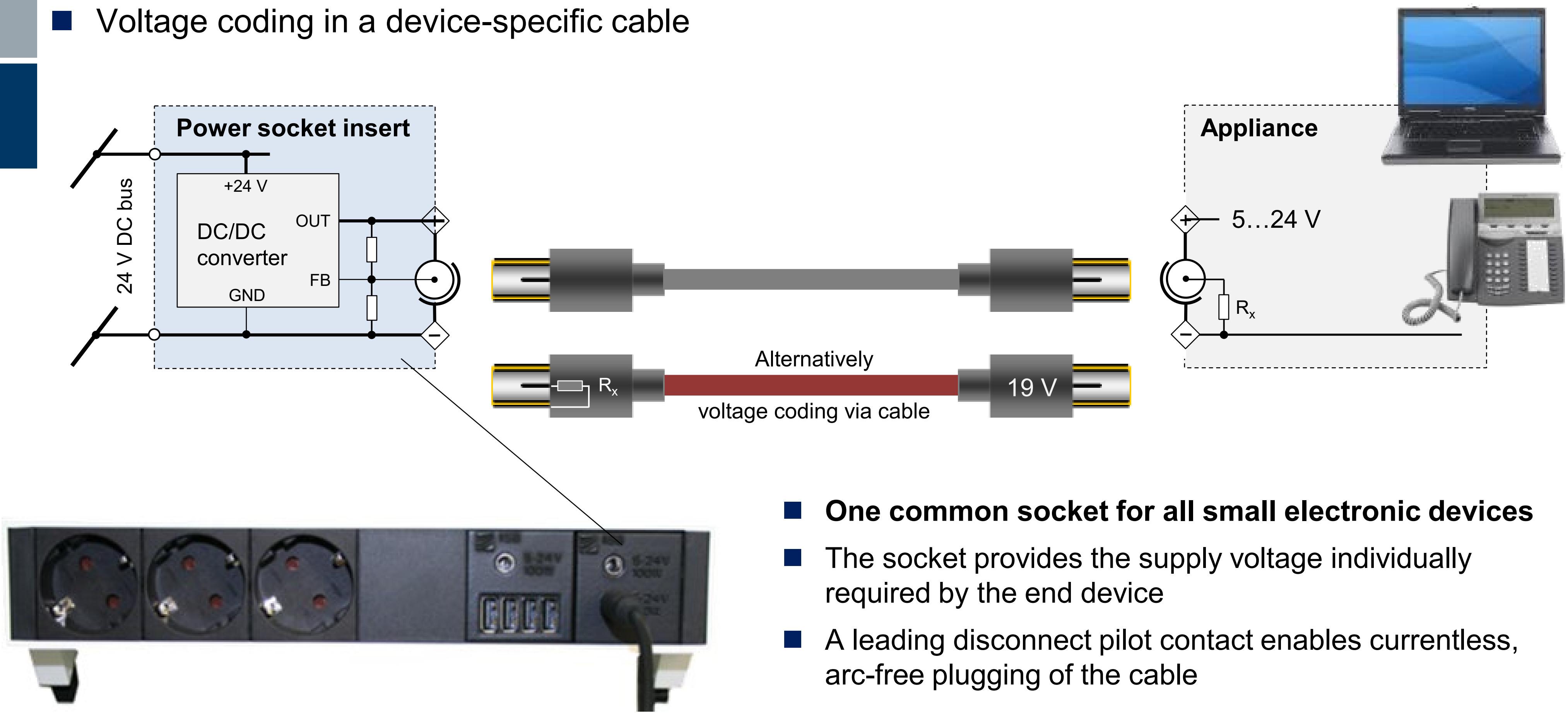


Source: www.powerguru.org

Modern Power Supply with Safety Extra-low Voltage

Solution options for existing end devices not supporting any communication protocol

- Pilot conductor in the supply cable and coding resistor in the end device
- Voltage coding in a device-specific cable



- **One common socket for all small electronic devices**
- The socket provides the supply voltage individually required by the end device
- A leading disconnect pilot contact enables currentless, arc-free plugging of the cable

Modern Power Supply with Safety Extra-low Voltage

Infrastructure-independent office workplaces

Wireless and energy self-sufficient thanks to integrated energy storage

Advantages for the operator of commercial real estate (offices, schools)

- No changes to the building installation when refurnishing
- No tripping hazards in the room
- Tidy desk (no cable and adapter clutter) thanks to uniformly DC-supplied devices


Source: Febrü

↳ a student spin-off of IISB and LEE

ceus

Energy content of nearly 1 kWh is enough to supply any office workplaces for more than 10 hours

Publications

Y. Han, J. Kaiser, L. Ott, M. Schulz, F. Fersterra, B. Wunder, M. März: *Non-isolated three-port DC/DC converter for ±380 VDC microgrids*. PCIM, Nuremberg 2016

L. Ott, J. Kaiser, K. Gosses, Y. Han, B. Wunder, M. März: *Model-Based Fault Current Estimation for Low Fault-Energy in 380 VDC Distribution Systems*. INTELEC 2016, Austin, TX, 2016

Wunder, B., Ott, L., Han, Y., Kaiser, J., März, M.: *Voltage Control and Stabilization of Distributed and Centralized DC Micro Grids*. PCIM, Nuremberg 2015

Wunder, B., Ott, L., Kaiser, J., Han, Y., Fersterra, F., März, M.: *Overview of Different Topologies and Control Strategies for DC Micro Grids*. IEEE ICDCM, Atlanta, 2015

Wunder, B., Kaiser, J., Fersterra, F., Ott, L., Han, März, M.: *Energy Distribution with DC Microgrids in Commercial Buildings with Power Electronics*. EDST, Vienna, 2015

Ott, L., Han, Y., Stephani, O., Kaiser, J., Wunder, B., Maerz, M.: *Modelling and Measuring Complex Impedances of Power Electronic Converters for Stability Assessment of Low-Voltage DC-Grids*, ICDCM, Atlanta, 2015

Ott, L., Han, Y., Wunder, B., Kaiser, J., Fersterra, F., Schulz, M., Maerz, M.: *An Advanced Voltage Droop Control Concept for Grid-Tied and Autonomous DC Microgrids*. INTELEC, Osaka, 2015

Weiss, R., Ott, L., Boeke, U.: *Energy Efficient Low-Voltage DC-Grids for Commercial Buildings*. ICDCM, Atlanta, 2015

Rykov, K.; Duarte, J. L.; Szpek, M; Olsson, J.; Zeltner, S.; Ott, L.: *Converter Impedance Characterization for Stability Analysis of Low-Voltage DC-Grids.* ISGT 2014, Washington D. C., 2014

K. Rykov, L. Ott, J. L. Duarte, E. Lomonova: *Modelling of Aggregated Operation of Power Modules in Low-Voltage DC Grids.* EPE, Laapeeranta, 2014

Rykov, K.; Duarte, J. L.; Szpek, M; Olsson, J.; Zeltner, S.; Ott, L.: *Converter Impedance Characterization for Stability Analysis of Low-Voltage DC-Grids.* ISGT 2014, Washington D.C., 2014

Selected Norms and Standards

Standard	Content
DIN VDE 0100	Elektrische Anlagen von Gebäuden
IEC 61557	Electrical safety in low-voltage distribution systems up to 1.000 V a.c. and 1.500 V d.c.
ETSI EN 300 132-3-1	Power supply interface at the input to telecommunications and datacom (ICT) equipment
ETSI EN 301 605	Earthing and bonding of 400VDC data and telecom (ICT) equipment
ETSI EN 300 253	Earthing and bonding configuration inside telecommunications centres
DKE Arbeitsgruppe TBINK	LVDC Niederspannungsgleichstromverteilnetze
IEC 60479-1 und -2	Effects of current on human beings and livestock
IEC 60898-3	Circuit-breakers for overcurrent protection for household and similar installations Part 3: Circuit-breakers for d.c. operation
IEC 60364	Low-voltage electrical installations
IEC 60445	Basic and safety principles for man-machine interface, marking and identification - Identification of quipment terminals, conductor terminations and conductors
IEC 60664	Insulation coordination for equipment within low-voltage systems
IEC 61851	Electric vehicle conductive charging system
DIN EN 60947	Niederspannungsschaltgeräte

Power Electronics for Decentral Energy Systems

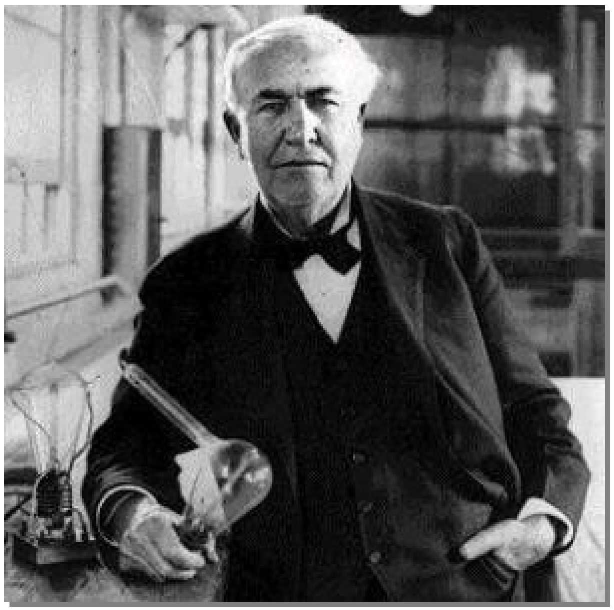
Friedrich-Alexander-Universität Erlangen-Nürnberg
Summer 2022

Accompanying information for the lecture

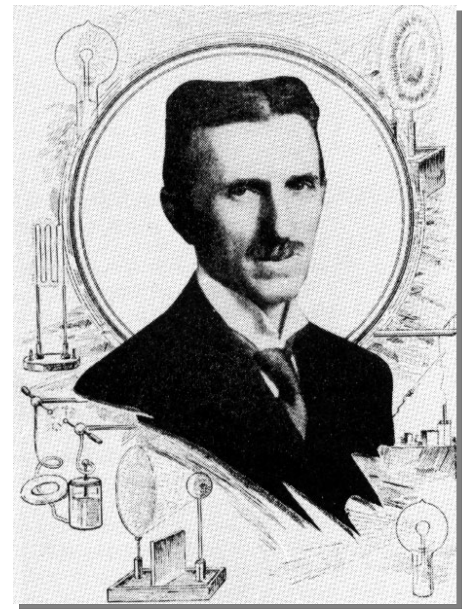
in german

Zwei wichtige Protagonisten

Thomas Alva Edison
1847 - 1931



Nikola Tesla
1856 - 1943



Gleichspannung

»Stromkrieg«
1885 - 1891

Wechselspannung

Meilensteine

1880 Edison erhält das Basispatent Nummer 223898 für eine gebrauchsfähige Kohlefadenglühlampe und beginnt mit der Elektrifizierung von New York mit Gleichspannung.

1883 Emil Rathenau gegründet die „Deutsche Edison-Gesellschaft für angewandte Elektrizität", die ab 1887 als „Allgemeine Elektricitäts-Gesellschaft" (AEG) firmiert.

1885 Erteilung eines Patents auf den Transformator an drei Ungarn. Zuvor hatten aber bereits Lucien Gaulard und John Dixon Gibbs 1881 erstmals einen Transformator in London ausgestellt.

1886 George Westinghouse errichtet das erste transformatorisch gekoppelte mehrstufige Wechselspannungsnetz in Great Barrington (USA-MA): Flußkraftwerk mit Generatoren für 500-V-Wechselspannung ⇨ Übertragungsspannung 3000 Volt ⇨ Ortversorgung 100 Volt.

1885 – 1891 Heftige Auseinandersetzungen um technische Standards und Marktanteile zwischen den Elektrofirmen Edison General Electric (später General Electric) und Westinghouse Electric („Stromkrieg").

1891 Erfolgreiche Drehstromübertragung Lauffen - Frankfurt anlässlich der Internationalen Elektrotechnischen Ausstellung in Frankfurt am Main.

1892 Westinghouse erhält den prestigeträchtigen Auftrag zur Lieferung eines Wechselspannungssystems für die Weltausstellung 1893 in Chicago.

1896 Durchbruch des Wechselspannungssystems in den USA mit dem Westinghouse-Kraftwerk an den Niagarafällen; Energieübertragung nach Buffalo unter Verwendung der Wechselspannungspatente von Nikola Tesla.

:

1998 In New York werden noch 4.600 Kunden mit Gleichspannung beliefert (vor allem für ältere Aufzüge in Manhattan).

2007 Der New Yorker Stromversorger Con Edison stellt die Lieferung von Gleichspannung endgültig ein.

FAU Friedrich-Alexander-Universität Technische Fakultät
LEHRSTUHL FÜR LEISTUNGSELEKTRONIK
Fraunhofer IISB

… und hier in Bayern: **Auszug aus der Stromchronik von Niederbayern**

1883 Mechanikermeister Johann Weiß (33) baut in Landshut seinen ersten Dynamo und beleuchtet den Platz vor seiner Fabrik mit elektrischem Bogenlicht. Damit brennt erstmals in Ostbayern öffentlich elektrisches Licht!

1887 Elektrizitätswerk (EW) der Wieninger-Mühle in Vilshofen versorgt über 100-V-Gleichstrom-Fernleitung zwei Privathäuser in der Innenstadt; die Lichtstromleitung wird gleichzeitig für Telephonzwecke genutzt.

1892 Passau: Kleinkraftwerk des Kaufmanns Gustav Gerstl mit 65-V-Gleichstrom für Beleuchtung

1895 Wolfstein-Waldkirchen: Mühlenbesitzer Süß errichtet ein Privat-EW, das den Markt Waldkirchen mit Strom versorgt (Wasserrad, 110-V-Gleichspannung, Akkumulatorenbatterie zur Stabilisierung)

1899 Deggendorf, Errichtung des Elektrizitätswerks (Gleichstrom, 2x 150-Volt-Dreileiternetz). Veranschlagte Kosten u.a. für 2 Dampfmaschinen u. Dynamos: 70.700 Mark; Batterien: 22.000 Mark; Leitungsnetz: 27.900 Mark.

1900 Eggenfelden: Privates EW Sailer (Dampfsäge, 2 Dynamos 38 PS, Pufferbatterie mit 64 Zellen) versorgt die Stadt mit 120-V-Gleichstrom (Zweileitersystem); bis 1923 schließen weitere 12 Gemeinden an.

Vilsbiburg-Gerzen: EW des Mühlenbesitzers Mathias Steiner nimmt Stromlieferung auf (125-V-Gleichstrom)

1905 EW Dingolfing: Dreileiternetz mit 2x 220-V-Gleichspannung und Pufferbatterie aus 250 Zellen je 108 Ah;
Im ersten Versorgungsjahr 58 Abnehmer mit insgesamt 16.500 kWh Stromverbrauch.

1906 Siemens-Schuckert erbaut Passauer städtisches EW (110-V-Gleichstrom)

1911 Eggenfelden-Straßkirchen: Stümpfl-Mühle nimmt die Stromversorgung der Gemeinde auf (220-V-Gleichstrom)

1919 Bezirksamt Grafenau: Mit einer Ausnahme liefern alle 19 Kraftwerke im Bezirk Gleichstrom (in der Regel 110 V)

1921 Bezirksamt Kötzting: Drei Wasserkraftwerke mit zus. 34 PS versorgen 12 Orte mit 220-V-Gleichstrom

Quelle: „Elektrizität in Ostbayern“, Toni Siegert, Bergbau- und Industriemuseum Ostbayern; Band 9

Eigeninitiativen, dezentrale Strukturen – aber auch fehlende Standards

… bald herrschte regelrechtes Chaos in den einzelnen Ortsversorgungen

So gab es beispielsweise alleine innerhalb von Landau/Isar Anfang der 20-er Jahre fünf verschiedene Gebrauchsspannungen:

110 V, 150 V, 190/110 V, 220/380 V

Die Konsequenzen schildert ein Prüfer-Gutachten von 1922:

„Diese Verschiedenheit der vorhandenen Spannungen erschwert einmal das Halten von Reservetransformatoren … außerdem verschiedener Lampen und Motoren … weil die Consumentenreihe Lampen für 110 oder 150 oder 220 Volt benötigt, die andere Motoren für 110 oder 150 oder 190 oder 380 Volt.“

Historischer Netzspannungswählschalter für Elektrokleingeräte

Quelle: „Elektrizität in Ostbayern“, Toni Siegert, Bergbau- und Industriemuseum Ostbayern; Band 9

… auch die Sicherheitsstandards galt es erst noch zu entwickeln

Bezirksamt Viechtach, 20.11.1896, Bericht des Bezirkstechnikers Pfeiffer über Installation in der Papierfabrik Teisnach:

„… Wenn, wie hier, der elektrische Strom für die Kraftübertragung 3500 Volt hat, so ist die Gefahr für Leben und Gesundheit eine nicht verkennenswerthe. 300 – 600 Volt kann jeder gesunde Mensch aushalten, jedoch bei nahezu 6x 600 = 3600 Volt stellt sich dies erheblich ungünstiger dar. …“

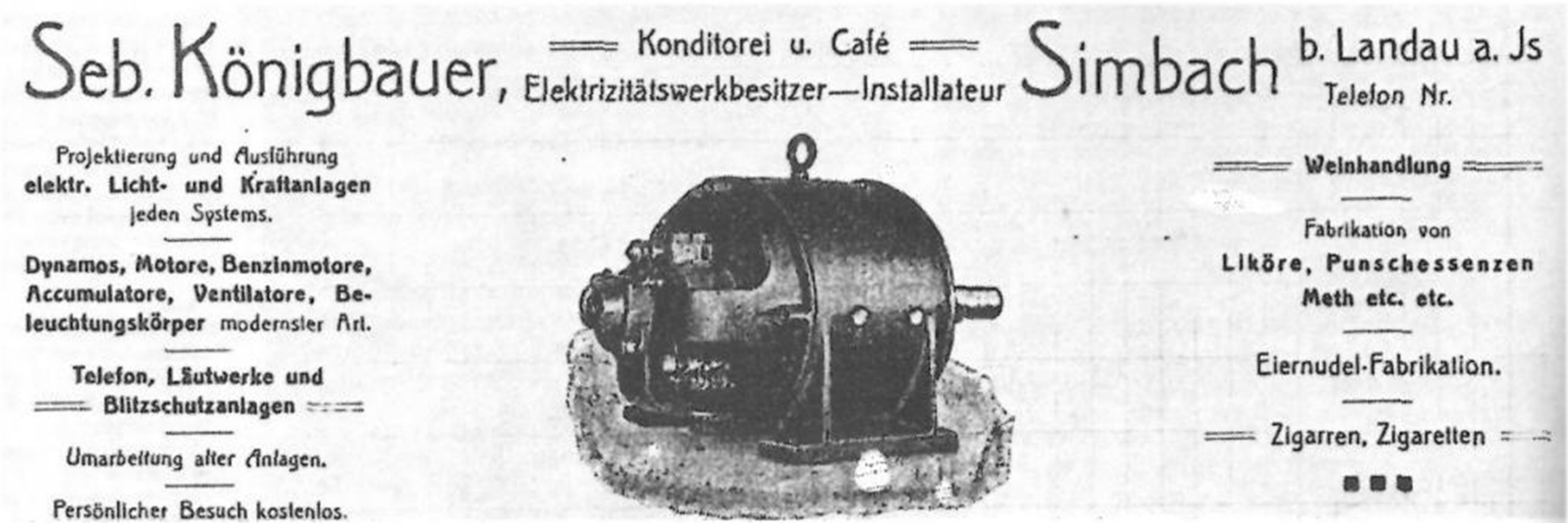
Bezirksamt Viechtach, 23.3.1904. In ihrem Bericht verlangen Prüfer aus Nürnberg, die Freiwillige Feuerwehr von Viechtach über den Umgang mit elektrischem Strom aufzuklären:

„… Im übrigen wäre das Feuerwehrpersonal dahin zu instruieren, dass der Mensch beim Berühren der blanken elektrischen Leitungen, besonders bei nassem Wetter einen im allgemeinen ungefährlichen elektrischen Schlag erhält. Das Feuerwehrpersonal soll darauf vorbereitet sein, damit nicht […] die getroffene Person von der Leiter oder dem Dache herabstürzt. Das Anspritzen der Leitungen ist völlig ungefährlich.“ 1)

Quelle: „Elektrizität in Ostbayern“, Toni Siegert, Bergbau- und Industriemuseum Ostbayern; Band 9; 1) Netzspannung in Viechtach zu dieser Zeit: 120 Volt

Viele selbst ernannte Experten

Typisch für die Flexibilität und „Qualifikationserweiterung“ im Handwerk ist diese Anzeige aus der Pionierzeit



Bildquelle: „Elektrizität in Ostbayern“, Toni Siegert, Bergbau- und Industriemuseum Ostbayern; Band 9

Viele selbst ernannte Experten

Typisch für die Pionierzeit:

Am 14. April 1911 schloß die Gemeinde Johanniskirchen (Bezirksamt Eggenfelden) mit dem Mühlenbesitzer Johann Stümpfl eine Vertrag mit der alleinigen Berechtigung, im Gebiet der Ortsgemeinde Leitungen und sonstige Anlagen zur Lieferung von elektrischem Strom zu errichten.

Der E-Werksbesitzer Stümpfl, von Beruf **Müller und Bäcker**, setzte später unter seine Unterschrift noch die Berufsbezeichnung „**Elektrotechniker**“ hinzu, war aber nach späterem Urteil eines Fachmanns „.. *so ziemlich der ungeeigneste Mensch zum Betrieb elektrischer Anlagen*…“.

Nach mehreren Vorkommnissen mußte er sich auf Veranlassung des Bezirksamts Eggenfelden in Plattling einfinden, um vor einem Fachmann der Elektrotechnischen Abteilung der Bayerischen Landesgewerbeanstalt Nürnberg eine Prüfung abzulegen - diese endete katastrophal:

„ Mit der Berechnung von Hausinstallationsanlagen ist der Gesuchsteller nicht vertraut. Das Vorhandensein von Vorschriften des Verbandes Deutscher Elektrotechniker über die Ausführung elektrischer Anlagen ist dem Gesuchsteller nicht bekannt. …“

Quelle: „Elektrizität in Ostbayern“, Toni Siegert, Bergbau- und Industriemuseum Ostbayern; Band 9

… hemdsärmlich und nicht selten an der Grenze zu Bastelei oder Pfusch

Typisch für die Pionierzeit:

Eine Überprüfung des Zellnerschen E-Werkes durch den Elektriker Sträußl und begleitende Beamte des Bezirksamts Eggenfelden fiel schlimm aus. Zitat aus dem Gutachten vom 20.8.1907:

„Besonders hervorzuheben sind folgende Mängel:

….

2. *Sind in diesem Raum die Sicherungen entfernt und teilweise durch Kupferdraht oder viel zu starkes Fensterblei ersetzt. …*
3. *Die Verteilungstafel besteht aus blankem Holz und ist wieder ohne jede Feuerschutzvorrichtung an der Holzwand befestigt. Auch auf dieser Tafel sind fast sämtliche Sicherungen entfernt und durch Kupferdrähte ersetzt.*
4. *… in diesem Raum gehen mehrere einfache [blanke] Leitungslitzen ohne jeden Schutz durch eine leicht entzündliche größere Menge Hobelspäne.*
6. *… Die Drähte sind schlecht gespannt, hängen wirr durcheinander.*
7. *Die Akkumulatorenbatterie befindet sich im 1. Stock auf schwankendem, von Schwefelsäure durchtränktem Holzboden. Die Batterie funktioniert zur Zeit nicht. Dieselbe ist ganz verlottert und unbrauchbar …*
14. *[beim] Ökonom Reiter: … Die Drähte gehen ohne Schutzrohr durch das Gebälk. Der Leitungsquerschnitt ist zu schwach, dagegen die Sicherung viel zu stark. …*

Quelle: „Elektrizität in Ostbayern“, Toni Siegert, Bergbau- und Industriemuseum Ostbayern; Band 9

… hemdsärmlich und nicht selten an der Grenze zu Bastelei oder Pfusch.

Zitat aus dem Zustandsbericht eines Ingenierbüros aus Osterhofen über das Stromnetz im Bereich Schwaigen/ Mamming (Bezirksamt Dingolfing)

„…[er] hat in seinem Elektrizitätswerk seit einiger Zeit andauernd mit Betriebsstörungen zu tun. Ein Kurzschluß und Erdschluß folgt auf den anderen. Die Sicherungen der Konsumenten sind größtenteils durch Nägel, Kupferdrähte usw. ersetzt, so daß es zu keinem Durchschmelzen kommt. … Es ist überhaupt staunenswert, daß Brandunfälle noch nicht zu verzeichnen sind …“.

Aus einer Beschwerde des „Reichsverband des deutschen Elektro-Installateurgewerbes VEI“ beim Bezirksamt Dingolfing im Oktober 1933

„… Das Pfuschertum in der Elektroinstallation bedeutet eine große Gefahr für die öffentliche Sicherheit. Gerade die Kleinversorger sind Brutstätten des Pfuschertums, weil dort die Zulassung von Elektroinstallateuren nicht geregelt ist. Es können dort ungehindert Leute installieren, die keine richtige Fachausbildung haben. …“

Quelle: „Elektrizität in Ostbayern“, Toni Siegert, Bergbau- und Industriemuseum Ostbayern; Band 9

Auch Umweltschutz-Aspekte spielten damals schon eine Rolle

Hofrat Dr. Brunnhuber, Vorsitzender des Ausschusses für Naturpflege Regensburg, an Bezirksamt Stadtamhof (1909):
„Es wäre sehr wünschenswert, wenn die Holzmasten der Leitungen ebenso wie die eisernen mit einem graugrünen Anstrich versehen würden, wenigstens soweit sich die Leitung im Gebiet des Donautales ... erstreckt. Mit einem gleichen Anstrich sollten auch die Transformatorenhäuschen versehen werden, um sie möglichst unauffällig zu gestalten.“

… und der Heimatschutz rügt:
„... die Ausbildung der Transformatoren-Häuschen, welche meist mit wenig Liebe durchgearbeitet sind, nur als notwendiges Übel rein konstruktiv betrachtet werden ..... - es fehlt an der künstlerischen Durchbildung.“

Aus einem Bericht des Bezirksamtmann Kaiser nach einer Leitungsbegehung (Bezirk Grafenau, 4.4.1921):
„Sehr wünschenswert wäre es dagegen, wenn an Stelle der stets auffallenden weißen Isolatoren besonders in waldigen Gegenden grüne Isolatoren verwendet werden könnten“.

Das Landbauamt Landshut mußte schon im August 1923 diagnostizieren:
„Das Bestreben zur Wahl des kürzesten Weges hat bereits dazu geführt, daß das Gelände zwischen Landshut und Altdorf durch ein Gewirr von elektrischen Masten vollständig verunstaltet ist. Es herrscht hier eine Unordnung in der Leitungsführung, die jeden, der ein Landschaftsbild zu schauen vermag, auf das tiefste betrüben muß ...“

Und das Landeswirtschaftsamt Fürth i. Bay. bewilligt am 8.9.1943 den Bau einer 20.000-Volt-Leitung nach Ober- und Unterwaltenkofen (Bezirksamt Landshut) unter der Auflage:
„Die kriegsbedingte Verwendung weißer Isolatoren wird gestattet. Auf Antrag der Naturschutzbehörde sind diese jedoch nach Kriegsende zu entfernen und durch andersfarbige zu ersetzen.“

Quellen: „Elektrizität in Ostbayern - Niederbayern“, Toni Siegert, Bergbau- und Industriemuseum Ostbayern; Band 6 und Band 9

… und auch das Thema Lastverschiebung war schon aktuell!

Bezirksamt Eggenfelden:

„… Die fehlende Disziplin unter den Stromabnehmern führte auch dazu, daß zur Durchführung des elektrischen Dreschens bestimmte Teile des Netzes abgeklemmt werden mußten. Wurde beispielsweise in Uttigkofen gedroschen, trennte man einfach das Laimbacher Netz am Verteilermasten in Reith ab, damit niemand durch zusätzlichen Stromverbrauch das elektrische Dreschen unmöglich machte.“

Zitat: „Elektrizität in Ostbayern - Niederbayern“, T. Siegert, Band 9
Bildquelle: Elektrizität in Ostbayern - Oberpfalz“, T. Siegert, Bergbau- und Industriemuseum Ostbayern; Band 6: **Häckselmaschine aus den 30er Jahren**

Dezentrale Erzeugungsstrukturen – Gleichstrom dominiert

Aus dem Jahresbericht 1911 des Städtischen Elektrizitätswerkes Regensburg:

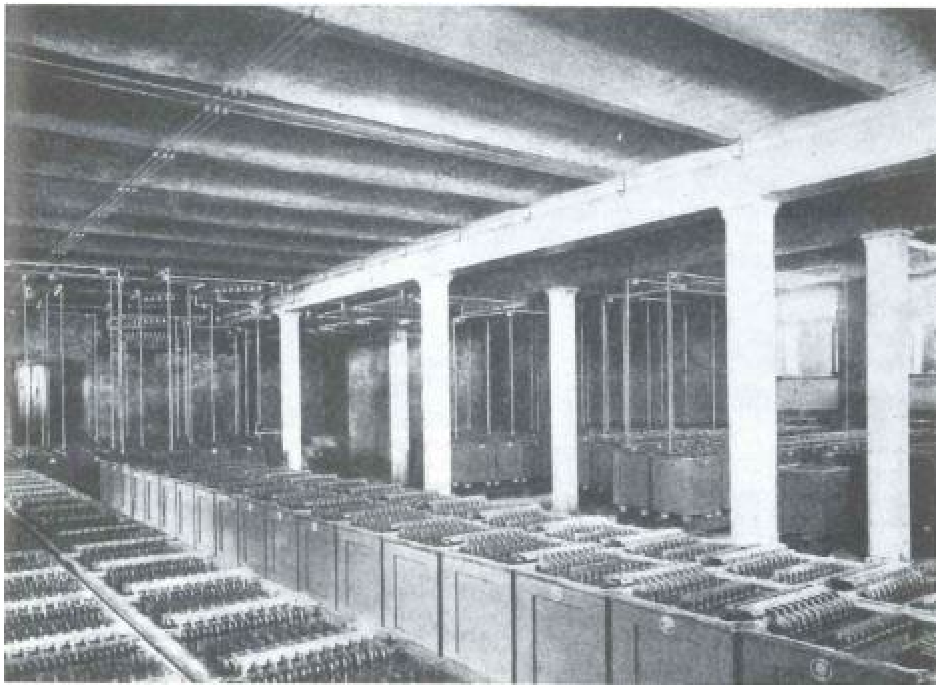
Die Entwicklung der Anschlußbewegung seit dem Jahre 1900 bis auf das Berichtsjahr ergibt sich aus der nachstehenden Aufstellung.

Am 31. Dezbr.	Anschlußwert in KW							Zunahme in % gegen das Vorjahr	
	Gleichstrom				Drehstrom				
	Licht[1])	Kraft[2])	Bahn	Zusammen	Licht	Kraft	Zusammen	Gleichstr. Licht	Gleichstr. Kraft
1900	512,87	125,68	—	638,55	—	—	—	—	—
1901	625,83	235,00	—	860,83	—	—	—	22,0	87,2
1902	774,30	358,32	—	1 132,62	—	—	—	23,7	52,4
1903	866,64	436,42	545,60	1 848,66	—	—	—	11,9	21,8
1904	1 049,46	556,96	545,60	2 152,02	—	—	—	21,1	27,6
1905	1 160,70	634,96	545,60	2 341,26	—	—	—	10,6	14,0
1906	1 262,96	683,28	545,60	2 491,84	—	—	—	8,8	7,6
1907	1 351,45	797,55	545,60	2 694,60	—	—	—	7,0	16,3
1908	1 479,73	963,26	545,60	2 988,59	—	—	—	9,5	20,9
1909	1 585,21	1 129,60	545,60	3 260,41	—	—	—	7,1	17,3
1910	1 681,41	1 229,87	715,25	3 626,53	20,09	243,04	263,13	6,1	8,9
1911	1 761,62	1 285,88	715,25	3 762,75	31,84	469,82	501,66	4,8	4,4

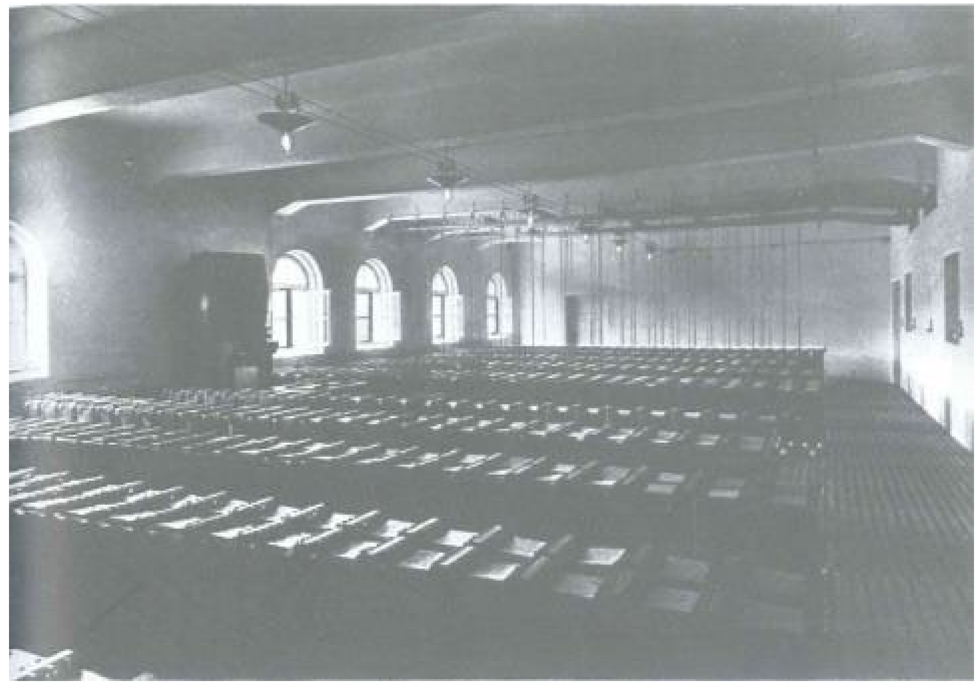
Quelle: Elektrizität in Ostbayern - Oberpfalz“, Toni Siegert, Bergbau- und Industriemuseum Ostbayern; Band 6;

Pufferung der Gleichstromenergieversorgung

Akkumulatorensaal des städtischen Elektrizitätswerks Straubing (Foto von 1901)



Akkumulatorensaal des städtischen Elektrizitätswerks Landshut



Bildquelle: „Elektrizität in Ostbayern", Toni Siegert, Bergbau- und Industriemuseum Ostbayern; Band 9

Gleichstrom – lange Zeit die dominierende Stromform bei uns!

Städt. Elektrizitätswerk Landshut: Wirtschaftsdaten 1933–1938[281]

		1933	1938	Differenz nominal	Differenz in Prozent
Stromerzeugung					
Drehstrom (Eigenerzeugung)	in kWh	1819240	4311090	+ 2491850	+ 137,0 %
Gleichstrom (Eigenerzeug.)	in kWh	3361390	4613528	+ 1252138	+ 37,3 %
Gesamte Eigenerzeugung	in kWh	5180630	8924618	+ 3743988	+ 72,3 %
Strombezug	in kWh	34680	156630	+ 121950	+ 351,6 %
Gesamterzeugung	in kWh	5215310	9081248	+ 3865938	+ 74,1 %
Nutzbare Stromabgabe	in kWh	4525987	8185879	+ 3659892	+ 80,9 %
Netzverluste	in kWh	689323	895369	+ 206046	+ 29,9 %
Netzverluste	in %	13,2 %	7,6 %		– 5,6-%-Punkte
Höchstlast	in kW	1440	1830	+ 390	+ 27,1 %
Benutzung der Höchstlast	in Stunden	3088	3788	+ 700	+ 22,7 %
Stromverteilung					
Niederspannung – Leitung	in km	53,5	58,9	+ 5,4	+ 10,1 %
Niederspannung – Kabel	in km	28,0	32,6	+ 4,5	+ 16,4 %
Hochspannung – Leitung	in km	19,3	18,4	– 0,9	– 4,7 %
Hochspannung – Kabel	in km	1,1	5,1	+ 4,0	+ 363,6 %
Gesamtleitungslänge	in km	101,9	115,0	+ 13,1	+ 13,0 %

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Umstellung von Gleich- auf Wechselstrom - ein langsamer Verdrängungsprozess

Gleichstromentwicklung in Straubing (1940–1950)[134]

Jahr	Bezug und Erzeugung in Mio. kWh	Gleichstromabgabe in Mio. kWh	in %
1940	6397	3265	51,0
1941	6568	3594	54,5
1942	7186	3611	50,0
1943	7231	3549	49,2
1944	8428	3744	44,4
1945	8925	3569	40,0
1946	10655	3551	33,3
1947	11124	3561	32,0
1948	11624	3577	30,7
1949	12550	2868	22,8
1950	13718	2439	17,8
1940/50:	+ 7321	– 826	
in Prozent:	+ 114,4 %	– 25,3 %	– 33,2

- Dingolfing: Die Umstellung der Elektrizitätsversorgung von Gleich- auf Wechsel-/Drehstrom war erst im Februar 1959 abgeschlossen.
- New York: Der Stromversorger Con Edison stellte erst 2007 die Lieferung von Gleichstrom endgültig ein.

Bildquelle: „Elektrizität in Ostbayern“, Toni Siegert, Bergbau- und Industriemuseum Ostbayern; Band 9

Netzumstellungsprobleme sind nichts Neues …

Im Oktober 1919 klagt die Gemeinde Dorfbach (Bezirksamt Passau), daß erneut ein Umbau des Ortsnetzes auf eine andere Stromspannung drohe – zum drittenmal innerhalb von nur fünf Jahren. Damit hätten die Landwirte ihre Elektromotoren erneut wegwerfen können. Der Bayerische Revisionsverein ergänzt am 2.10.1919:

„… da außerdem Einrichtung mit 440 Volt Gleichstrom in landwirtschaftlichen Betrieben wegen der erhöhten Feuersgefahr nicht empfehlenswert ist, sollte der Umbau der bestehenden Anlage auf 440 bezw. 2x 220 Volt wenn irgend möglich vermieden werden."

Anfang September 1920 schreibt dann der Dorfbacher Bürgermeister Wagner:

„Seitdem das Elektrizitätswerk … von 220 auf 440 Volt umgestellt ist, wurde die Wahrnehmung gemacht, daß die Feuerunsicherheit erheblich gewachsen ist."

Am 25. Juli 1945 meldete der Bürgermeister von Kötzting an den Landrat:

„… Abhilfe [der Versorgungsprobleme] ist möglich, wenn …. ein Anschluß an die Überlandzentrale – Kraftwerk Höllenstein – hergestellt wird. In letzterem Falle ist Voraussetzung, daß neben dem Transformator auch ein Umformer von Wechselstrom auf Gleichstrom eingebaut wird, weil sonst sämtliche Motoren, Radios, Bügeleisen, Glühbirnen und sonstige gewerbliche Anlagen wie Kühlgeräte, Röntgen- und Bestrahlungsgeräte usw. gegen Geräte mit Wechselstrom ausgetauscht werden müssen. …"

Quelle: „Elektrizität in Ostbayern", Toni Siegert, Bergbau- und Industriemuseum Ostbayern; Band 9

… auch nicht die Widerstände etablierter Energieversorger!

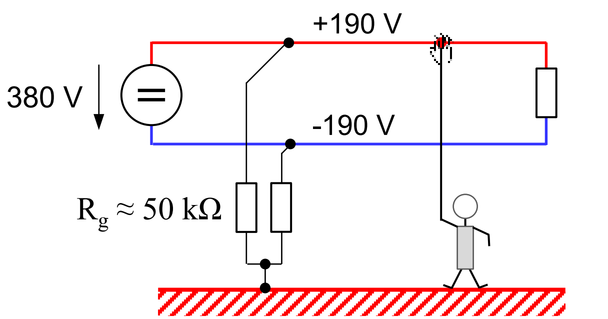
Kötzting, 9.12.1929: Gemeindeflugblatt des Elektrizitätswerksbesitzers Franz Schrötter gegen die Umstellung von Gleich- auf Wechselstrom in Lam – darin weist er auf die Gefährlichkeit des Drehstroms hin:

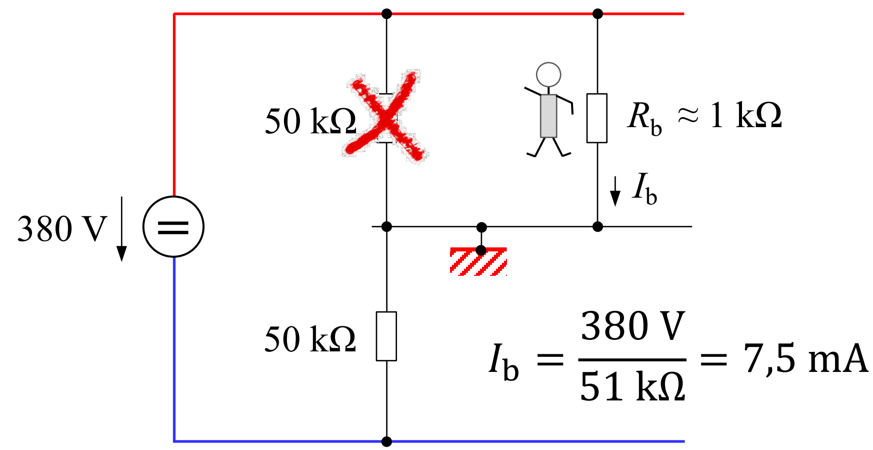
„Mit erschreckender Häufigkeit ereignen sich Todesfälle beim Auswechseln einer elektrischen Glühbirne, einer Arbeit, die doch jedermann für völlig ungefährlich hält und auch halten darf. Des weiteren sind häufig Tötungen, wo die örtliche Niederspannungsleitung des Drehstromnetzes mit einer Radio-Antenne in Berührung kommt …“

Quelle: „Elektrizität in Ostbayern“, Toni Siegert, Bergbau- und Industriemuseum Ostbayern; Band 9

Explanation of slide 38

Symmetrisch hochohmig geerdet





$$I_b = \frac{380\ \mathrm{V}}{51\ \mathrm{k\Omega}} = 7{,}5\ \mathrm{mA}$$