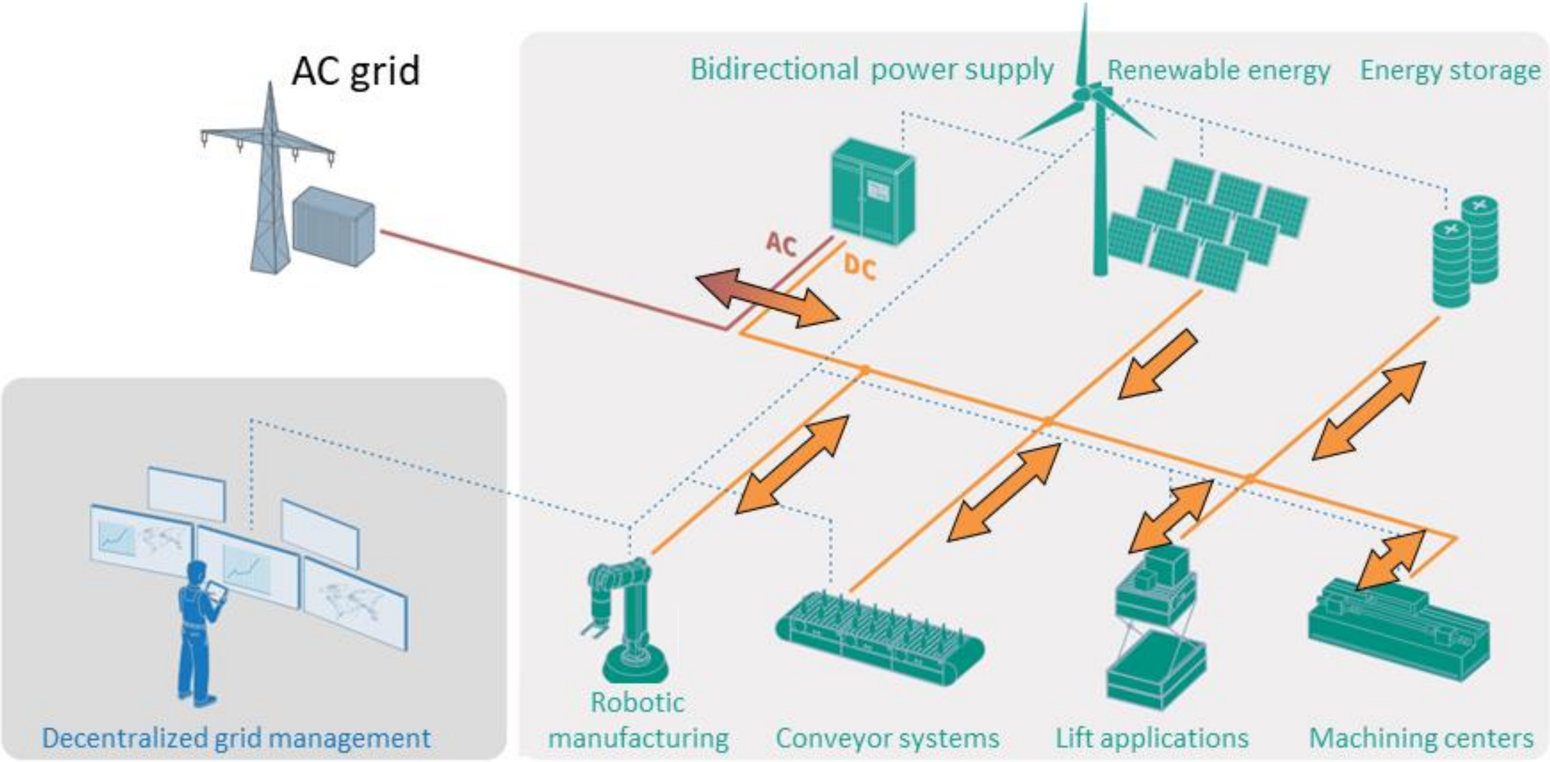

DC-INDUSTRIE
ENERGIEWENDE TRIFFT INDUSTRIE 4.0

DC-INDUSTRIE2 | **Nov. 2022**

DC-INDUSTRIE2 – open DC grid for sustainable factories

Joint research project: DC-INDUSTRIE2 – Direct current for the factory of the future

Contact:

Dr. Hartwig Stammberger
(Eaton, Bonn, project coordinator)

Prof. Dr.-Ing. Holger Borcherding
(TH OWL, Lemgo, scientific lead of the project)

Supported by:
Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

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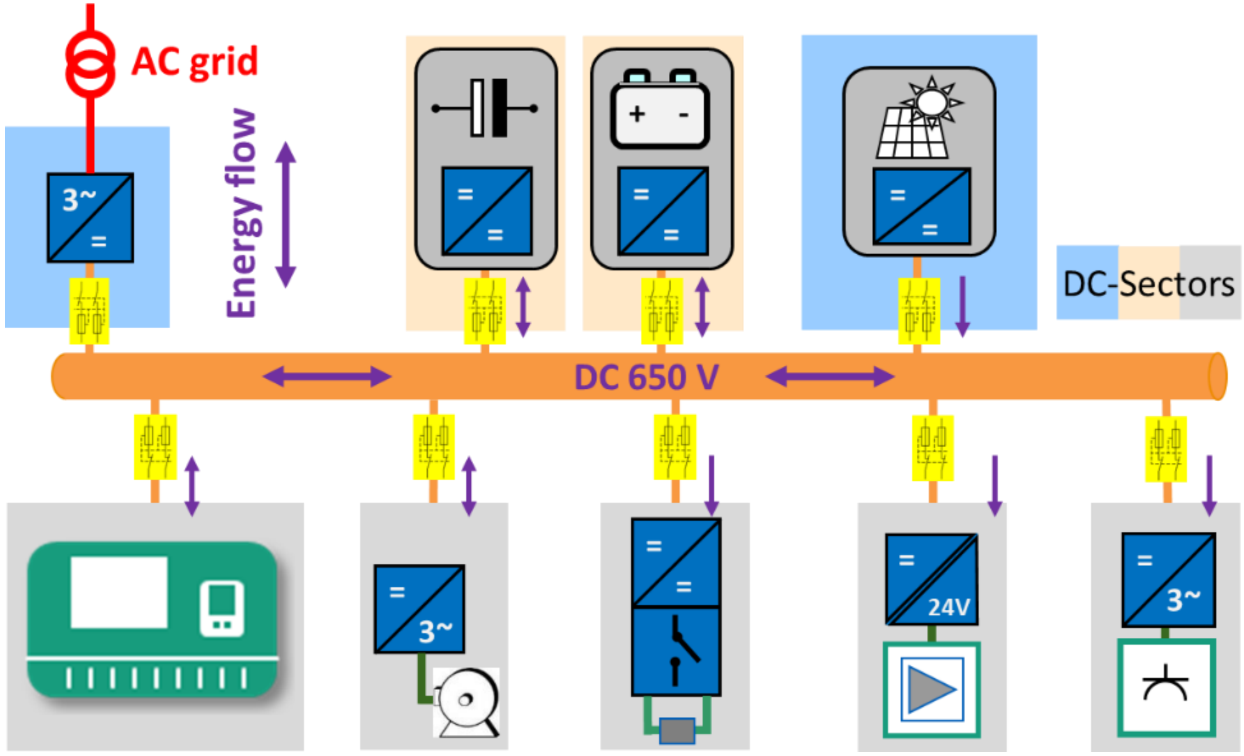
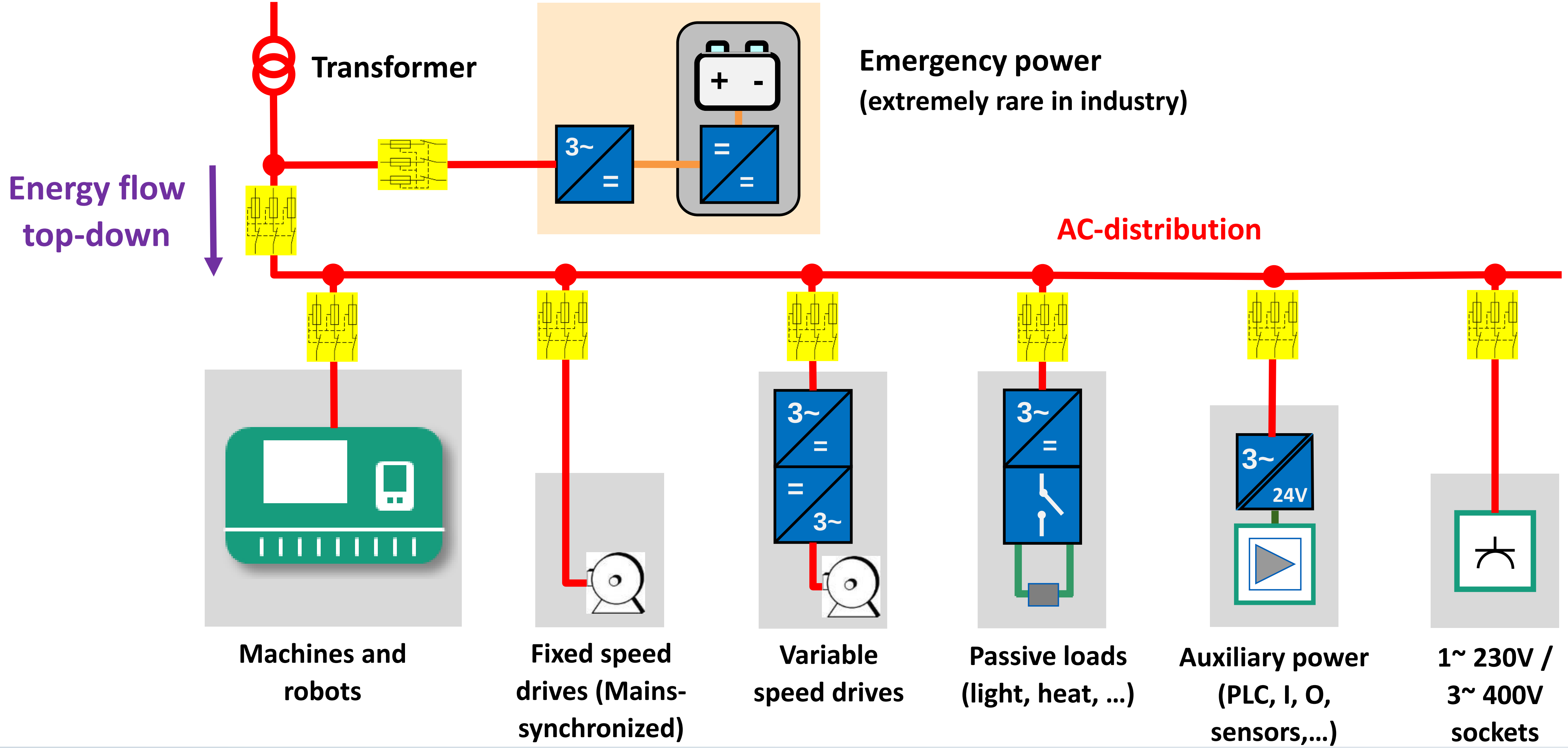
Overview: research project DC-INDUSTRIE2

- **Funded by the German Federal Government**
  - Funding codes: 03EI6002A-Q
- **3.5 years until March 2023**
- **39 industry and research partners**
  - Some 140 engineers & researchers
- **Objectives:**
  - Safe and robust energy supply for production
  - Mains-supporting connection to the supply grid
  - Maximum use of decentralized, regenerative energy
  - Simple project planning
- **Implementation and validation**
  - 10 model plants and transfer centers

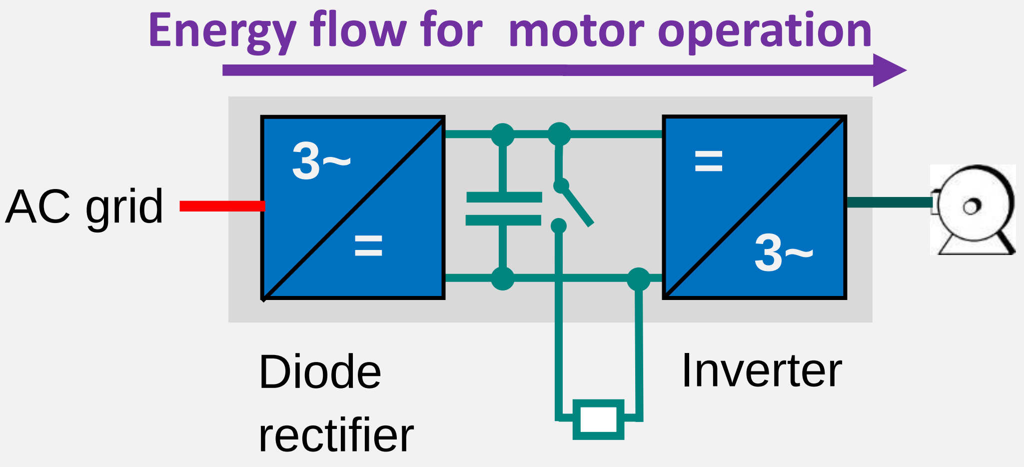


Status quo: Topology of an industrial AC grid

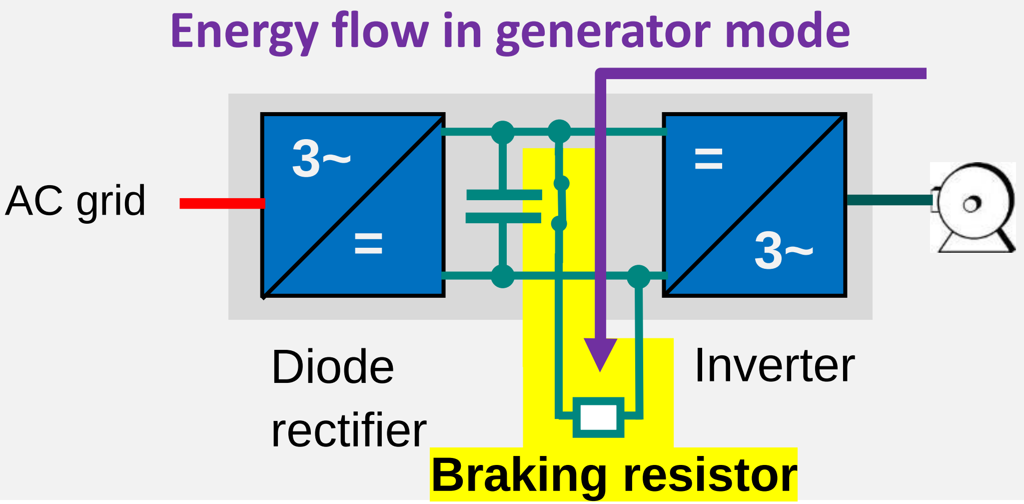


Energy: Current situation with frequency converters (AC-AC)

Basic wiring of frequency converters is optimized for **motor** applications



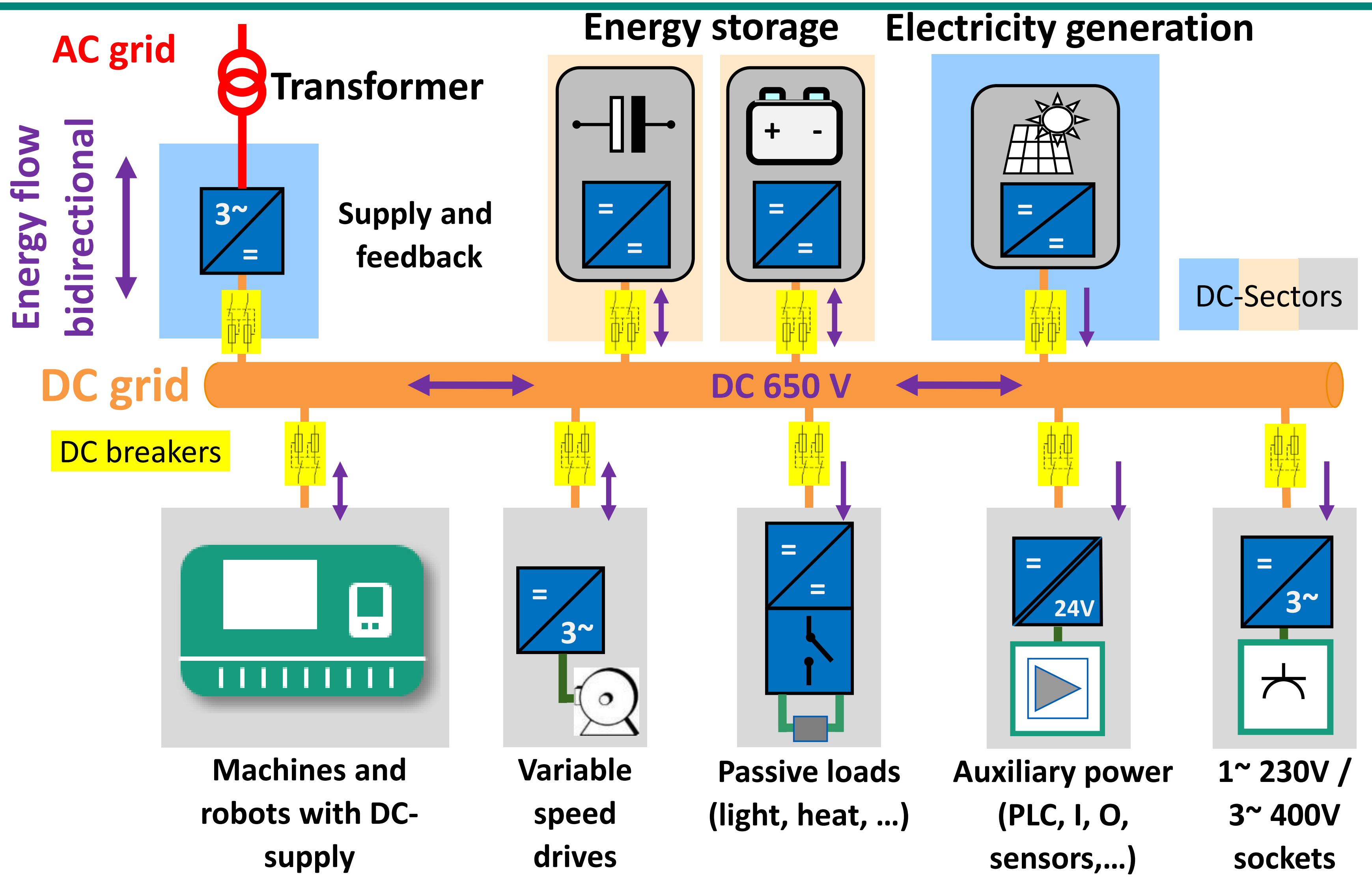
In **braking** mode, the inverter needs to dispose of the stored energy.
The most common method is the **dissipation of the energy to heat** in braking resistors



Topology of an industrial DC grid

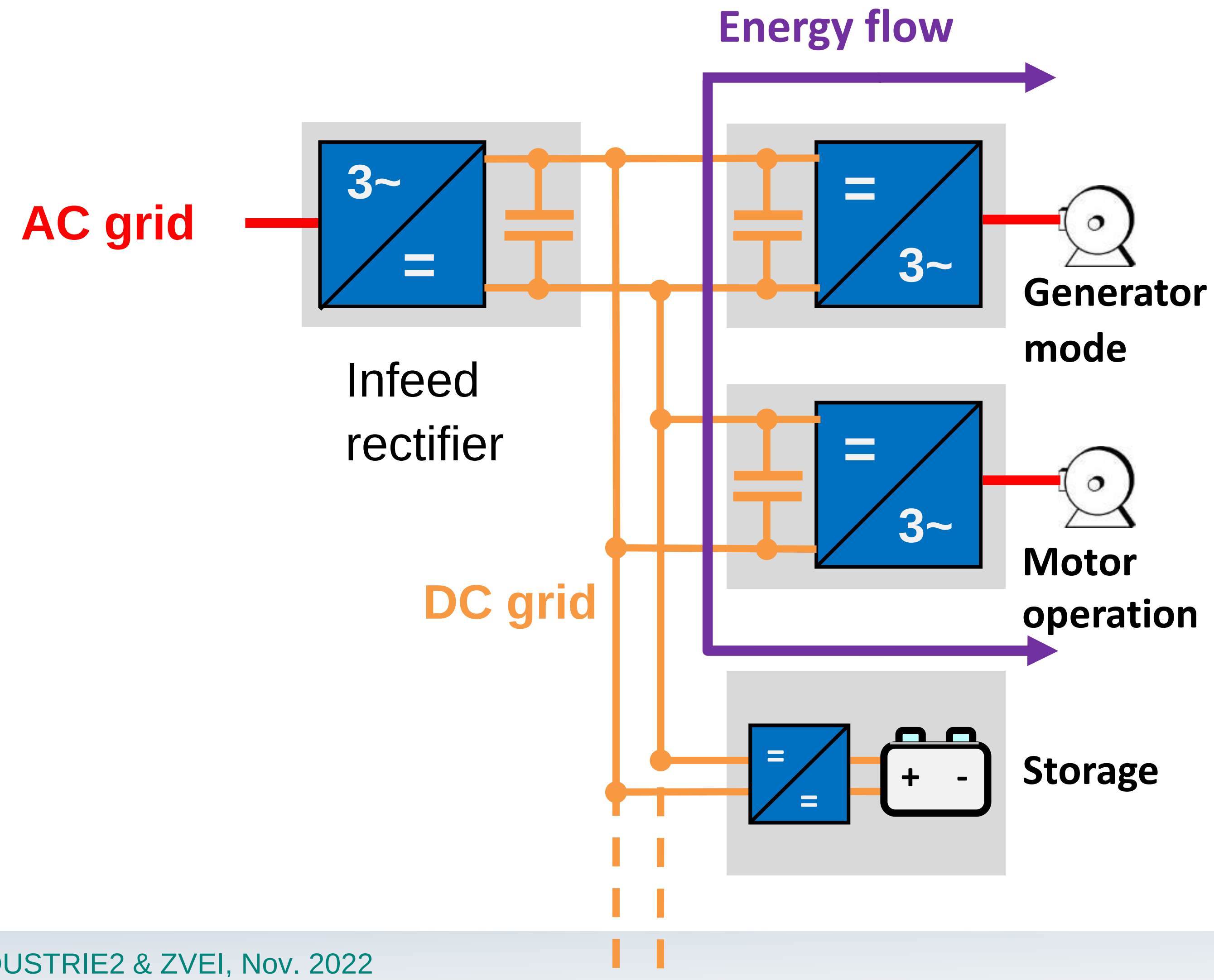
Many AC applications already use DC internally

- For example, frequency converters
- Connecting the DC links with each other makes the many AC-to-DC conversion steps redundant.



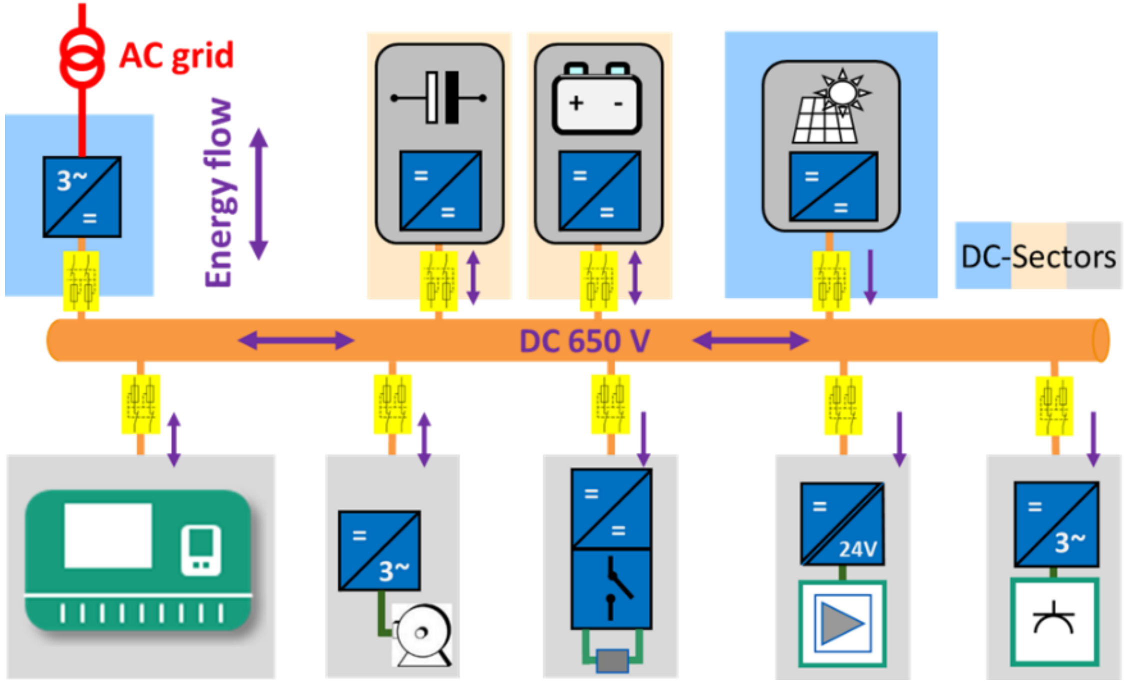
Electrical energy exchange with a DC grid

DC grid
- Reduces effort
- Enables direct energy exchange – no additional components needed



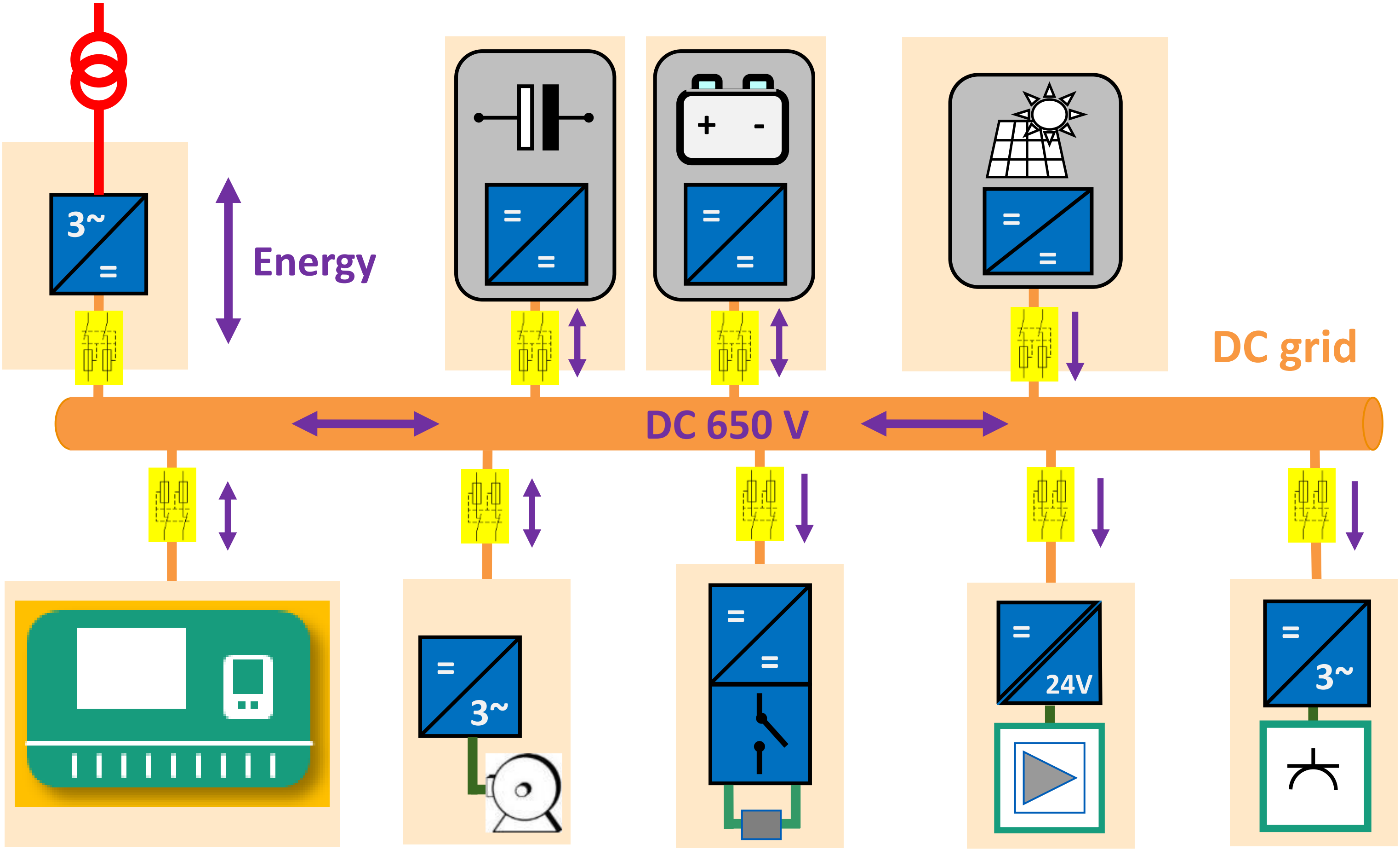
Advantages of DC grid for industrial plants

- **Energy efficiency**
  - Lower losses (typically 2-4% *)
  - Total recovery of braking energy *
  - Direct use of renewable energy sources *
  - Peak power reduction through suitable storage (up to 80%) *
- **Resource efficiency**
  - Reduction of copper use and power loss (cables)
  - Lower equipment costs and space savings in the field
- **Grid stability**
  - Additional investments for mains filtering and compensation can be omitted, and existing grids are supported
  - Production failures through mains disturbances can be prevented / reduced
- **Industrial Smart DC-Grid / flexibility**
  - Infrastructure for intelligent control of energy flows enables advantages in energy purchasing
  - Supports modular machine concepts



*: Evaluated in model applications

DC sectors organize the grid



DC sectors

- Build a logical unit
- Include components with strong functional dependencies to each other
- Provide sufficient capacity to suppress switch-frequency compensation processes from the DC-grids
- Are protected with a smart DC breaker

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Simplified power calculation AC vs DC

- **Power for AC**
  - Active power
    - $P = U \cdot I \cdot \cos(\varphi)$
  - Reactive power
    - $Q = \sum_{n=1}^{\infty}\left[U_n \cdot I_n \cdot \sin\left(\varphi_{U_n} - \varphi_{I_n}\right)\right]$
  - Distortion power
    - $D = U \cdot \sqrt{I_2^2 + I_3^2 + \ldots} = \mathrm{U} \cdot \sum_{m=2}^{\infty}[I_m^2]$
  - And everything three times for three-phase systems …

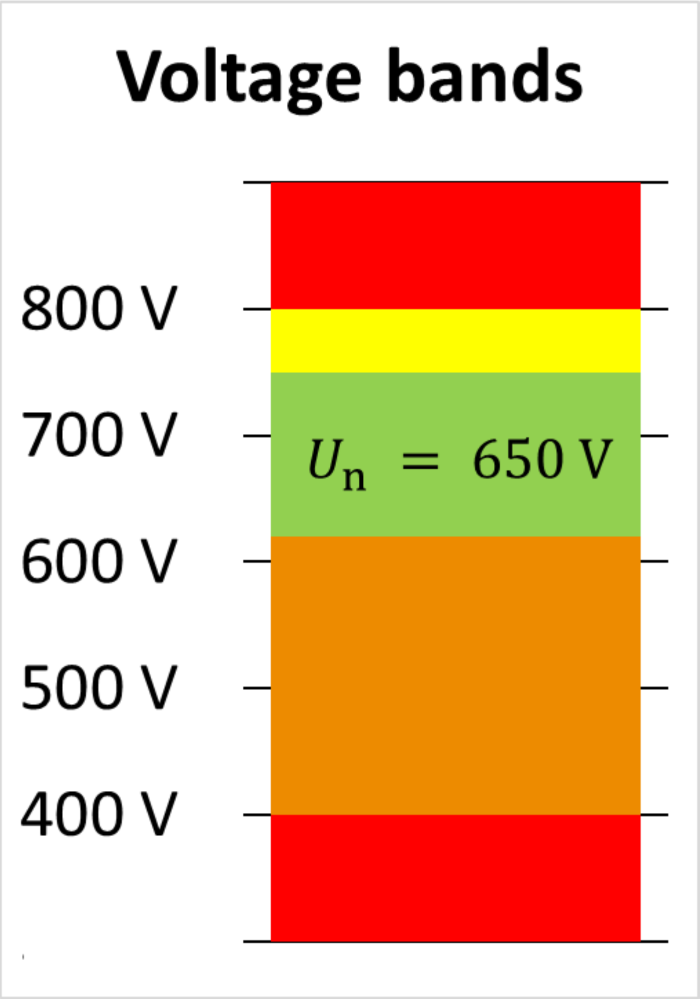
- **Power for DC**
  - Active power $P = U \cdot I$
  - It really is that simple …

- **In AC reactive power and distortion power need to be transmitted to the end user via cabling**
- **No such overhead in DC**

Voltage bands – here for active infeed converters

- **In DC, voltage mirrors power balance**
  - Load > supply → voltage drops ↘
  - Supply > load → voltage rises ↗

- **Nominal voltage band → full operation 620 V – 750 V**
  - Unlimited functionality
- **Overvoltage band 750 V – 800 V**
  - Supply > demand → Shall not last longer than 60 s
  - Active participants counteract the voltage deviation
  - Storage devices charged, convenience loads are added
- **Emergency band (undervoltage) 400 V – 620 V**
  - Overload condition → loads are reduced; storage supplies energy
  - Devices may lose function & must resume function after voltage recovery
  - Shall last less than 60 s
- **Switch-off limits: 400 V, 800 V**
  - No operation → breakers disconnect



Operating status – function of voltage and duration

Voltage level Bx and duration Sx determine operating status Ax

- **A7 Prohibited**
  - Damage very likely
- **A6 Overvoltage protection active**
- **A5 Overvoltage protection not active**
  - Devices may switch off
- **A4 Abnormal status**
  - Devices shall function dynamically
- **A3 Normal operation**
  - Full functionality
- **A2 Acute undervoltage**
  - Devices may reduce power
- **A1 Blackout status**
  - Switch off
  - Pre-charge on startup

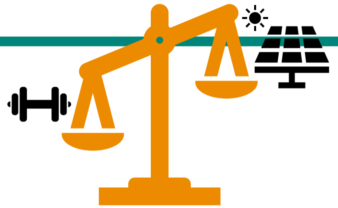
Upper voltage limit Ux in DC grid for nominal voltage 540 V / 650 V	**Voltage band**	**S1:** *t* < 50 µs 1)	**S2:** 50 µs ≤ *t* ≤ 1 ms	**S3a:** 1 ms ≤ *t* ≤ 5 s	**S3b:** 5 s ≤ *t* ≤ 60 s	**S4:** t > 60 s
	B7	A7				
1) U6: 2000 V	B6	A6	A7			
U5: 880 V	B5	A4	A5	A5	A7	A7
U4: 800 V	B4	A3	A3	A3	A4	A5
U3: 750 V	B3	A3	A3	A3	A3	A3
U2: 485 / 620 V	B2	A4	A4	A2	A2	A2
U1: 400 V	B1	A4	A2	A1	A1	

Voltage ↑ Time →

Based on IEC Technical Report TR63282

1) 2000 V and 50 µs are used for simplicity since devices have to withstand a 2 kV 1.2/50 µs surge pulse during type testing.

Voltage stability and droop curves



Grid voltage mirrors power balance

a) Uncontrolled operation (basic network)

- No active control of the DC-voltage (operation with diode rectifier)

b) Autonomous droop control

- Active feeders regulate their power depending on the level of DC voltage
- The characteristic is defined by a non-linear characteristic curve
- No communication required

c) Droop control with communication

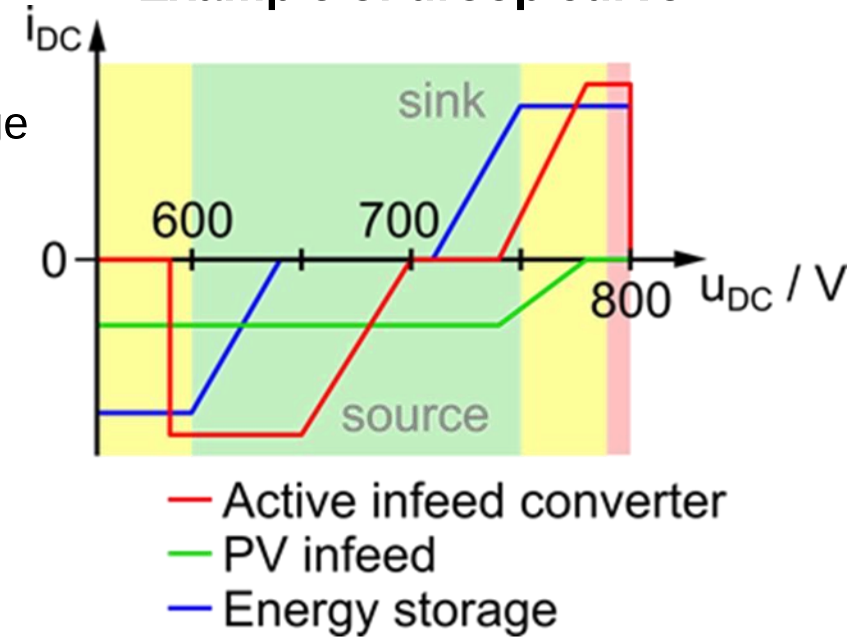
- Setting of the characteristic curve can be changed by a central control unit during operation
- Only slow communication required

d) Central voltage control

- Central control unit provides the setup power values
- Fast communication required – real time control

Choosing the control method allows for simple as well as complex DC-grids with several sources

Example of droop curve



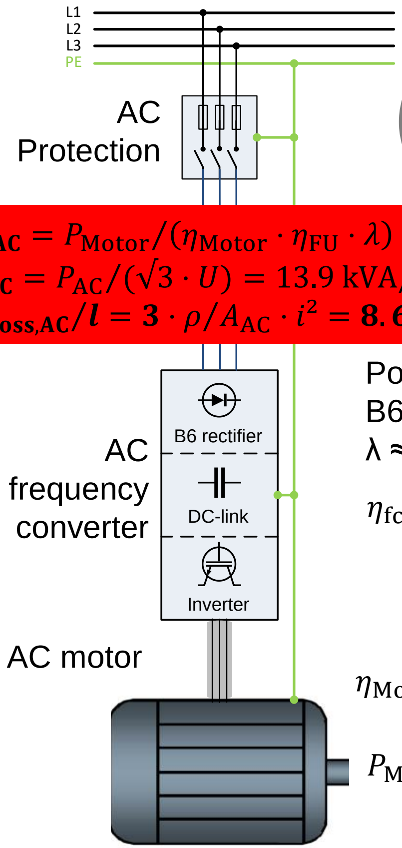
Cabling: Resource- and energy efficiency

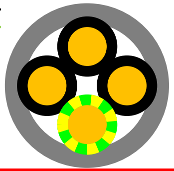
Same insulation!

Example:

Supply of inverter driven three-phase motor 7.5 kW

3~ AC grid





$P_{AC} = P_{Motor}/(\eta_{Motor} \cdot \eta_{FU} \cdot \lambda) = \mathbf{13.9\ kVA}$

$I_{AC} = P_{AC}/(\sqrt{3} \cdot U) = 13.9\ kVA/(\sqrt{3} \cdot 400V) = \mathbf{20\ A}$

$P_{loss,AC}/l = 3 \cdot \rho/A_{AC} \cdot i^2 = \mathbf{8.6\ W/m}$

Power factor of B6 rectifier
λ ≈ 0.63

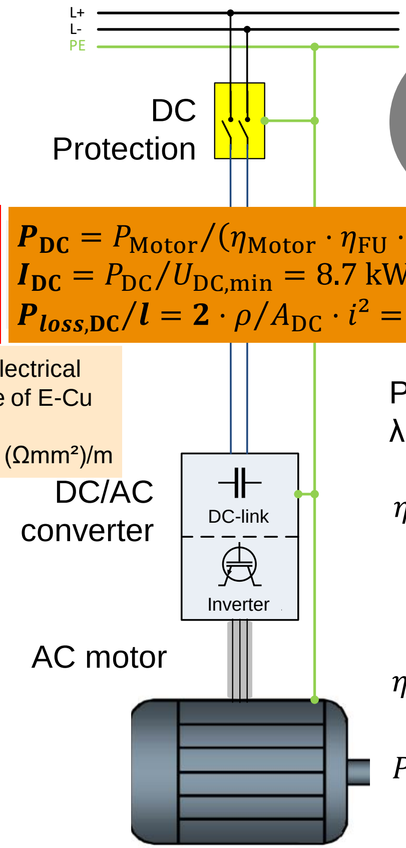
$\eta_{fc} = 0.968$

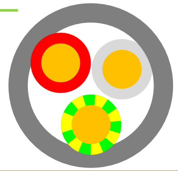
$\eta_{Motor} = 0.887$

$P_{Motor} = 7.5$ kW

Specific electrical resistance of E-Cu at 30°C:
ρ = 0,018 (Ωmm²)/m

2 wire DC grid





$P_{DC} = P_{Motor}/(\eta_{Motor} \cdot \eta_{FU} \cdot \lambda) = \mathbf{8.7\ kW}$

$I_{DC} = P_{DC}/U_{DC,min} = 8.7\ kW/650\ V = \mathbf{13.4\ A}$

$P_{loss,DC}/l = 2 \cdot \rho/A_{DC} \cdot i^2 = \mathbf{4.3\ W/m}$

Power factor DC
λ = 1

$\eta_{fc} = 0.968$

$\eta_{Motor} = 0.887$

$P_{Motor} = 7.5$ kW

AC: 20 A

- Cross section → 2.5 mm²
- Total copper: 4 × 2.5 mm² = 10 mm²

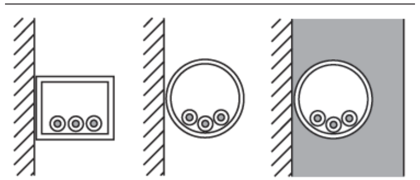
DC: 14.1 A

- Cross section → 1.5 mm²
- Total copper: 3 × 1,5 mm² = 4.5 mm²

- **55% less copper for same power**
- **50% less power loss in cables (R × i²)**

Wiring type	**B1**	
Number of wires simultaneously loaded	2	3
Wire cross section in mm²	current in A	
1.5	17.5	15.5
2.5	24	21
4	32	28
6	41	36

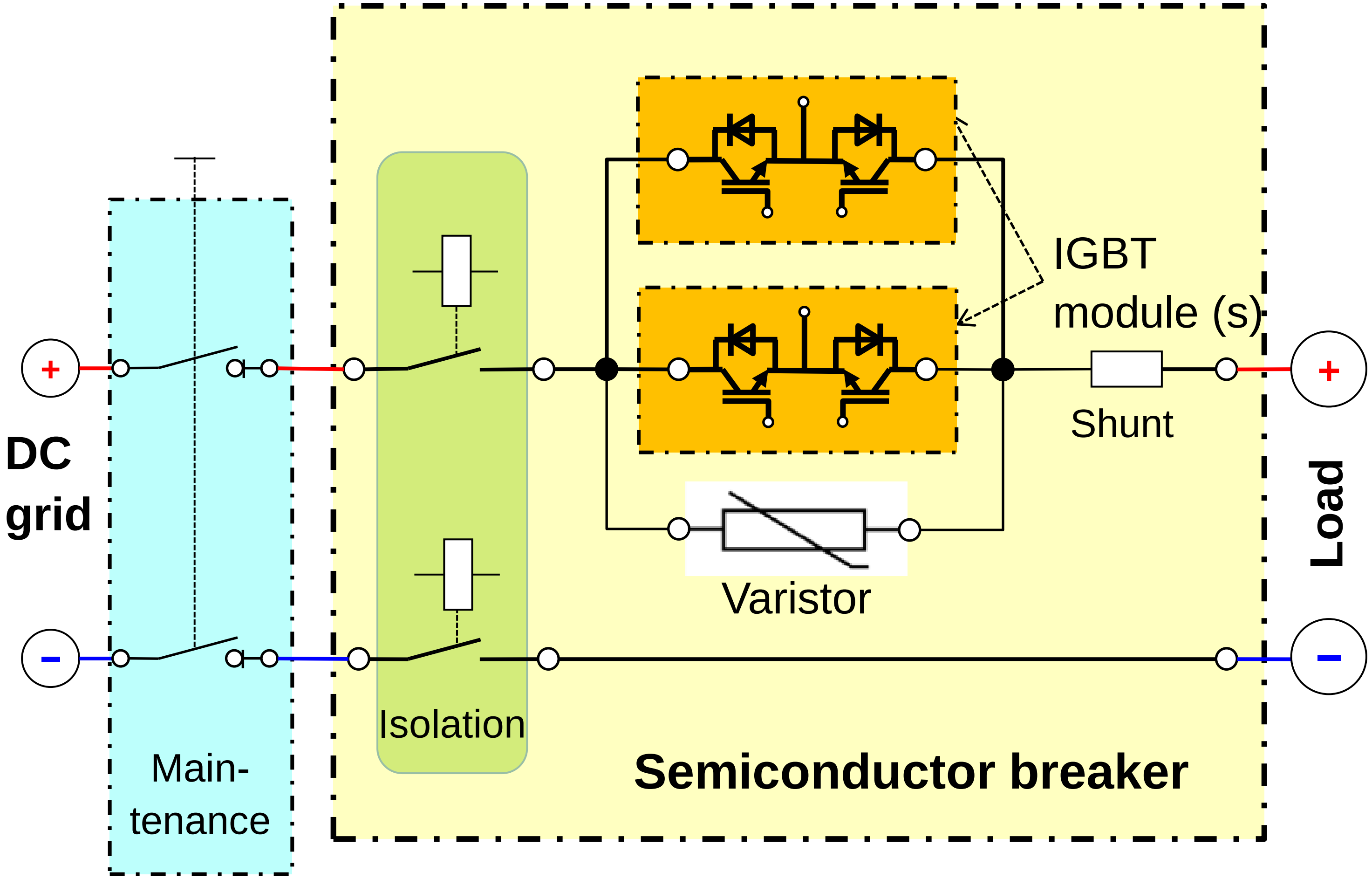
B1



Permitted current in A @ 30°C ambient temp. acc. to IEC 60364-5-52

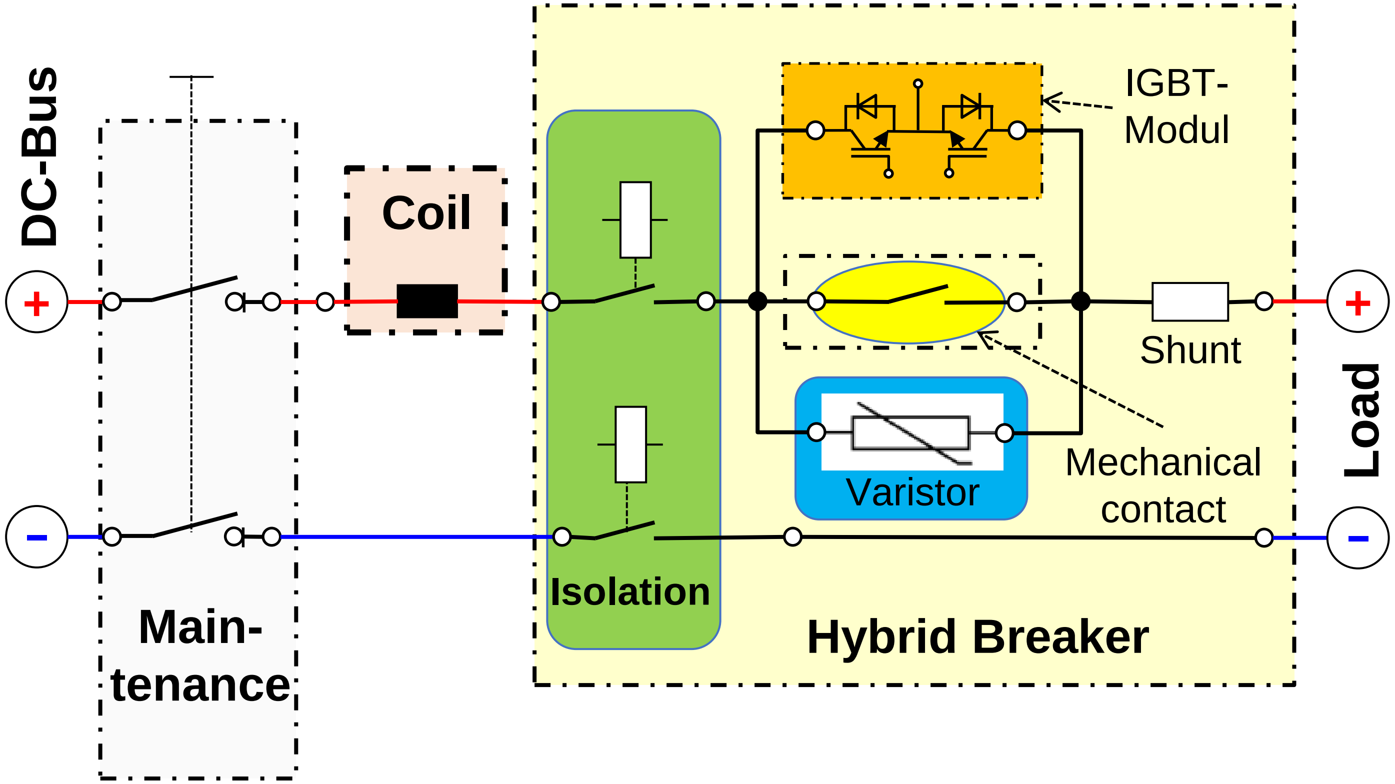
Smart DC Breakers: fast and reliable protection

- **Requirements**
  - Fast operation – avoid voltage dips
  - Bi-directional
- **Power semiconductors**
  - IGBT + Diode
  - (Mechanical breakers too slow)
- **Functions**
  - Switching
  - Overcurrent protection
  - Isolation
  - Detection of over- & undervoltage
  - Pre-charging
  - Communication
- **Properties**
  - Fast (< 100 µs switch-off time)
  - Low fault energy (<< 1% of mechanical breaker)



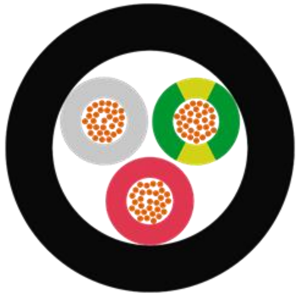
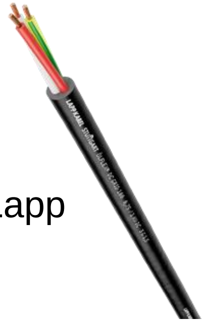
Smart Hybrid Breaker reduces power loss

- **Mechanical contact conducts current**
  - low power loss
- **Power semiconductors interrupt**
  - Fast
- **Switch-Off procedure**
  - Actor opens mechanical contact → short arc
  - IGBT picks up the current (forward voltage < arc voltage) and switches off →
  - Varistor limits voltage
  - Isolation contacts open load- less and isolate
  - Coil limits current increase during short-circuit



Insulating materials for DC cables and DC housing materials

- **Basics electrical field E**
  - AC: E-field dependent on voltage and geometry
  - DC: E-field is rectified and is subject to pronounced temperature
- **Impacts**
  - Different mechanisms between AC and DC
  - Higher stress on the insulating material at DC possible:
    - Conductivity changes with temperature and moisture content
    - Polarization processes, field elevations, field migrations
    - Material behavior nonlinearly dependent on field distribution
- **DC-INDUSTRIE2**
  - Accelerated aging of selected typical AC insulating materials under DC stress at elevated temperatures in laboratory conditions
  - Insulating materials: influence of plasticizers, fillers and the type of inner conductor (bare copper or tinned) on DC resistance
- **Results**
  - Suitable insulation materials for DC are available

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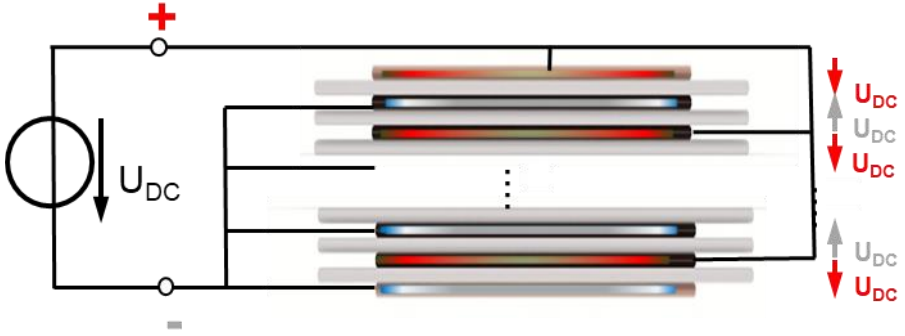

Model applications of DC-INDUSTRIE

- **Mercedes-Benz**
  - Production cell with 4 robots
  - Challenging energy demand (Al-welding)
  - Continued from EU project AREUS

- **Mercedes-Benz**
  - Suspension track
  - 5 individual carriers with slip rings
  - Coupling of two applications

- **Homag**
  - Wood working machines
  - Many loads
  - Sensors & actors
  - Integrated energy storage

- **KHS**
  - Beverage container handling
  - Open concept
  - > 30 drives

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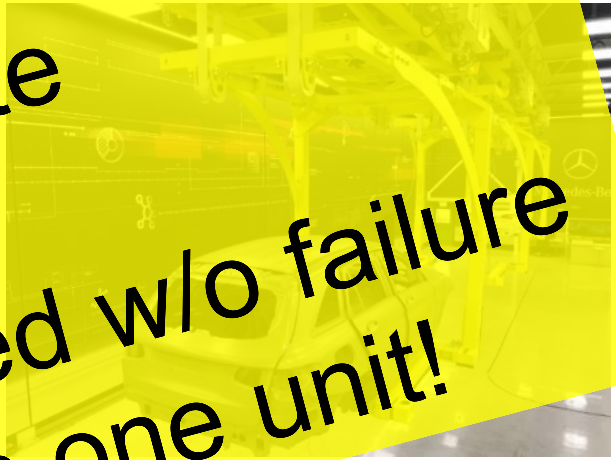


- **Homag**
  - Wood working machines
  - Many loads
  - Sensors & actors
  - Integrated energy storage

- **KHS**
  - Beverage container handling
  - Open concept
  - > 30 drives

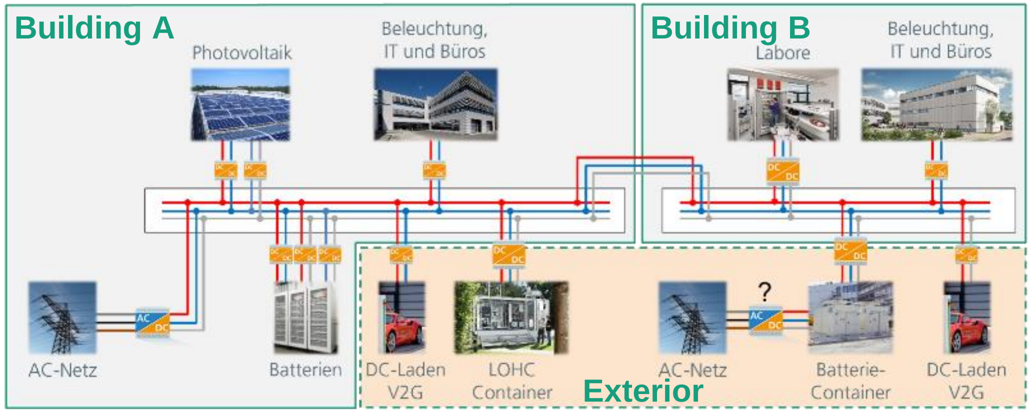
- Devices from all partners collaborate
- DC system concept confirmed
- About 60 short-circuit faults cleared w/o failure
- 80% reduction of feed-in power in one unit!

Model applications of DC-INDUSTRIE2 1 / 4

- **BMW**
  - Car body production cell
  - Focus
    - Energy distribution & storage
    - Energy feedback to grid
    - Switching and protection

- **KUKA**
  - Test cell with 4 robots
  - Focus: robot control

- **Fraunhofer IISB**
  - DC infrastructure in office building, EV charging

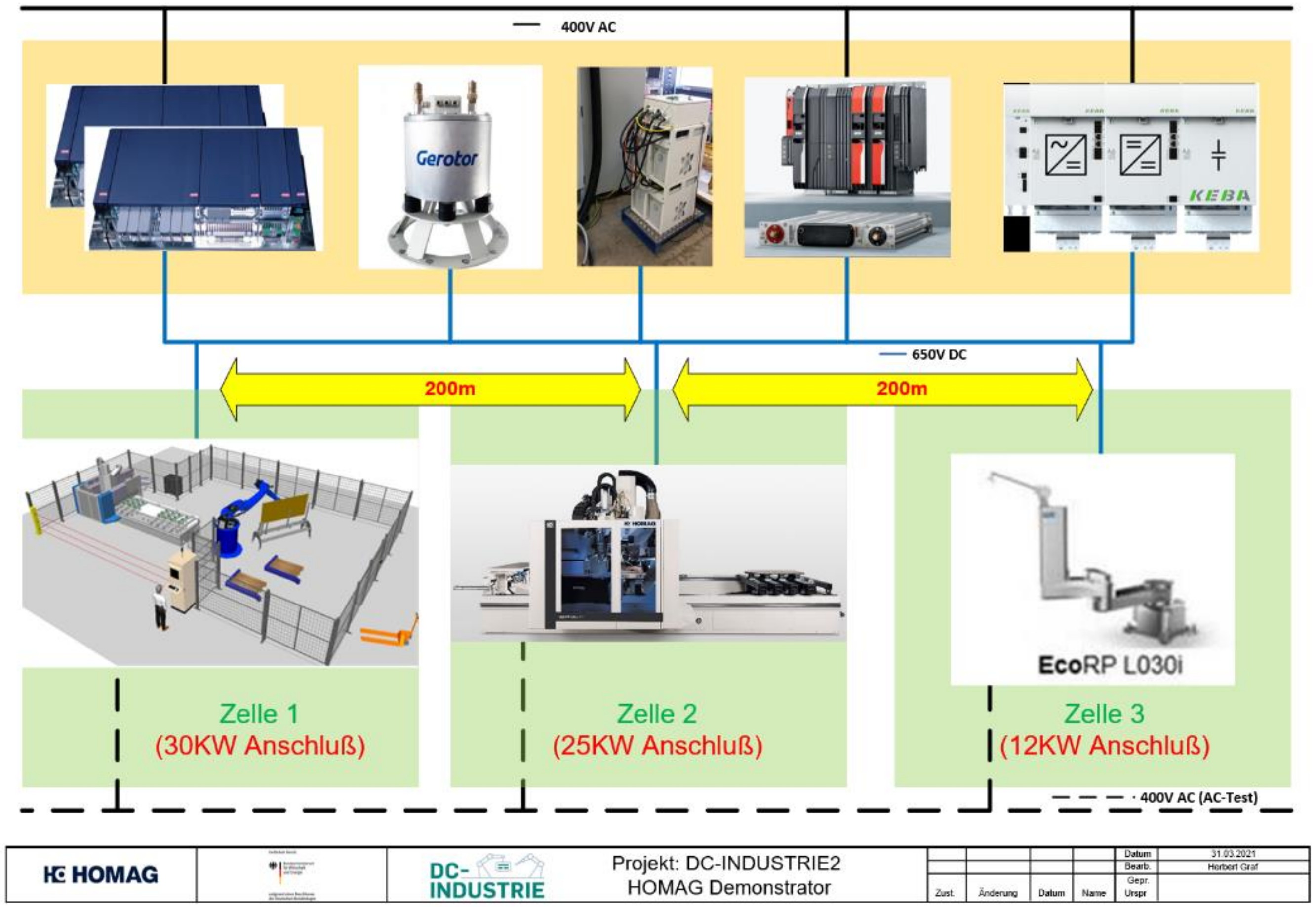


Model applications of DC-INDUSTRIE2 2 / 4

Mercedes-Benz Factory 56

- Large distances & power
- 222.000 m^2 production area
- 2 MW DC grid for hall infrastructure
- 1 MW solar energy, 5.7 MW peak
- Goal: CO_2-neutral production

Model applications of DC-INDUSTRIE2 3 / 4



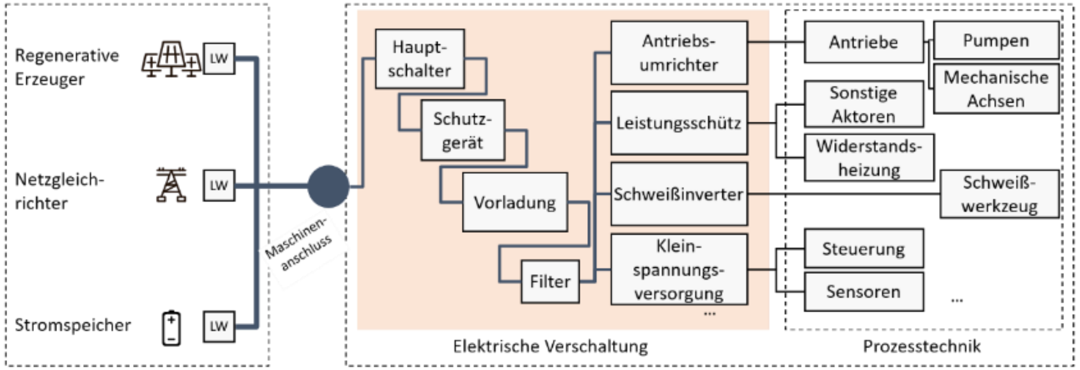
- **Homag**
  - Wood working machines
  - Three applications spread out in a factory hall
  - Setup
    - Multiple connections to AC grid
    - Several storage options
      - Flywheel
      - Capacitors
      - Batteries
  - Focus
    - Influence of long cables on voltage dips during supply failure or faults
    - Coordination between several active infeed converters

Model applications of DC-INDUSTRIE2 4 / 4

- **TH OWL**
  - Model electro-mechanical loads, up to 11 axes
  - Storage
  - Several infeed rectifiers
  - Focus
    - Model dynamic behavior in real time
    - Test virtual machines in a DC environment
    - Test of multiple failure scenarios

- **Fraunhofer IPA**
  - Industrial power distribution
  - AC-DC transformation
  - Protection concept
  - Parallel operation of AICs

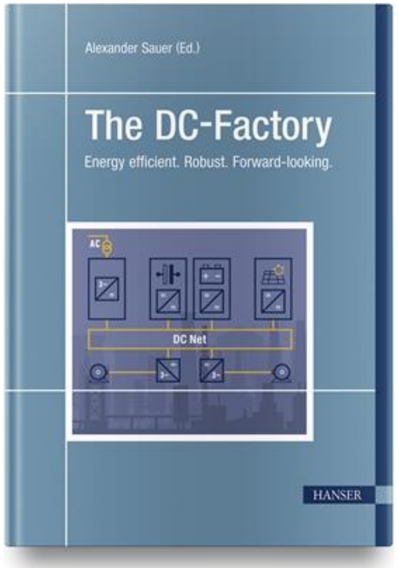
Which adaptations are necessary for machines and systems for DC?



More information and publications (examples)

- **DC-Industrie Homepage**
  www.dc-industry.com

- **Publications (excerpt)**
  - White paper
  - Several technical reports and papers
  - Textbook *The DC-Factory,* Hanser Verlag, 2021
    https://www.hanser-kundencenter.de/fachbuch/artikel/9783446471740
  - English and German version available

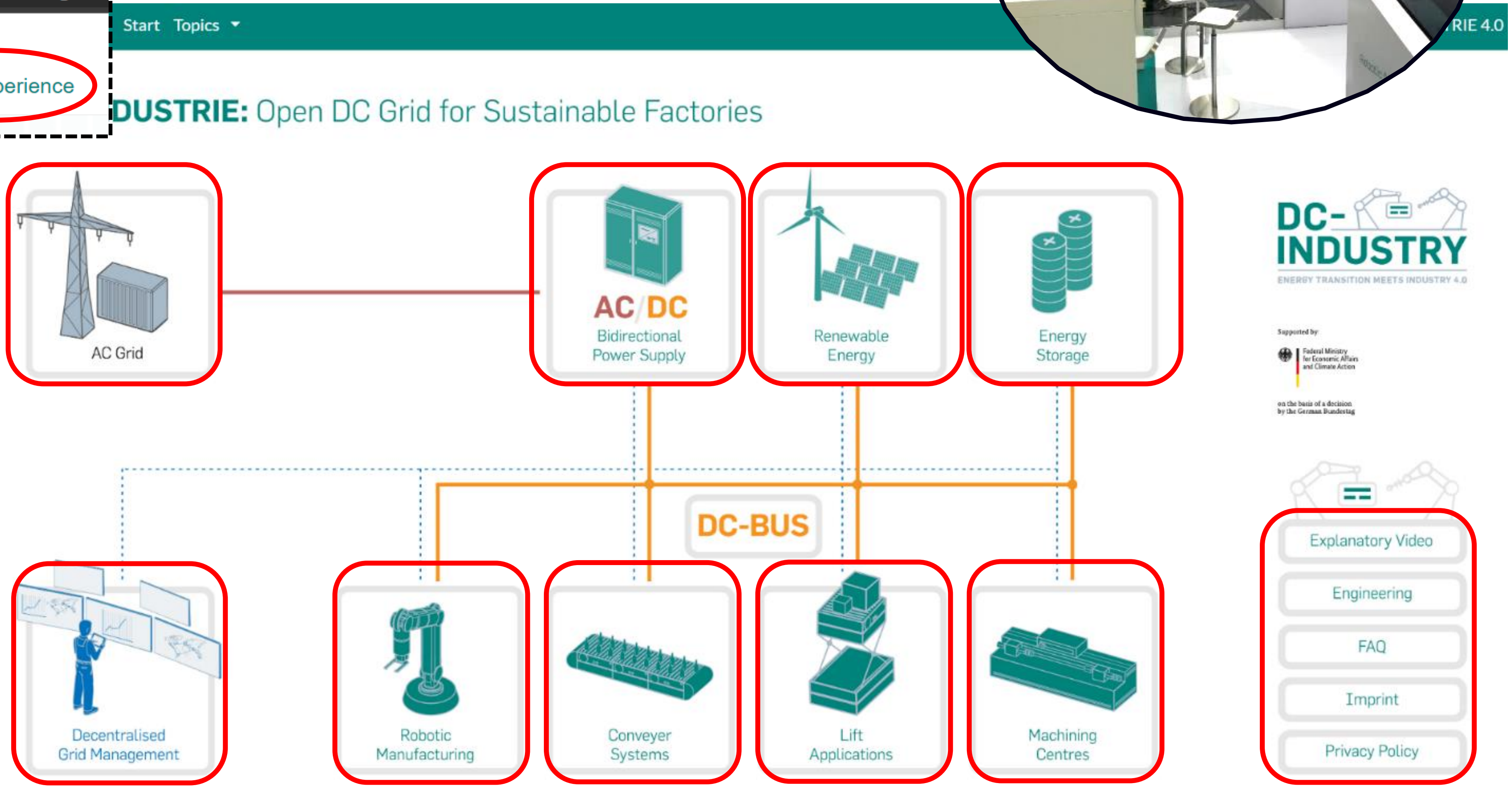


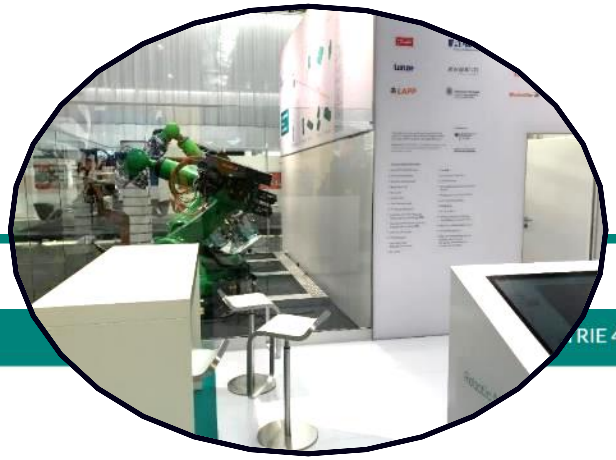
- **Computer & Automation**
  4 article technical paper series

- **Hannover Messe 2022**

Hannover Messe 2022 Presentations

https://experience.dc-industrie.zvei.org

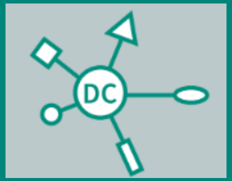


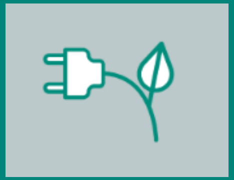


Click for more info

Benefits of DC & DC-INDUSTRIE

1. Open system
2. Efficient integration of green energy
3. Resource efficiency
4. Lower energy consumption
5. Reduced feed-in power
6. Increased system availability

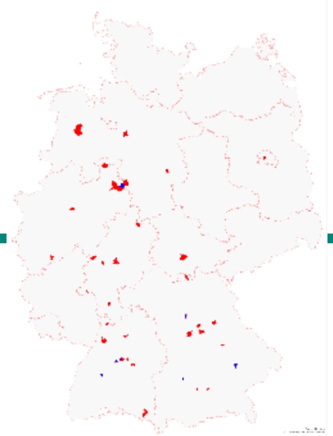





Part of the committed DC-INDUSTRIE team

Lemgo, Sep. 2019

Project partners – www.dc-industry.com



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Associated partners: ABB Stotz-Kontakt; AMK Arnold Müller; Audi; Bauer Gear Motor; Bender; Danfoss; DEHN; ESR Pollmeier; Gerotor; Harting; JEAN MÜLLER; KUKA; LEONI; Maschinenfabrik Reinhausen; Paul Vahle; Puls; Rittal; SEW-PowerSystems; Siemens; TU Ilmenau; Wöhner