Power Electronics for Energy-Efficient Buildings and Districts

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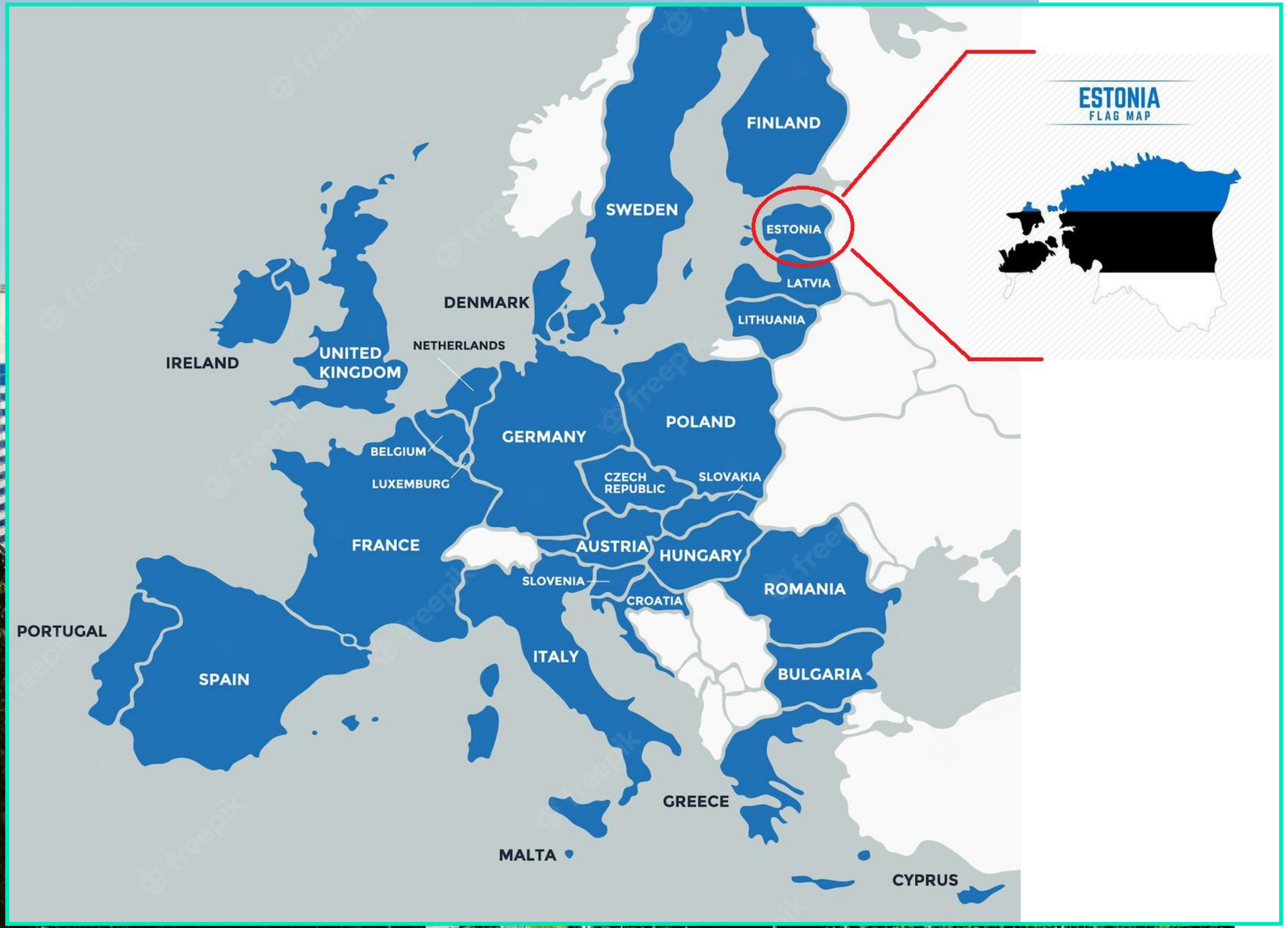
Santa Maria - BR

ESTONIA

UFSM
IEEE



- Area: 45,227 km^2
- Population:1.35 million
- Capital: Tallinn
- Currency: Euro
- Estonia leads Europe in startups, unicorns, and investments per capita (5.2 startups per capita)
- NATOs Cyber Defence Centre (CCDCOE)

wise
ID.me
pipedrive
playtech SOURCE OF SUCCESS
CCDCOE
Cooperative Cyber Defence Centre of Excellence
Tallinn, Estonia
Bolt
ZEGO
STARSHIP

TALLINN

UFSM
IEEE

- Population: 440.000
- Historic Centre (Old Town) of Tallinn: UNESCO world heritage
- Coast of the Baltic sea
- Annually welcoming over 4.5 million foreign visitors

visitestonia.com/en

TALLINN UNIVERSITY OF TECHNOLOGY

- Established in 1918, Tallinn Technical University (TTU)
- Since 2018, the Tallinn University of Technology (TalTech)
- More than 30 courses between Bsc. Master, and PhD
- More than 10.000 students from different countries
- School of Engineering
- **Department of Electrical Power Engineering and Mechatronics**

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Power Electronics Group

- Part of TalTech – the Estonian leader in technology and innovation
- Was founded in 2006. Recently has 20+ researchers and annual research budget over 1.5 mi EUR
- Largest research center for applied power electronics in Baltic countries and active member of the European Center for Power Electronics (ECPE e.V.)
- Co-founder and active member of Estonian Centre of Excellence in Zero Energy and Resource Efficient Smart Buildings and Districts (ZEBE)
- Founder of I3DC initiative
- First academic member of Current/OS foundation

Teadmistepõhise ehituse tippkeskus
Zero Energy Centre of Excellence

i³ DC
Accelerates Energy Transition

CurrentOS

ECPE

Power Electronics Group

Centre of Excellence in Energy Efficiency

i³ DC
Accelerates Energy Transition

CurrentDCs

ECPE

Power Electronics Group

- **Dmitri Vinnikov, IEEE Fellow**
  - PV converters
  - Impedance source converters

- **Edivan L. Carvalho, IEEE Senior Member**
  - AC grid integration of buildings
  - AC-DC converters

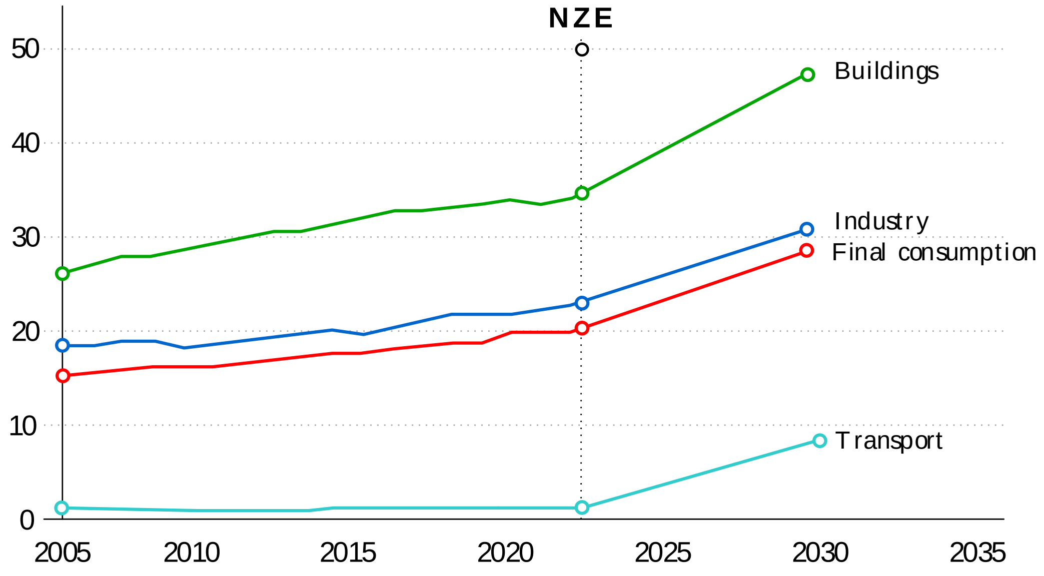
- **Andrii Chub, IEEE Senior Member**
  - PV converters
  - Partial Power converters

- **Andrei Blinov, IEEE Senior Member**
  - Battery and EV chargers
  - Current-fed converters

EU GREEN DEAL – Towards 2050 NZE Pathway

- By 2050 the EU aims to become the world's first "climate-neutral block" having an economy with net-zero greenhouse gas emissions (NZE)
- Electrification is considered one of the key strategies to reach NZE goals
- The share of electricity in the final energy consumption in 2050 is targeted to be more than 50%
- By 2050, almost 90% of electricity generation in EU is expected to come from renewable sources, with wind and solar PV together accounting for nearly 70%
- Much of the NZE need will be met by shifting towards electric transport and electrification of heating/cooling demand of buildings using heat pumps
- In 2050, electricity will become the dominant energy carrier for the buildings in EU: the prognosed growth in demand by 2030 is 12% and 35% by 2050

Share of electricity in total final energy consumption in the NZE scenario (2005-2030)

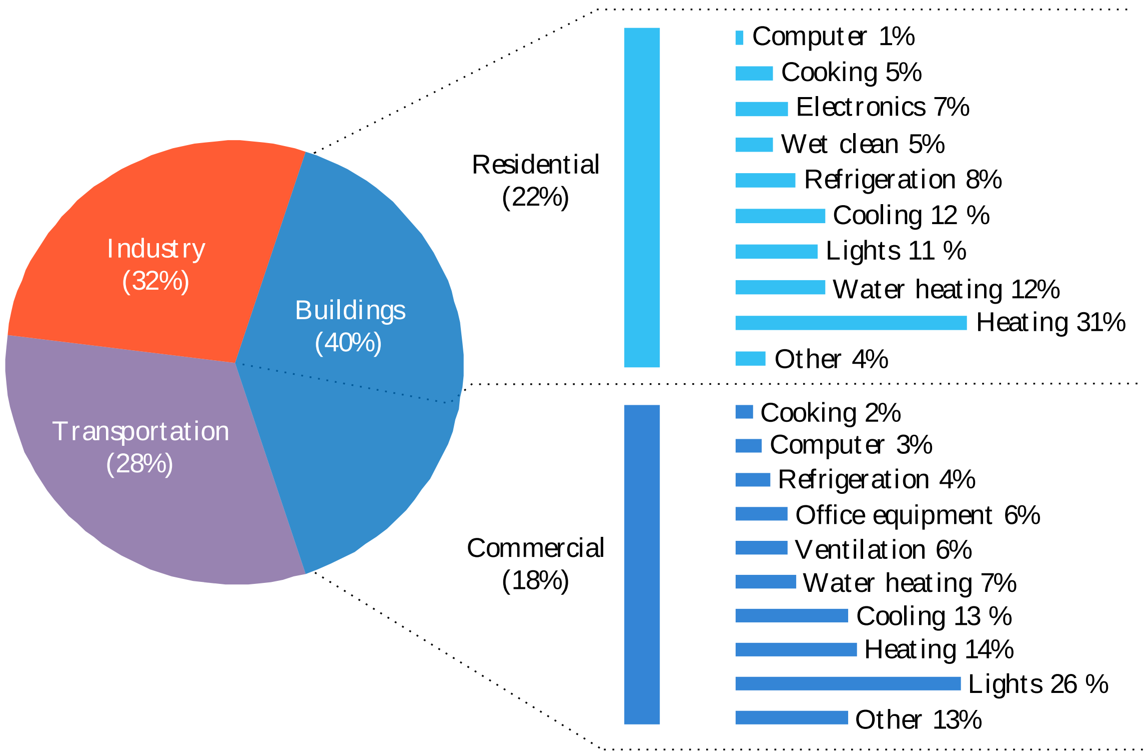


www.iea.org

Energy efficiency of buildings: AN ISSUE

- Buildings consume (and waste!!!) too much energy:
  - Annual energy consumption in Estonia 33...34 TWh/y
  - Share of buildings 50% (w/o industrial buildings)
  - EU average 40%
- Currently, roughly 75% of buildings in the EU are not energy efficient:
  - 85–95% of today's buildings will still be in use in 2050
- To boost decarbonization the EU requires all new buildings from 2021 to be nearly zero-energy buildings (nZEB)
- nZEB (or class A building) :
  - fully covered by energy from renewable sources and without on-site carbon emissions from fossil fuels

Energy consumption by sector



www.seas.ucla.edu

Labelling of buildings

- EC's Energy Performance of Buildings Directive (EPBD)
  - Labelling of energy efficiency of buildings
  - EPBD requires all new buildings from 2021 to be nearly zero-energy

Table 2. Estonian energy labels for the three categories of detached houses D1, D2, and D3; EPC ($kWh/(m^2a)$).

En. Label	D1 (EPC)	D2 (EPC)	D3 (EPC)
A	≤145	≤120	≤100
B	146–165	121–140	101–120
C	166–185	141–160	121–140
D	186–235	161–210	141–200
E	236–285	211–260	201–250
F	286–350	261–330	251–320
G	351–420	331–400	321–390
H	≥421	≥401	≥391

D1, <120 m^2
D2, 120–220 m^2
D3, >220 m^2

Building

Energy certificate	B
Building material	brick house
Parking	free parking
Extra spaces	basement wardrobe

Utilities

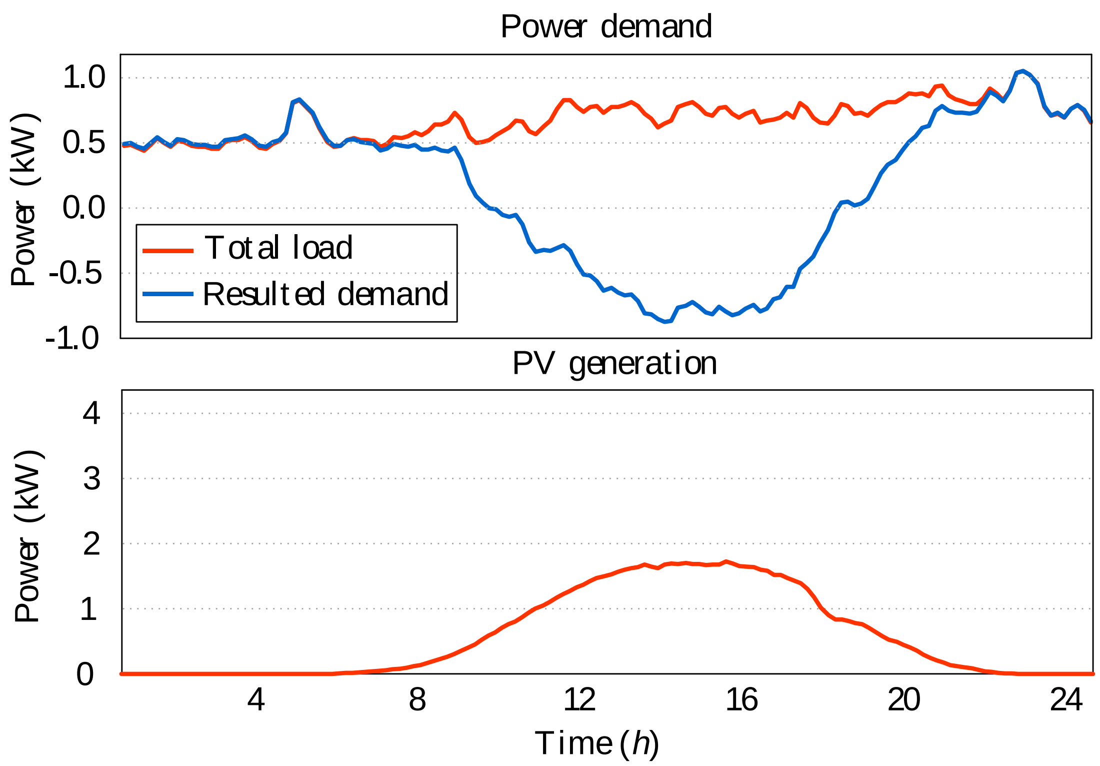
Heating type	radiator heating
Energy source	district central heating
Sanitary arrangements	shower washing maschine has central sewerage
Stove	induction
Communications	digi-tv internet cable tv fiber optic internet

energy.ec.europa.eu

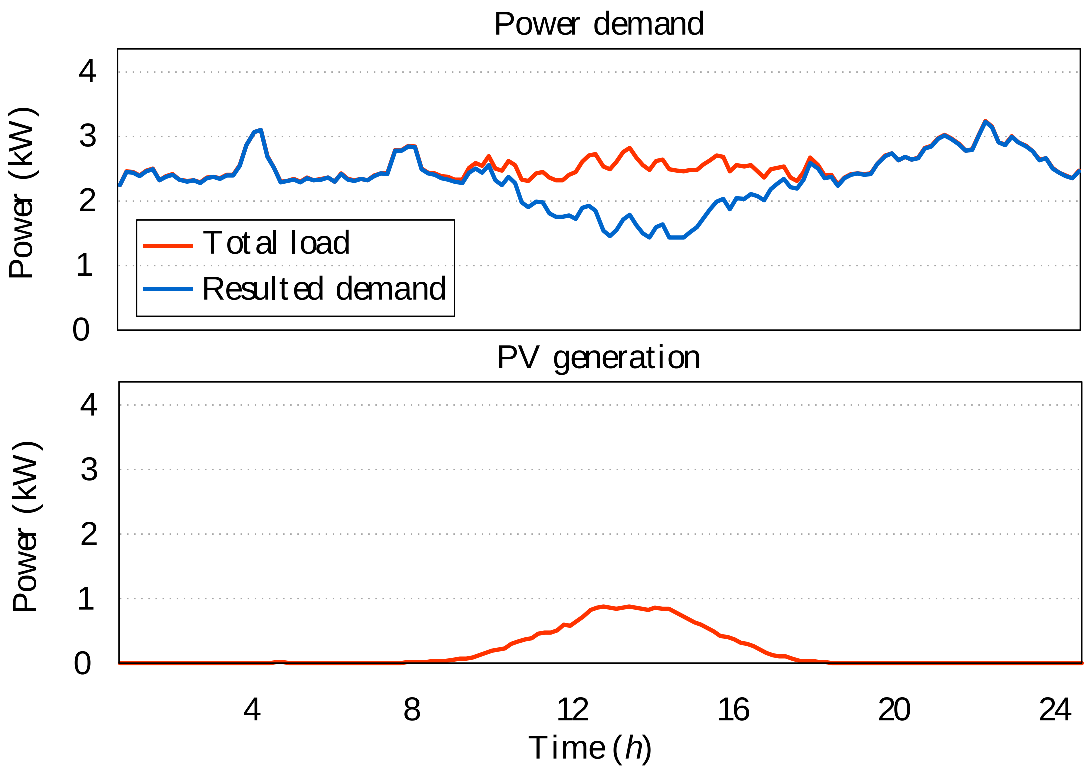
Labelling of buildings

- Importance of high-efficient buildings in Estonia:
  - Intermittency is a challenge for planning.

Summer

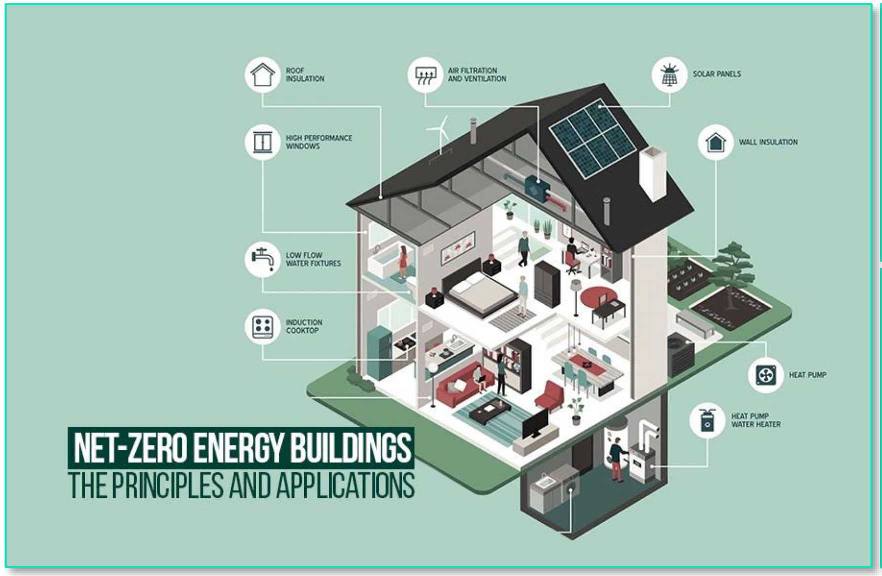


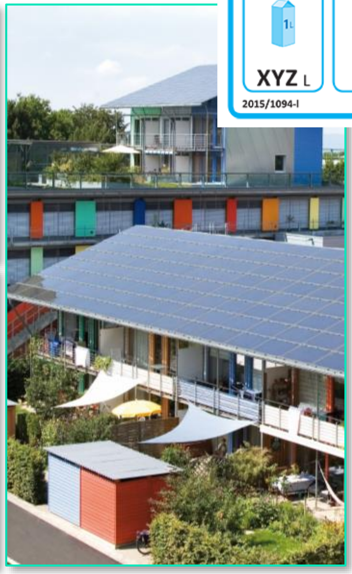
Winter



Nearly zero-energy buildings today

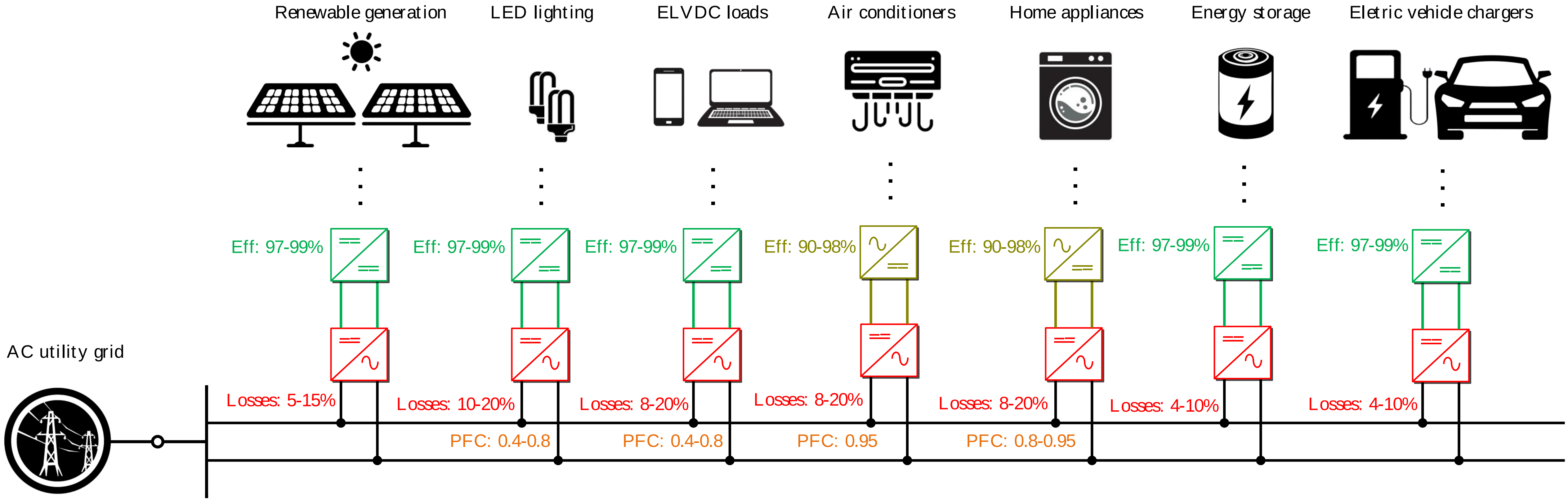
- In practice, NZEB consumes up to 4 times less energy than the traditional ones
- Energy efficiency is the main feature of ZEB - PV installation (backed up with energy storage), heat pump, heat recovery ventilation, energy-efficient appliances and lighting, smart control of loads
- nZEB:
  - High energy performance (low energy consumption)
  - Local renewable generation
  - Most of energy saving technologies are based on power electronics





Power electronics for AC-based nZEB today

- AC is rectified in every appliance, reducing efficiency, reliability, and power factor
- Power factor is an issue



Power electronics for AC-based nZEB today

- Power Factor Correction (PFC) is required only above 75 W, and the energy efficiency is further affected by a non-unity power factor
- Cumulative energy waste could become significant, even in installations where low-power devices are dominant

GU10 LED bulb (4.3 W)

1	Urms	1	—	232.40	V
2	Irms	1	—	0.0337	A
3	P	1	—	4.33	W
4	S	1	—	7.83	VA
5	Q	1	—	6.52	var
6	Uthd	1	—	0.964	%
7	Ithd	1	—	74.420	%
8	PF	1	—	0.5534	

Laptop charger (65 W)

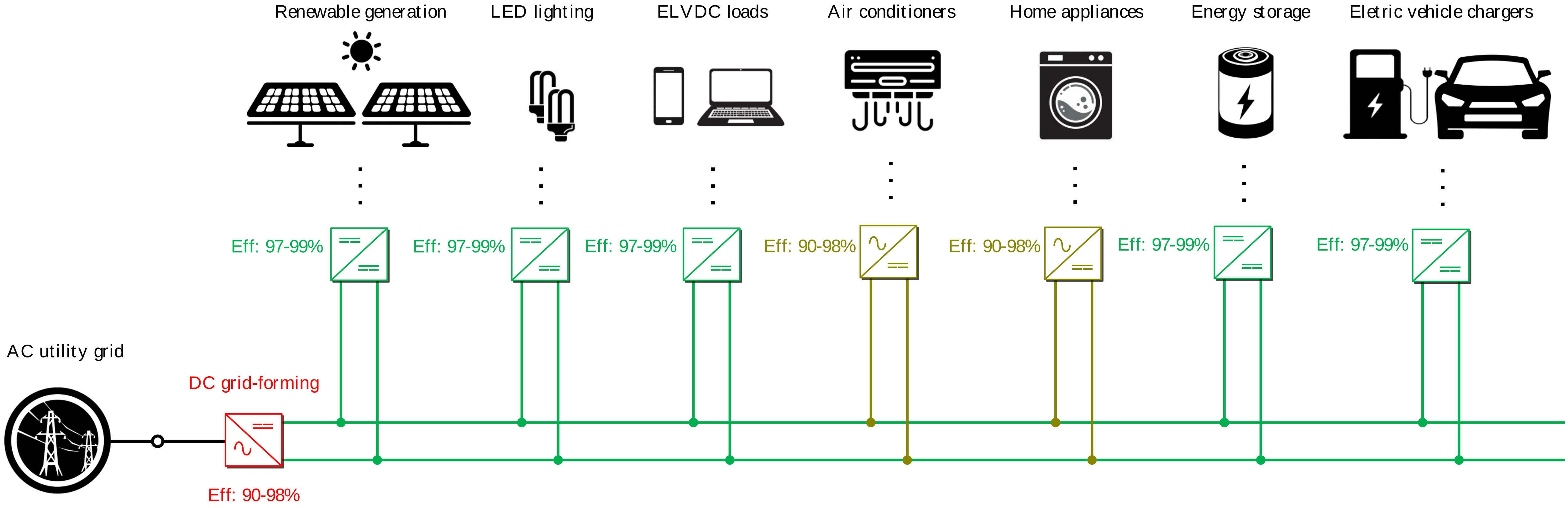
1	Urms	232.37	V
2	Irms	0.5766	A
3	P	65.09	W
4	S	133.99	VA
5	Q	117.12	var
6	Uthd	1.122	%
7	Ithd	86.841	%
8	PF	0.4858	
9	Udc	19.243	V
10	Idc	-3.022	A
11	P	-58.16	W

Power electronics for AC-based nZEB today

- **The elephant in the room:** AC generates more electronic waste

DC power distribution: the next-generation of nZEB

- Increased efficiency and maximized self-consumption of renewable energy due to the less energy conversion stages (DC can save up to 30% of energy waste)
- No reactive power – only active energy is delivered
- Simple coordination and control, better resilience, and energy security (droop control based)

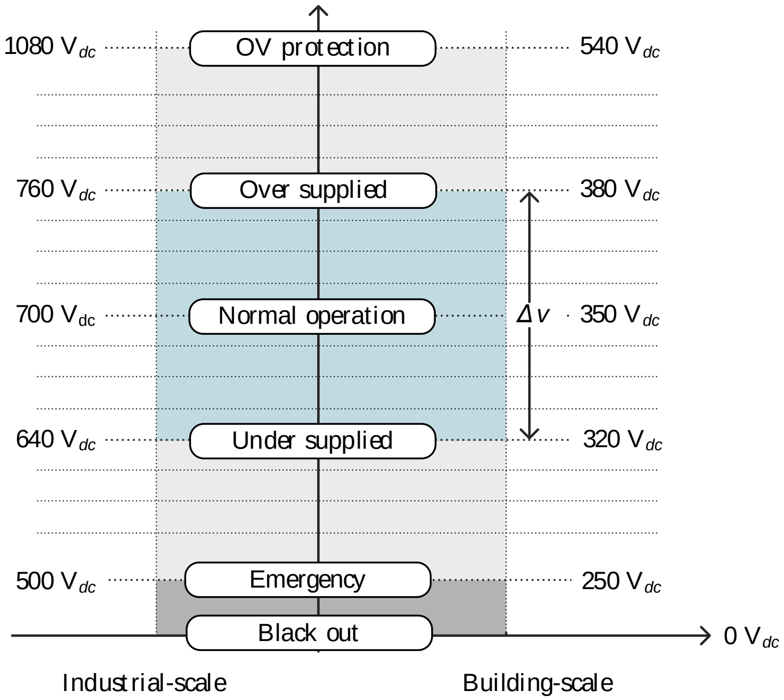


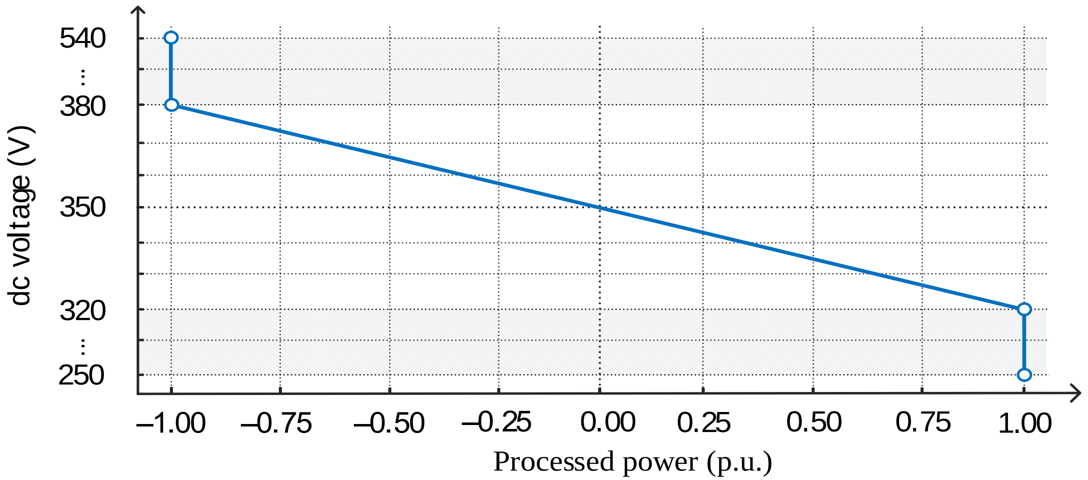
Main initiatives towards DC

- Current/OS Foundation: protocols under development
- NPR9090: first national practice guidelines for DC (2018)

Voltage levels, according to Current/OS

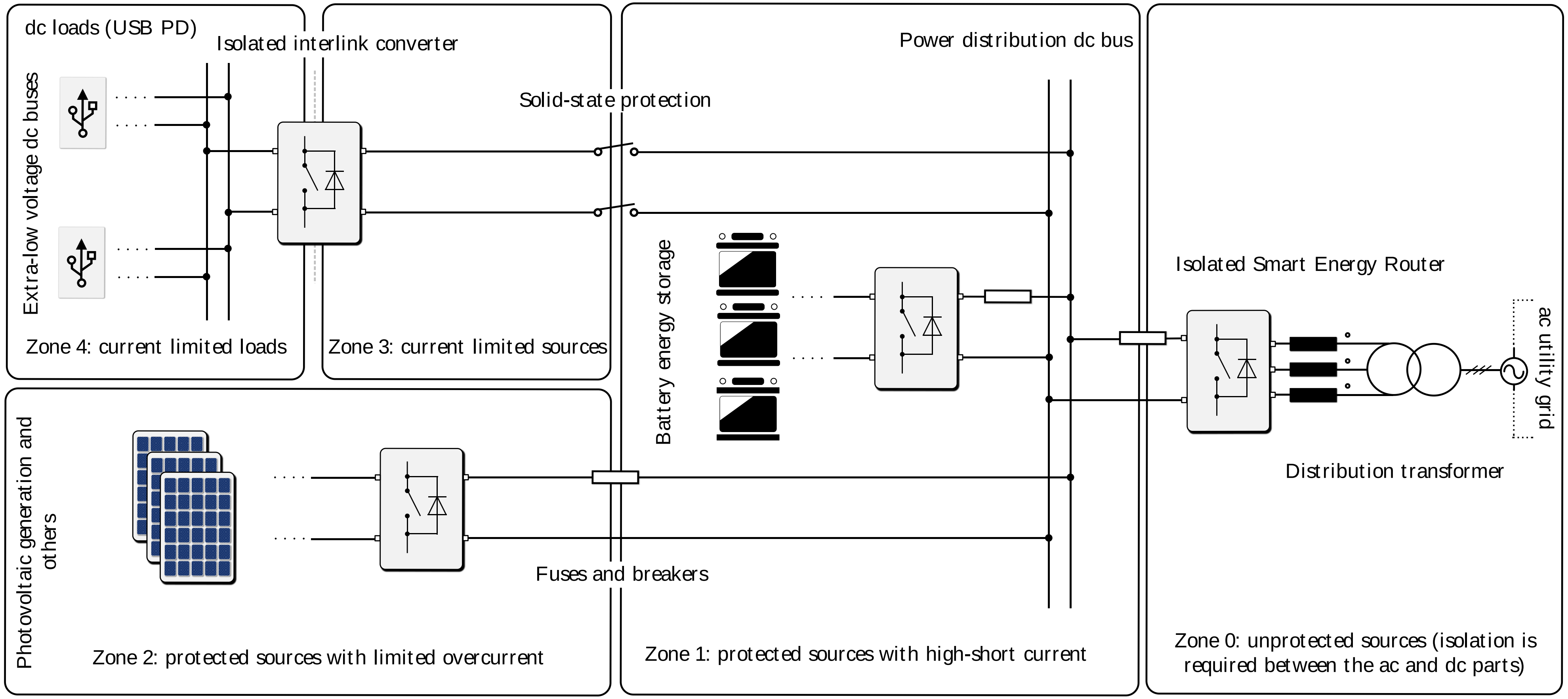
- Voltage levels and bands are selected according to the application
  - Industrial-scale: 640-760 Vdc
  - Building-scale:320-380 Vdc
    - ELVDC: 24-57 Vdc
- Droop control is essential to ensure compatibility between different sources and loads





Protection zones and isolation requirements

- Protection zones are defined according to the voltage levels and current limitation (NPR9090)



Zone 0: High current sources, with unlimited overcurrent, e.g., battery banks, 5 MW generators, utility grid:
$V \leq 1.5$ kV
$I > 500$ A

Zone 1: dc-dc converters with limited current and high short-circuit currents, e.g., renewable sources protected by fuses. ELV sources:
$V \leq 1.5$ kV
$I \leq 500$ A

Zone 2: dc sources with low short-circuit current. Residual current devices (RCD) are required:
$V \leq 120$ V dc (dry env.)
$V \leq 60$ V dc (humid env.)
$V \leq 30$ V dc (wet env.)
$I \leq 50$ A

Zone 3: Electronic protection without short-circuit current. Only RCD is required. Sources up to 1 kW.

Zone 4: Consumer dc buses with very limited overcurrent. USB-C and other devices.

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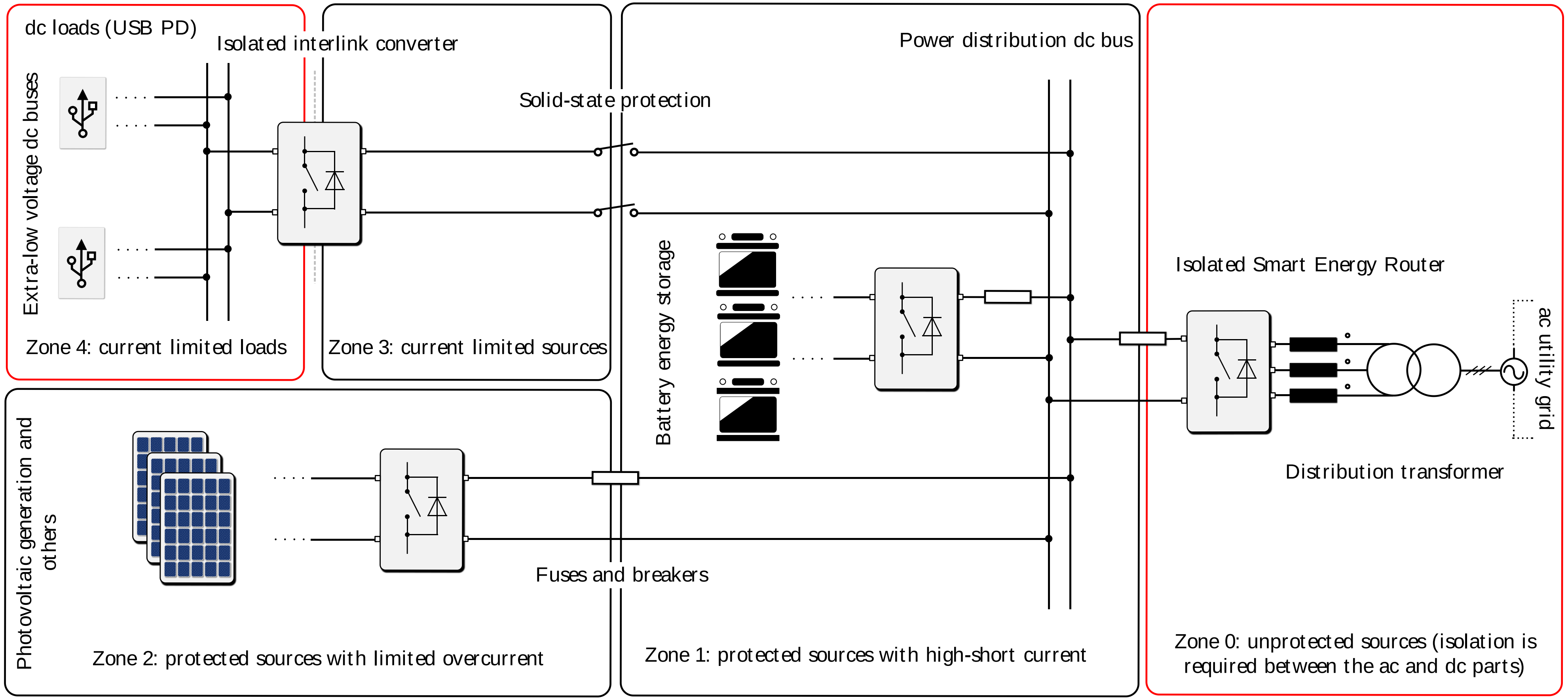

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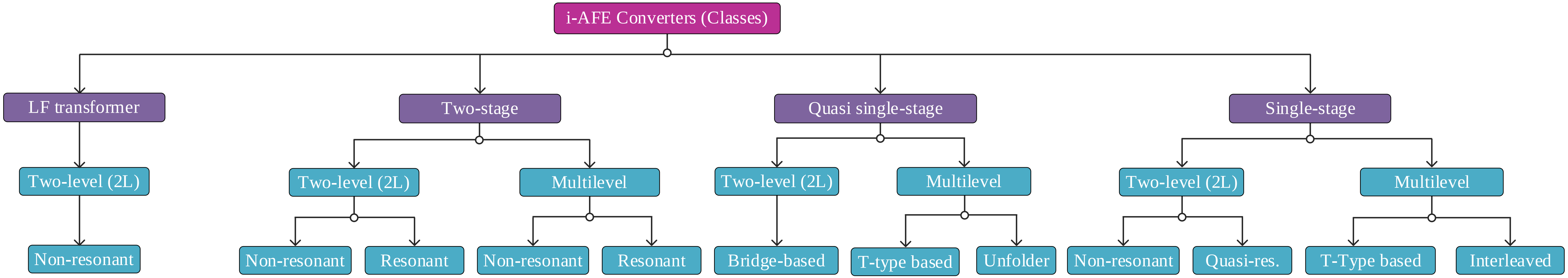
Previously publication and background

E. L. Carvalho, A. Blinov, A. Chub, P. Emiliani, G. de Carne and D. Vinnikov, "Grid Integration of DC Buildings: Standards, Requirements and Power Converter Topologies," in **IEEE Open Journal of Power Electronics**



Grid-interface converters and fuctionalities

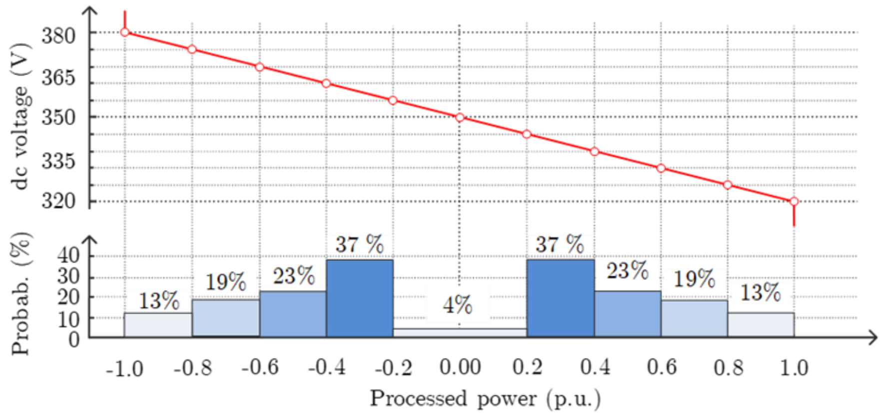
- Bidirectional power transfer
- Galvanic isolation (between AC and DC parts)
- Power 5-10 kVA
- Droop control operation(voltage range defined by the standard)
- Anciliary services for the AC grid side

Ancillary and basic services

Harmonics mitigation	Soft-starting
Voltage regulation	OV&UV RT
Power unbalance compensantion	PFC

Grid Interface Converter

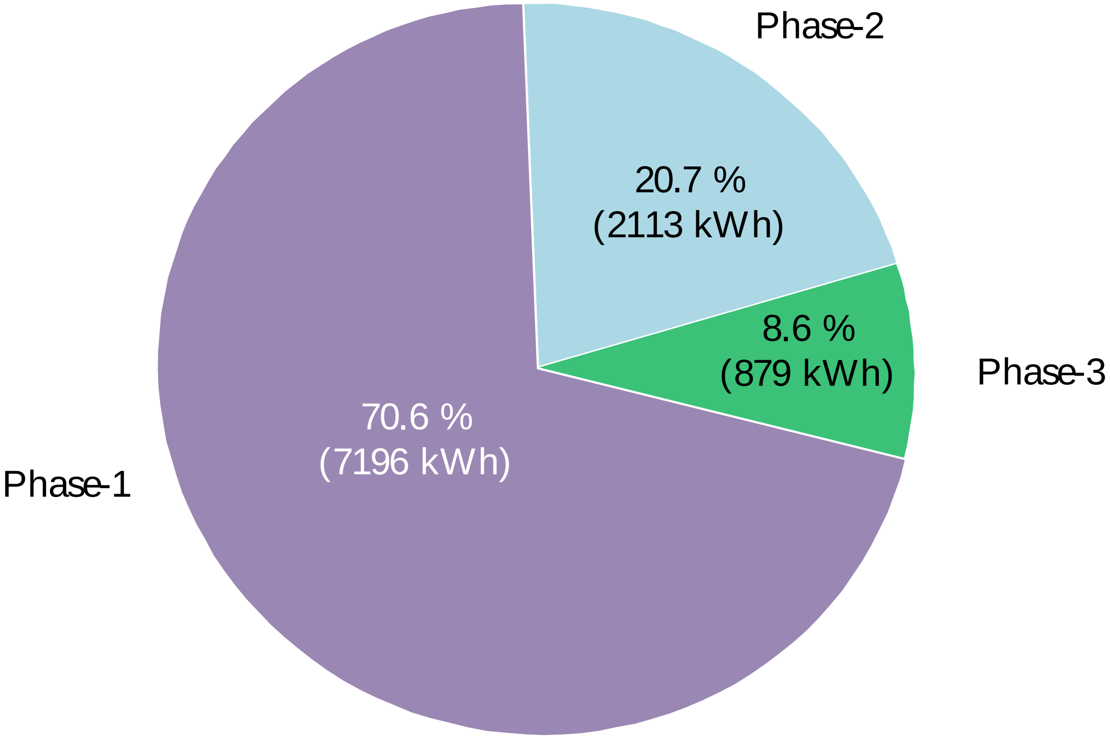
Droop control & DC bus signalling



Problems of existing installations

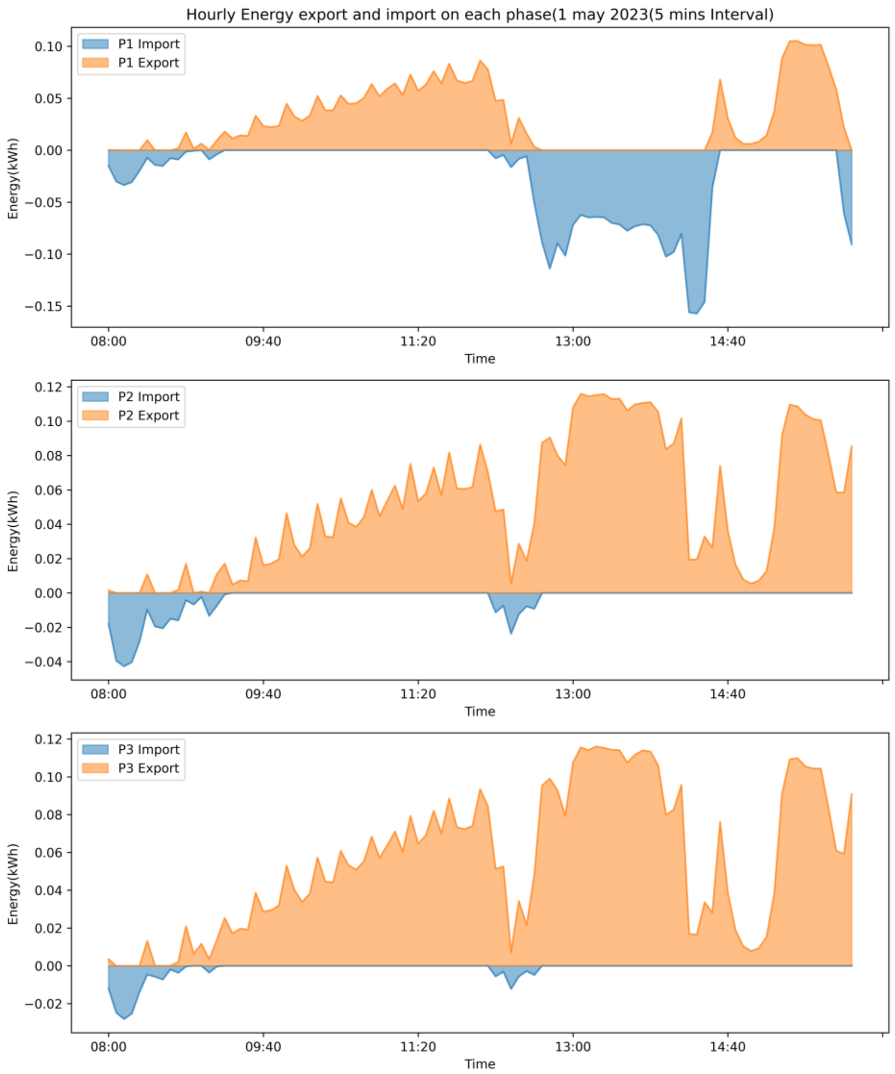
Parameter	Value
Location	Estonia, Tallinn
Heated area	176.7 m^2
Total power of PV	5 kWp
Model of HP	Thermia Atec HP 11
COP of HP	COP 3.8 (+7/+45 °C)
Habitants	4

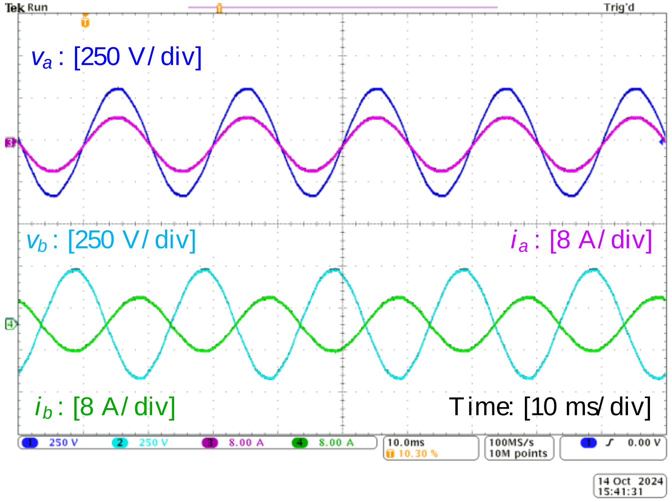
Anual energy consumption: 10187.46 kWh

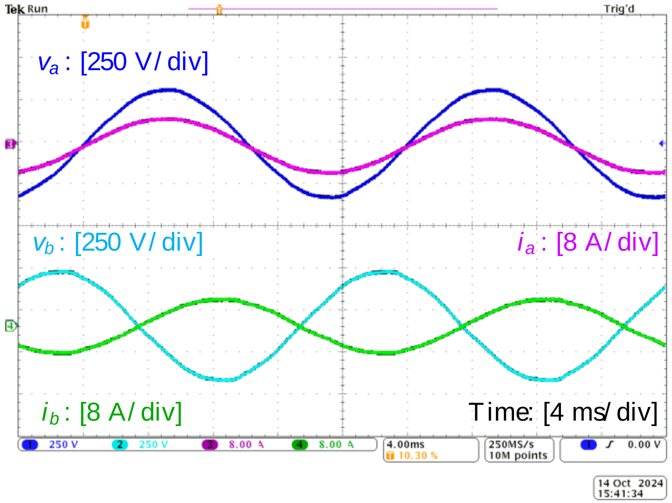


Problems of existing installations

Power demand/phase

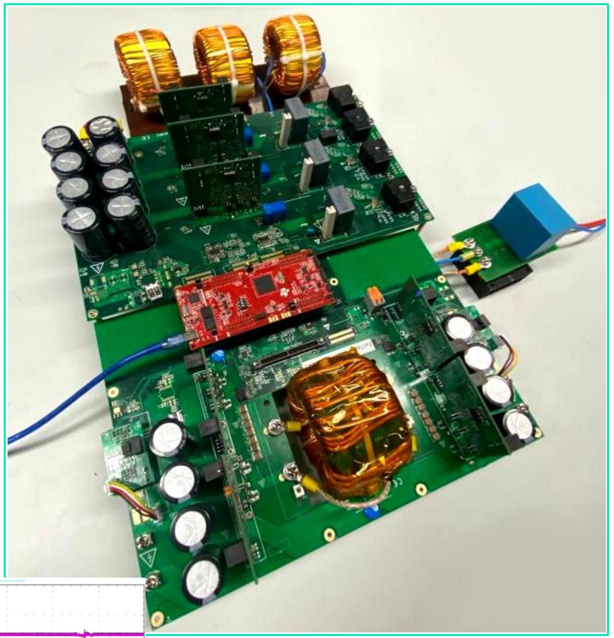


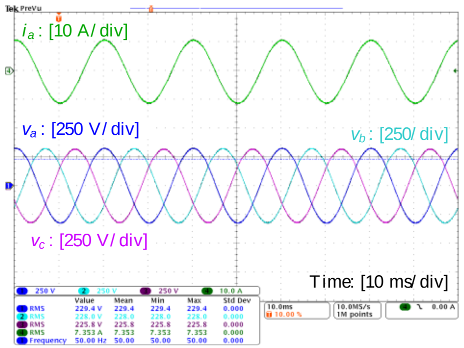


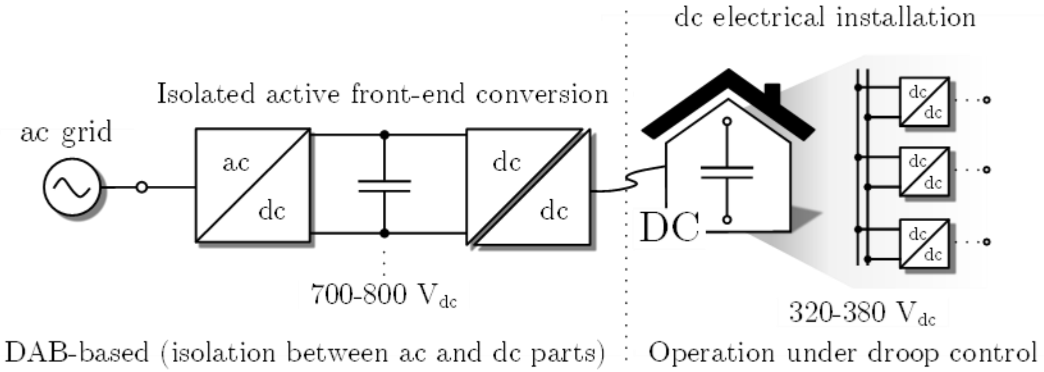


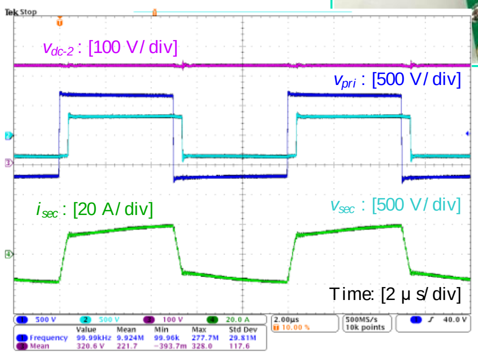
Power electronics solutions

- **Isolated active front-end converter (i-AFE)**
  - i-AFE based on voltage source (2L-VSC) and dual-active bridge (DAB) converter: ac-dc+dc-dc
  - Power-balance capability
  - A flat efficiency curve is the main challenge
  - Efficiency up to 95.8% / 5-kW









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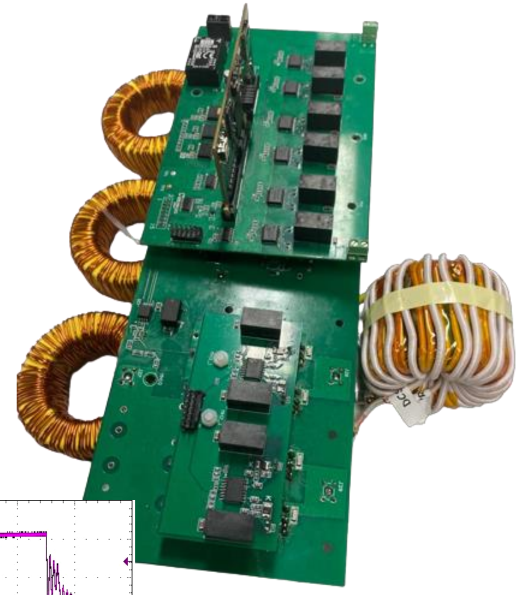
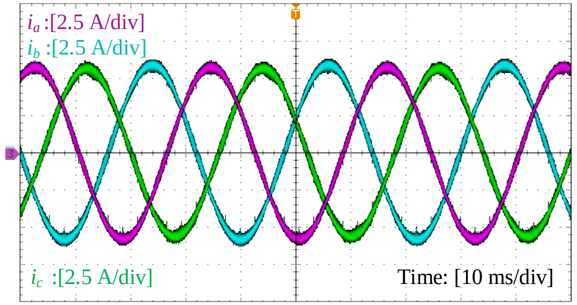
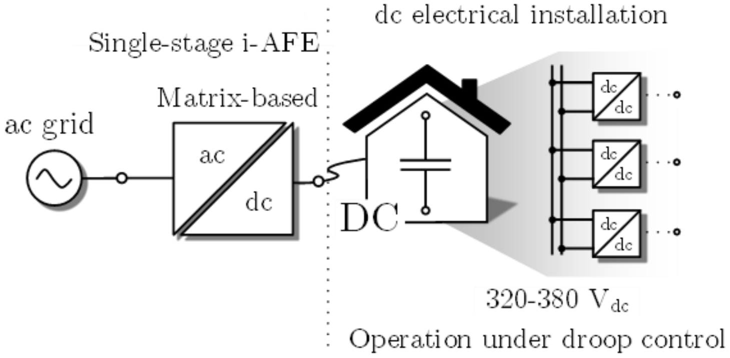
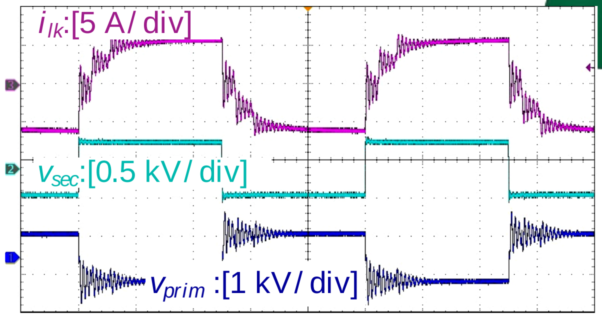
Power electronics solutions

- **Single-stage i-AFE:**
  - Lower number of sensors/feedback loops
  - No intermediate DC link
  - Compelex modulation strategy









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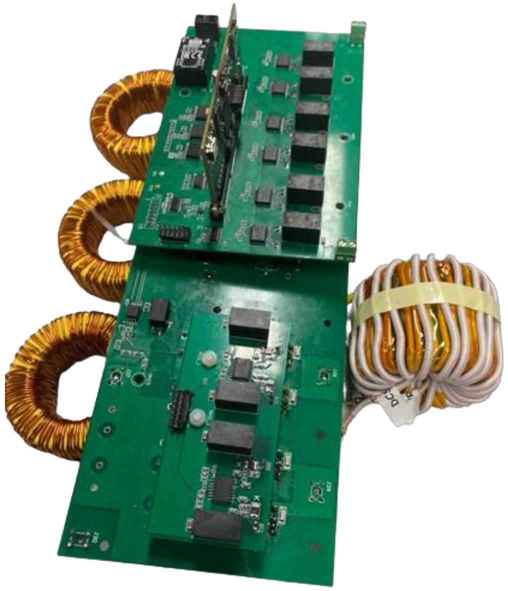
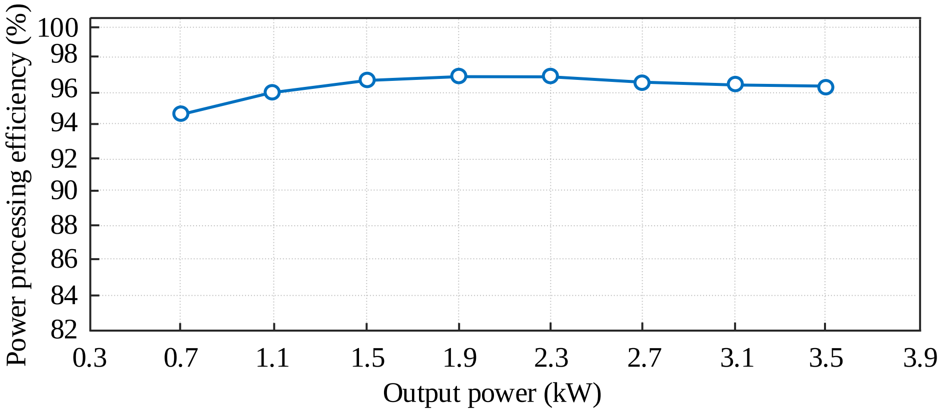
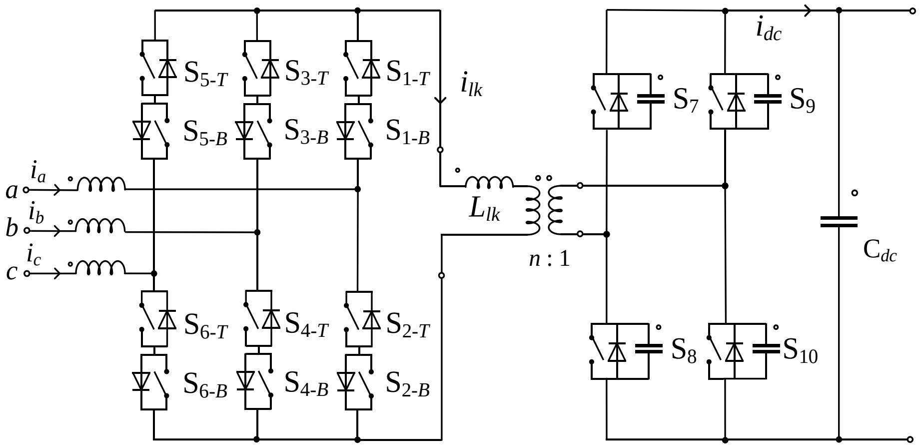
Power electronics solutions

- Single-stage i-AFE:
  - i-GIC based on matrix-converters (bidirectional switches)
  - Full soft-switching operation
  - Peak efficiency 96.7 % (96.5% / 3.5 kW)



Efficiency curve





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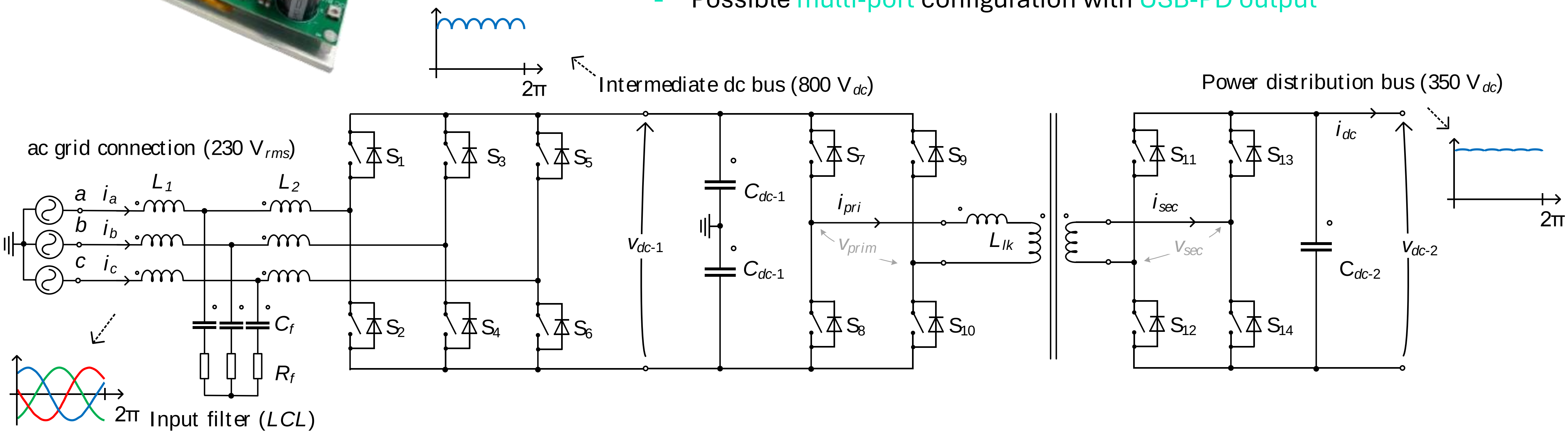
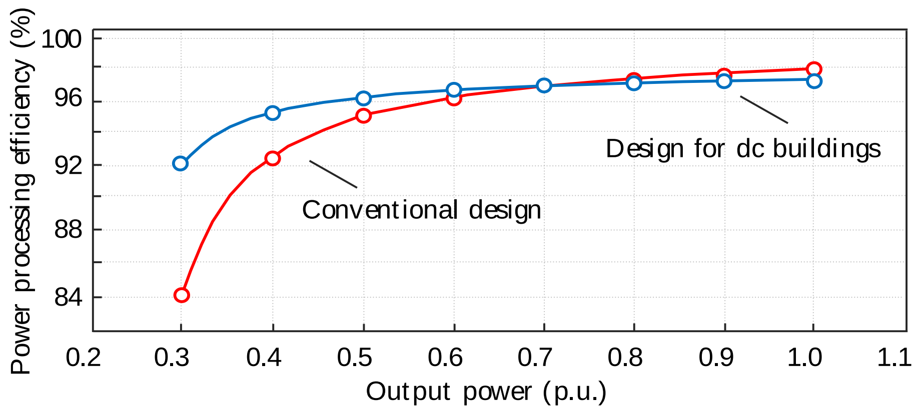
- Bidirectional power router for prosumer DC buildings
- High-frequency galvanic isolation
- Input 230/400 VAC, output 350 VDC, 5...10 kW
- Droop control according to Current/OS protocol
- Efficiency curve optimized for part-load operation based on statistical data (>97 %)
- Possible multi-port configuration with USB-PD output

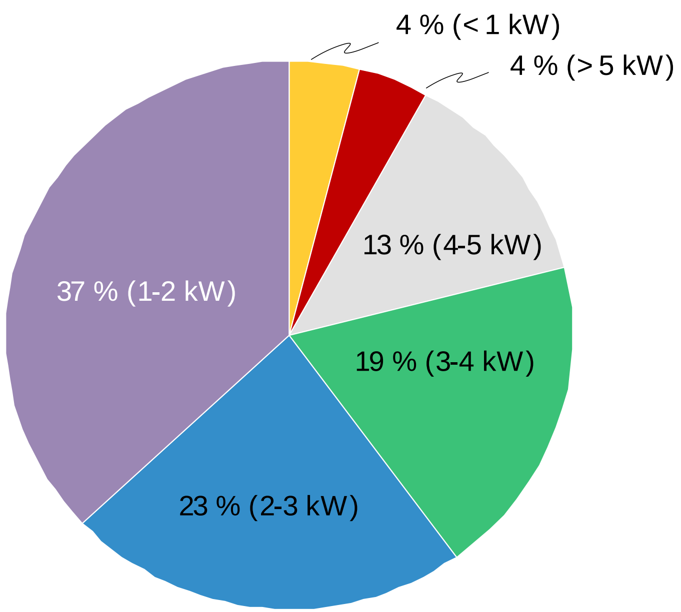


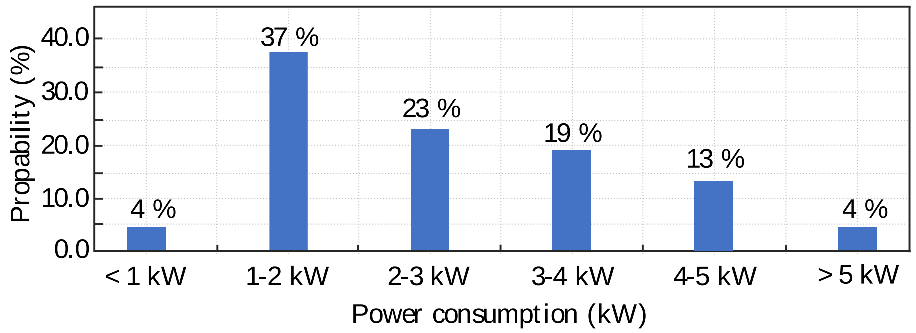
Design targets and priorities

- Aplication oriented design
- Investigate actual operational profile
- Indicate most probable working conditions
- Optimized design considering the droop curve



Average energy consumption





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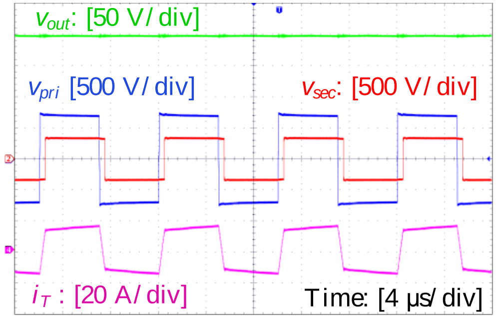
Effect of droop control on power converter efficiency

- **Dual active bridge *vs* Series resonant converter**: How to optimize the efficiency curve for buildings?

  - Similar component count
  - Different control design constraints
  - Possible operation at full soft-switching
  - Flat efficiency curve

DAB



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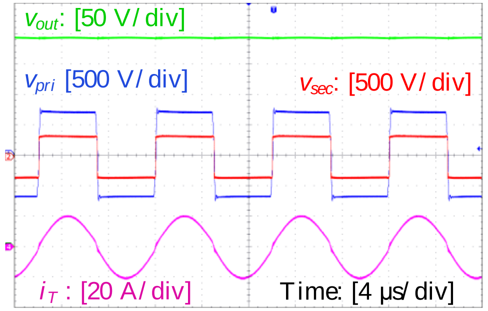
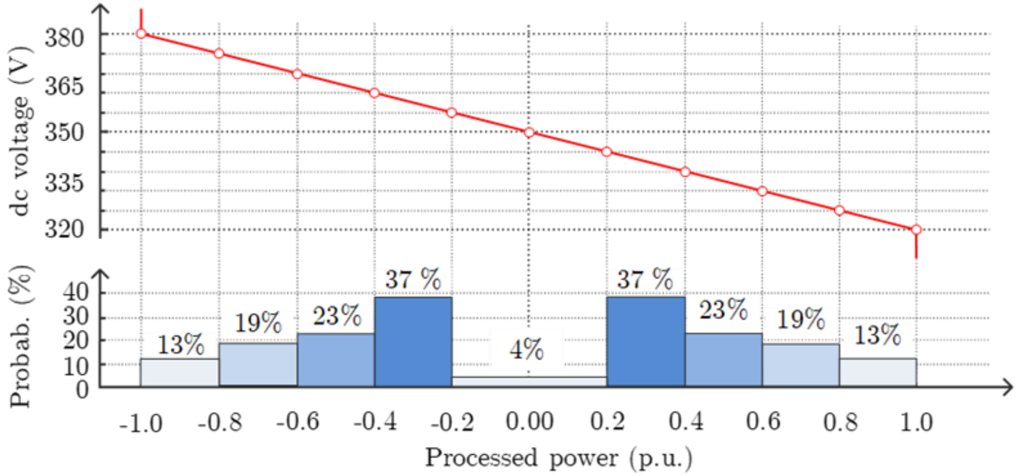
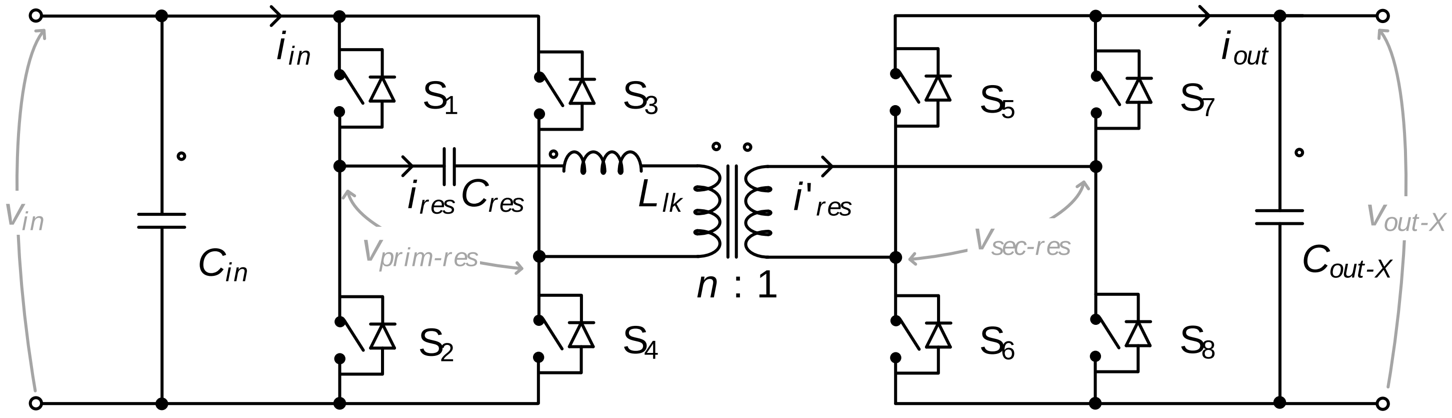


Design constraints



Power converter topology



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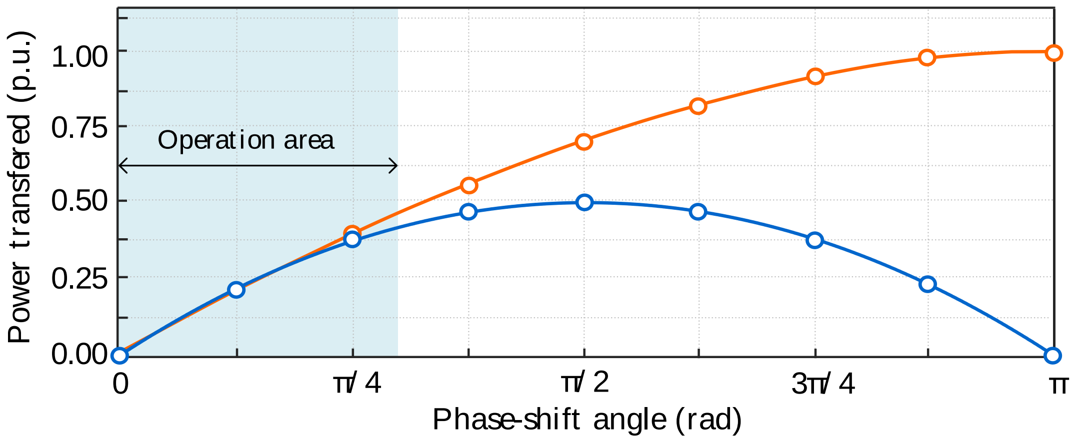
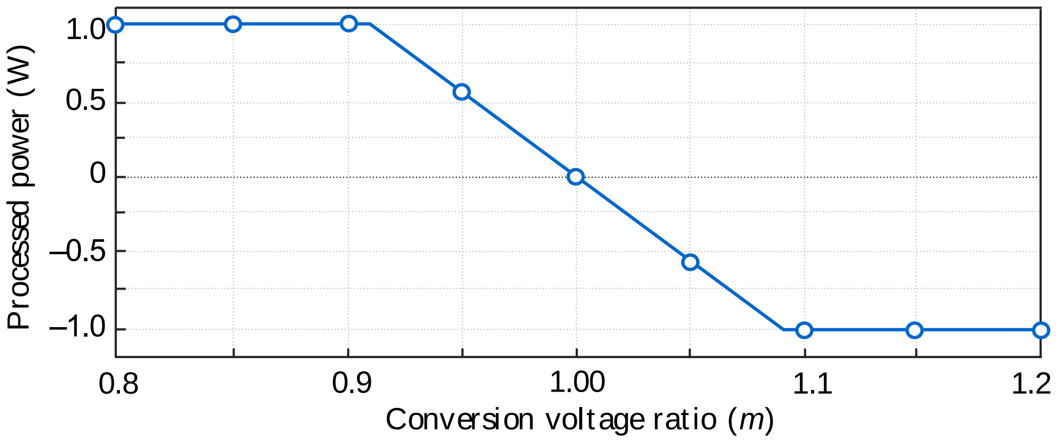
Effect of droop control on power converter efficiency

- **Efective operation area**
  - **Conventional design**: designed to operate within a predefined region of output power or voltage
  - **Operation under droop control**: the processed power is constrained to follow a specific line, which is determined by the droop control





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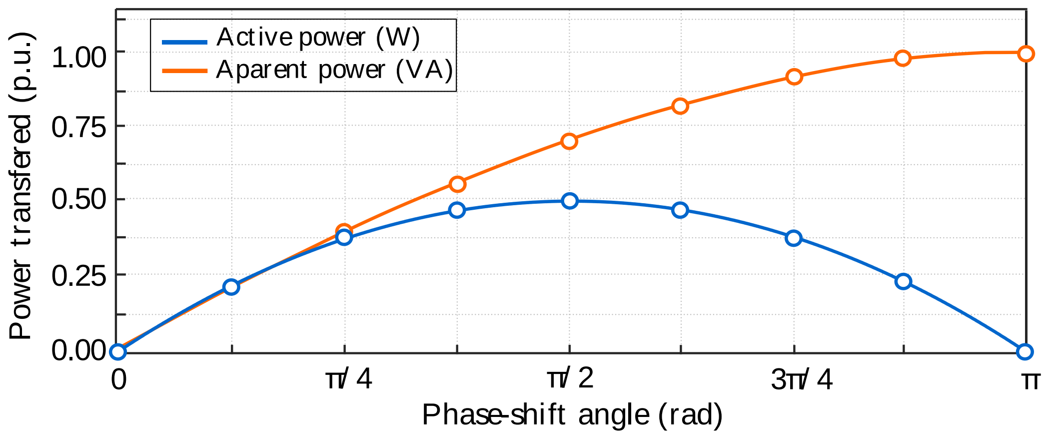
Effect of droop control on power converter efficiency

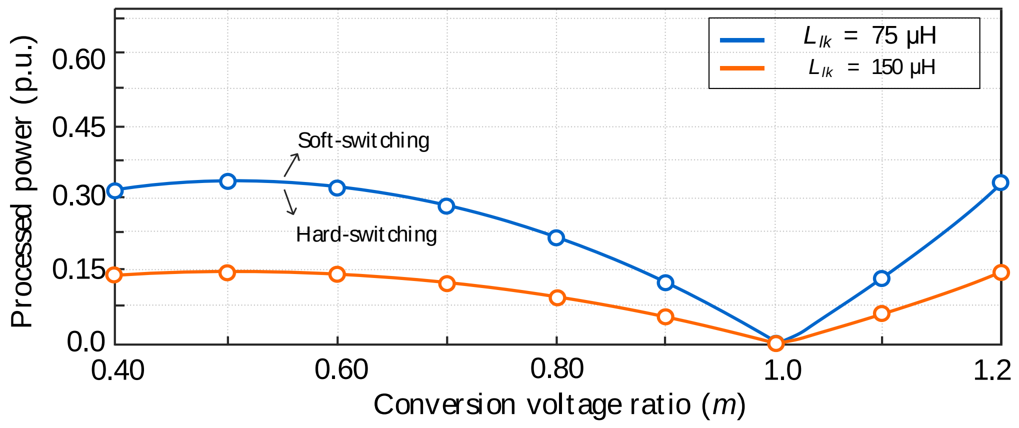
- Dual active bridge operation
  - Wide soft-switching range *vs* high reactive power

$$P = \frac{n \cdot v_{in} \cdot v_{out} \cdot \delta \cdot (\pi - \delta)}{2\pi^2 \cdot f_s \cdot L_{lk.}}$$

Output power



Soft-switching boundaries

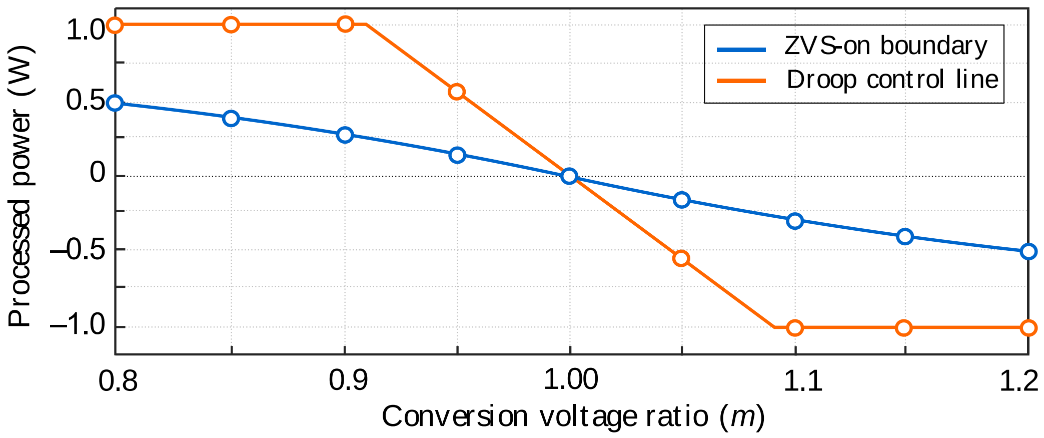


E. L. Carvalho, A. Blinov, A. Chub, D. Vinnikov, "Design Considerations of Dual-Active Bridge DC Grid-Forming Converter for DC Buildings", in **Trans. on Industrial Electronics**

Effect of droop control on power converter efficiency

- Dual active bridge operation
  - How does droop control affect soft-switching operation?

ZVS-on boundary / droop control line



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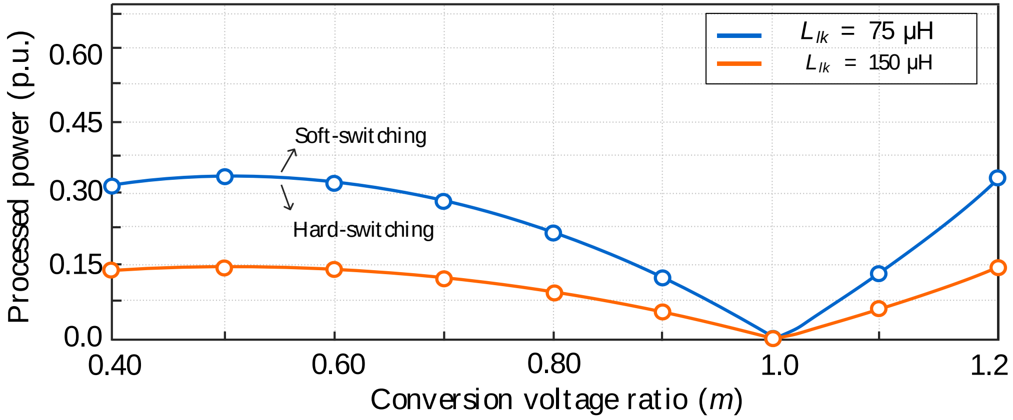

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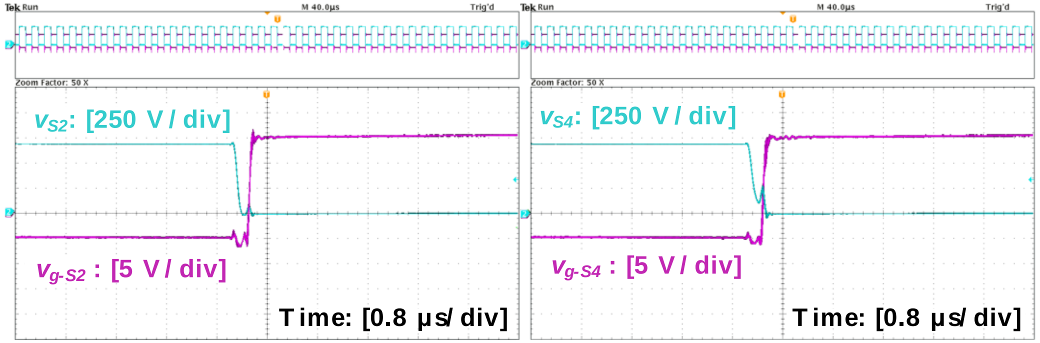

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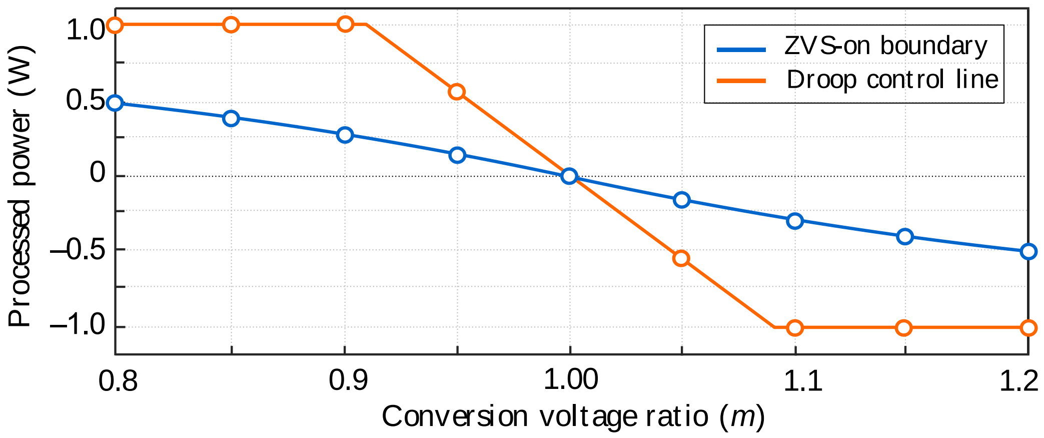
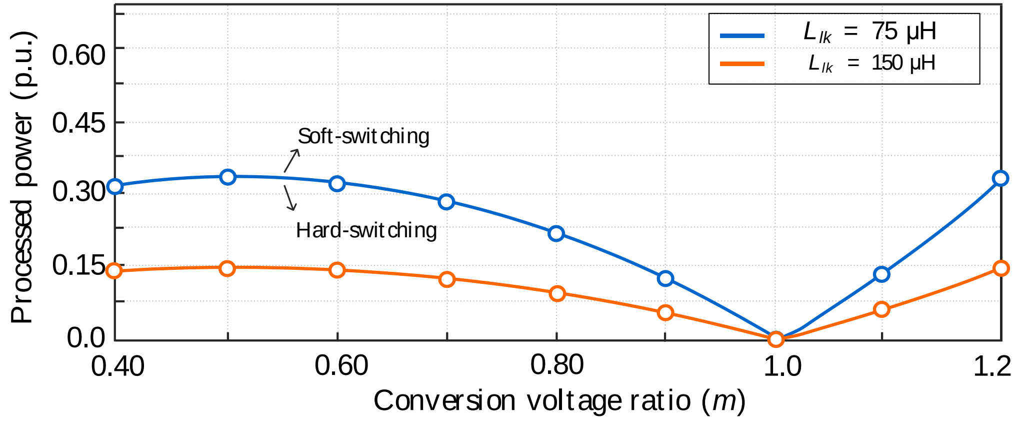


Soft-switching boundaries



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Effect of droop control on power converter efficiency

- Dual active bridge (5-kW/100 kHz)
- Series resonant converter (5-kW/100 kHz)

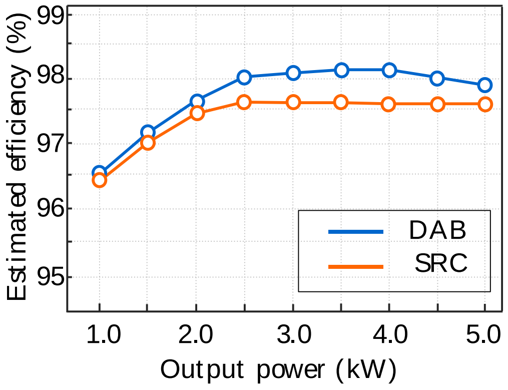
Design 1:

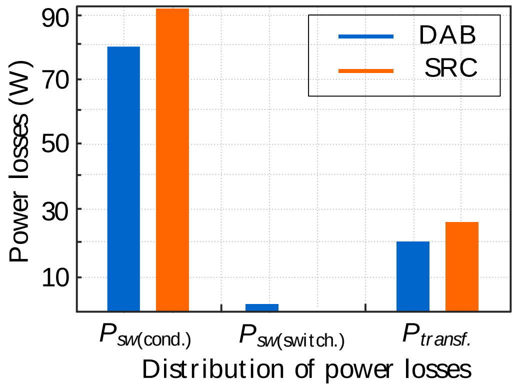
Primary side switches	C2M0160120D (1200 V/19 A), 160 mΩ /47 pF
Secondary side switches	C3M0120065D (650 V/22 A), 120 mΩ /45 pF

Design 2:

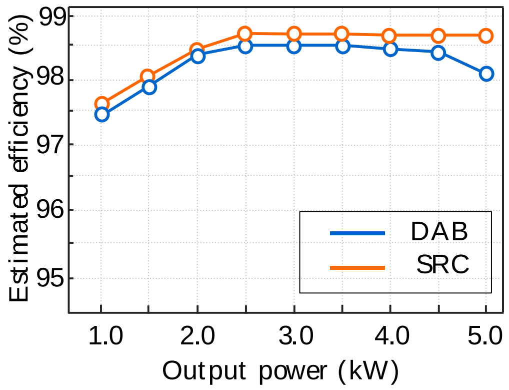
Primary side switches	UF3SC120009K4 (1200 V/65 A), 73 mΩ /210 pF
Secondary side switches	UF3SC065007K4 (650 V/120 A), 8.8 mΩ /1190 pF

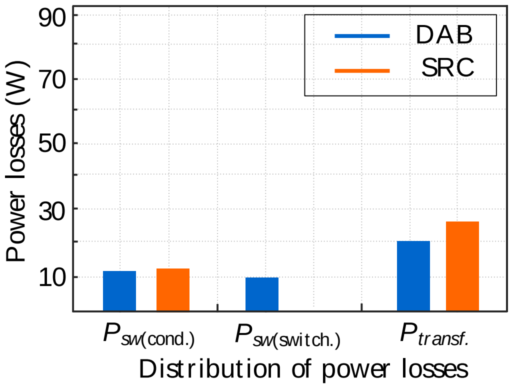
Design 1





Design 2





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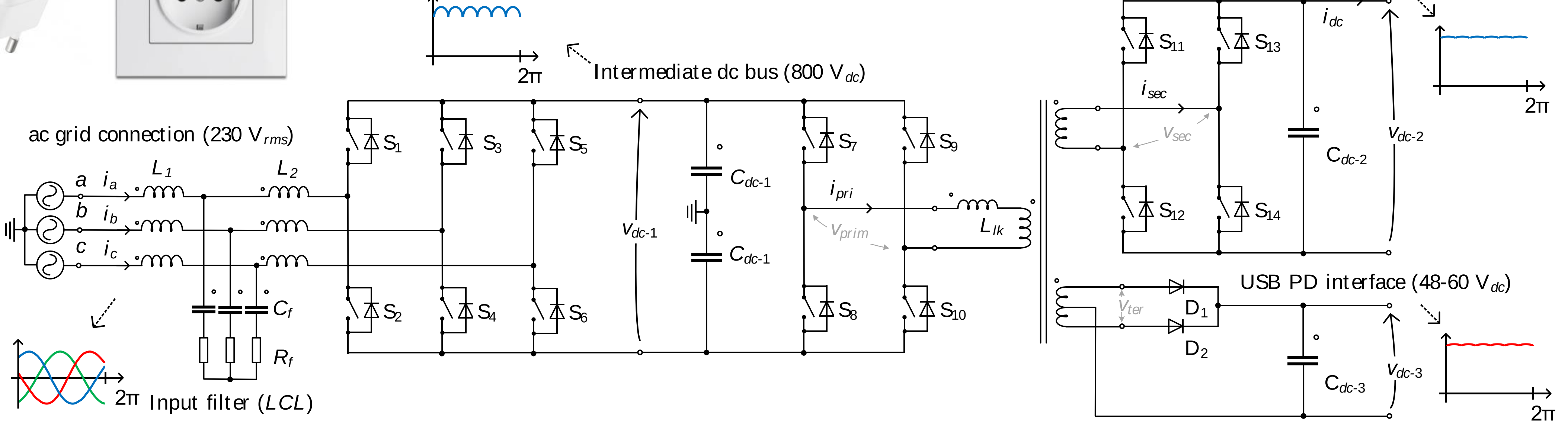
SMART ENERGY ROUTER

- Multiport converter with USB PD interface, according to Current/OS protocols



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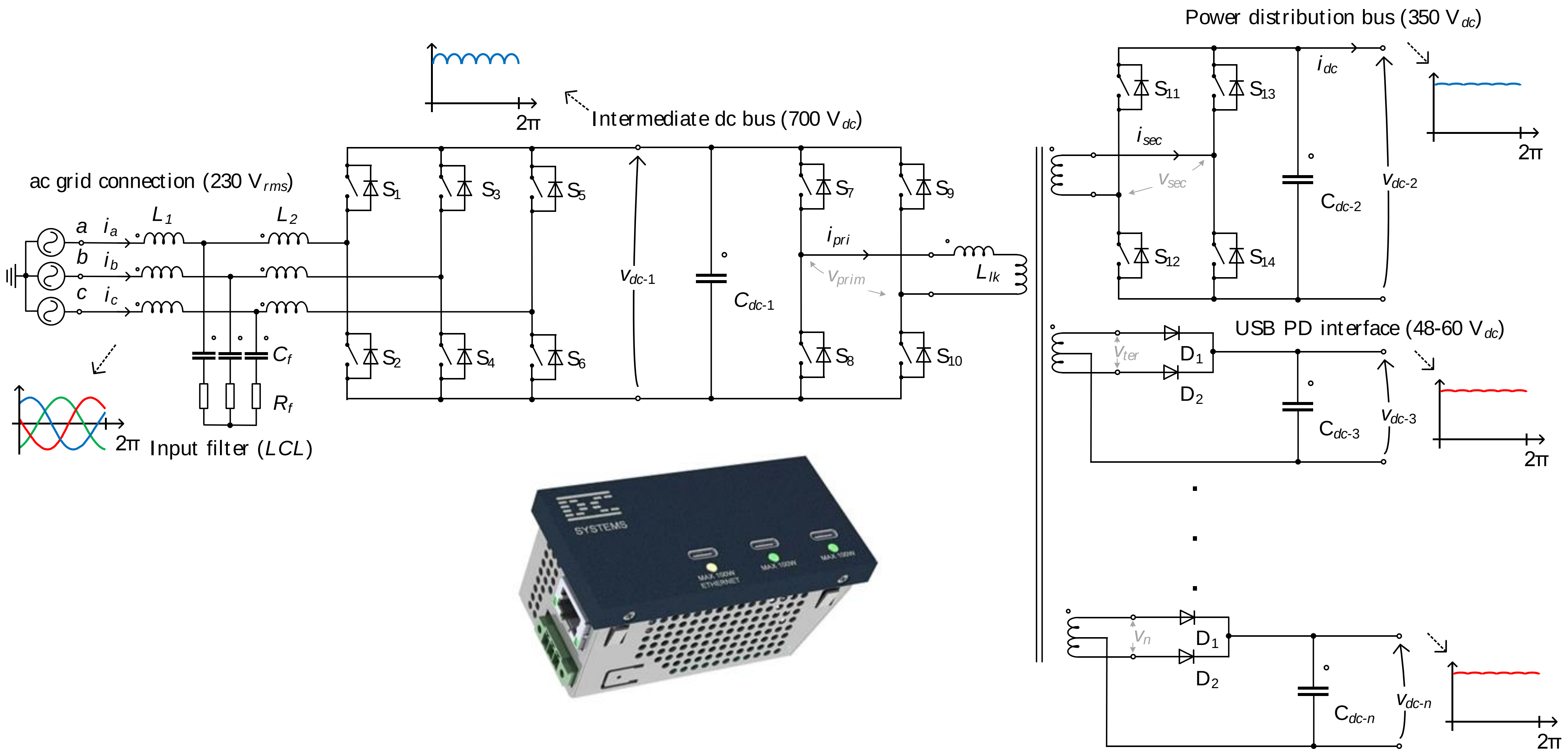
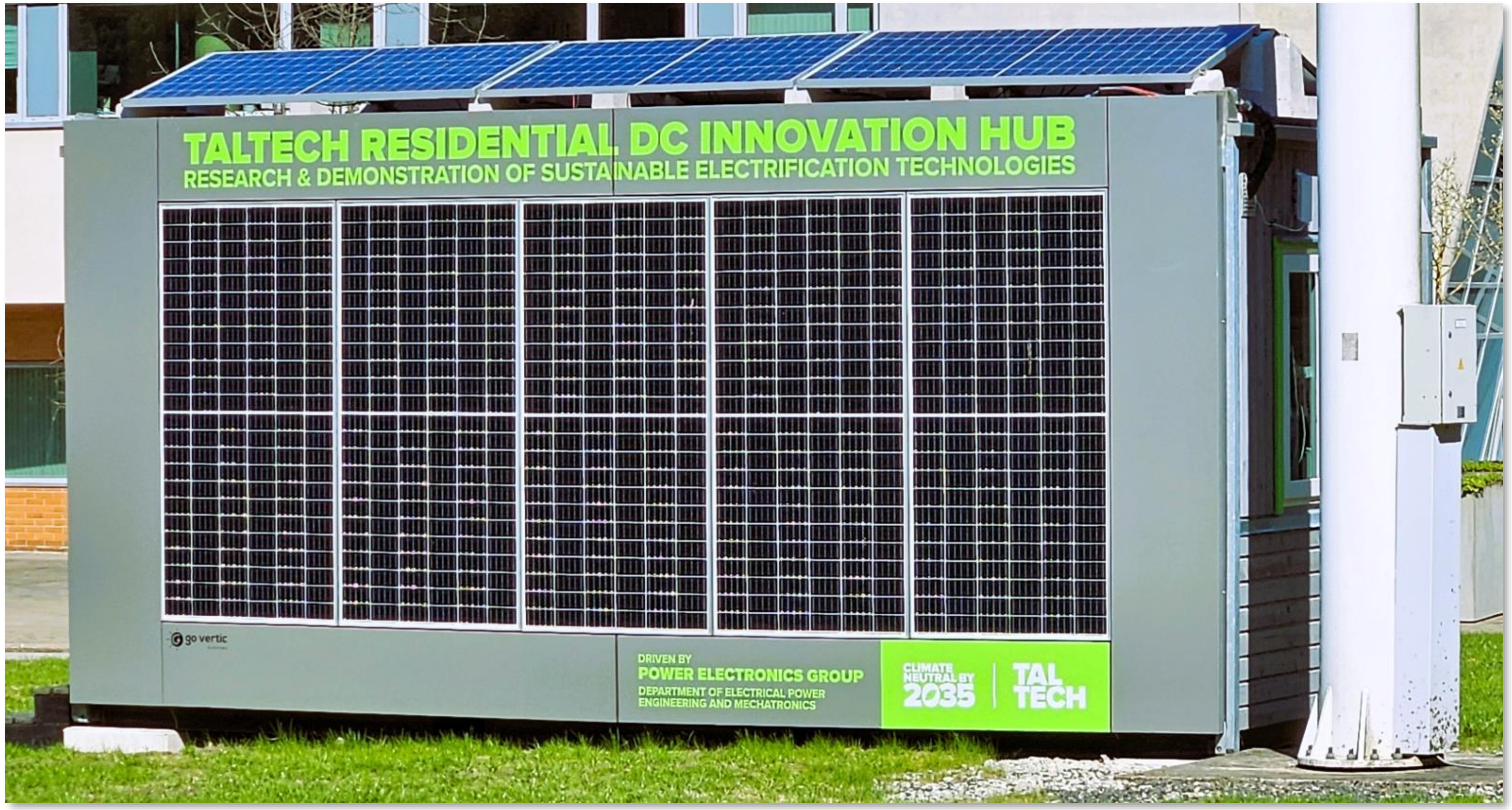


TALTECH Residential DC Innovation Hub

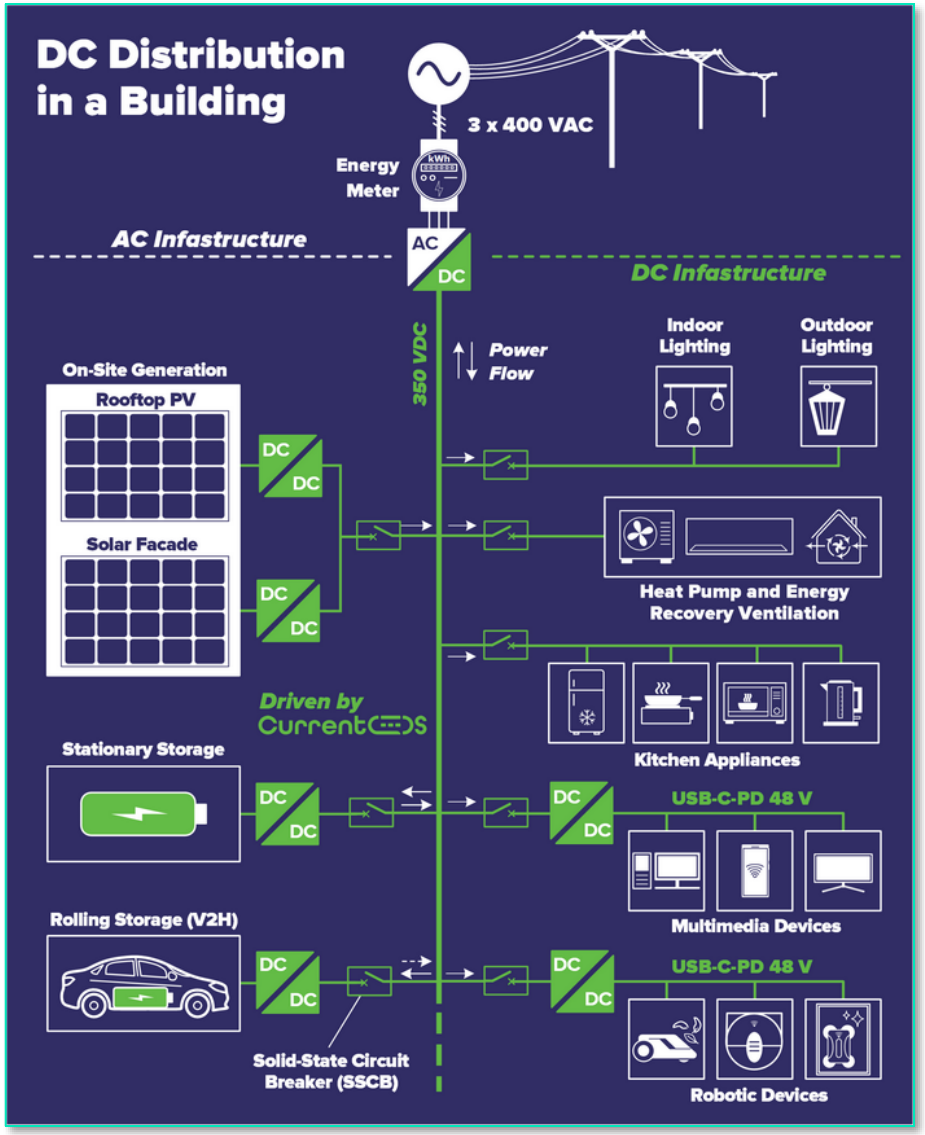
The first DC EXPERIENCE CENTER in Northern Europe



taltech.ee/en/i3dc-initiative

- First academic member of the Current/OS Foundation
- An international open platform for research and demonstration of residential DC power distribution technology
- Validation of net-zero-energy solutions (workplace, space heating and cooling, ventilation, etc.)
- The living lab blends the everyday real-life experiences of pilot users with academic research to develop future-proof, energy-saving technologies
- Data collection for the future design of the energy-neutral TalTech campus

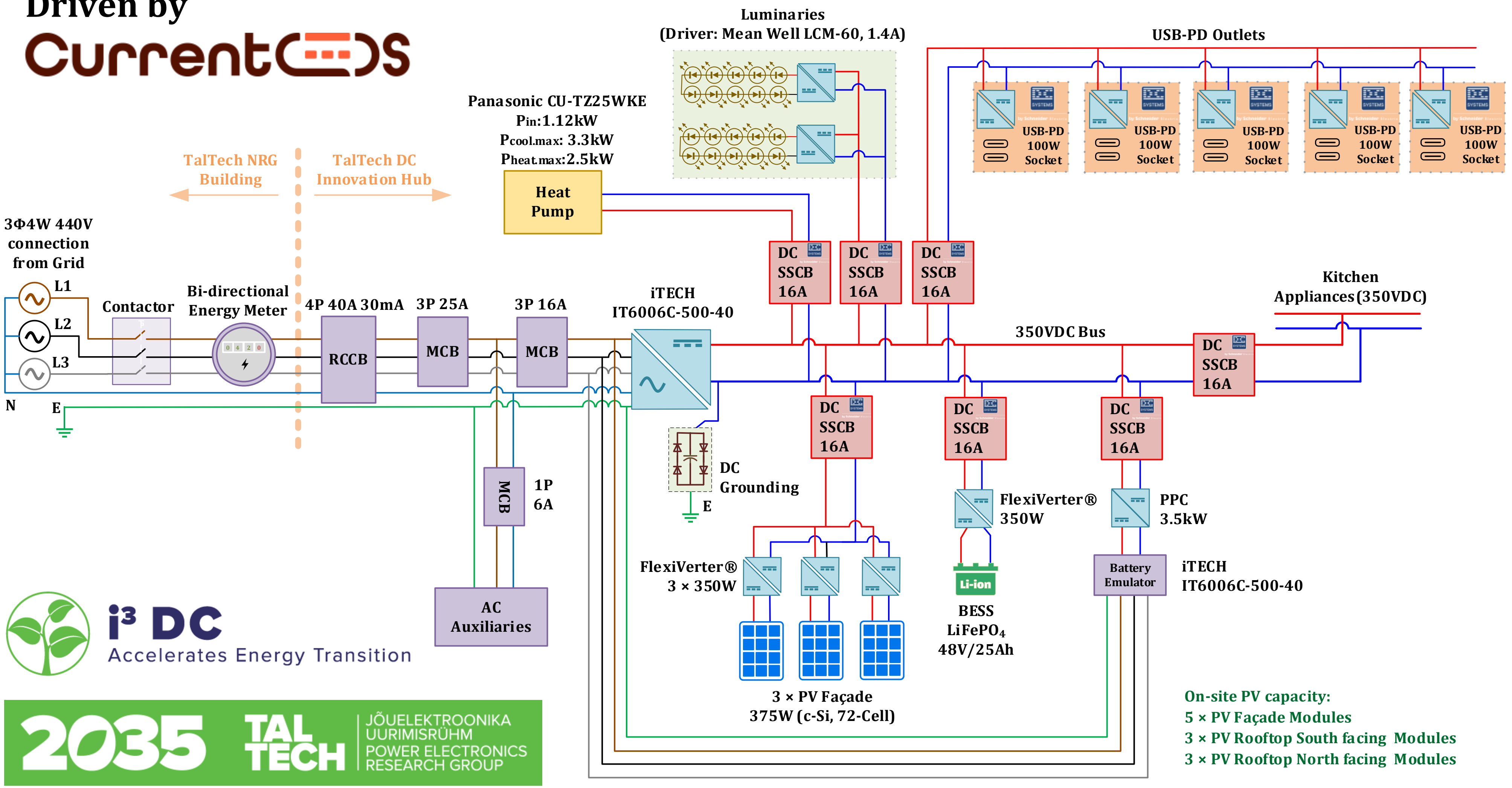
TALTECH Residential DC Innovation Hub



- Thermally insulated for year-round operation
- 350V droop-controlled microgrid (operating system Current/OS)
- Heat pump fed from DC
- Solar facade composed of 5 c-Si PV modules
- Solar roof with 3 south-facing and 3 north-facing c-Si PV modules
- LED lighting fed from DC
- Battery energy storage
- Solid-state protection (both commercial and research samples)
- DC appliances (continuous development)

TALTECH Residential DC Innovation Hub

Driven by CurrentOS

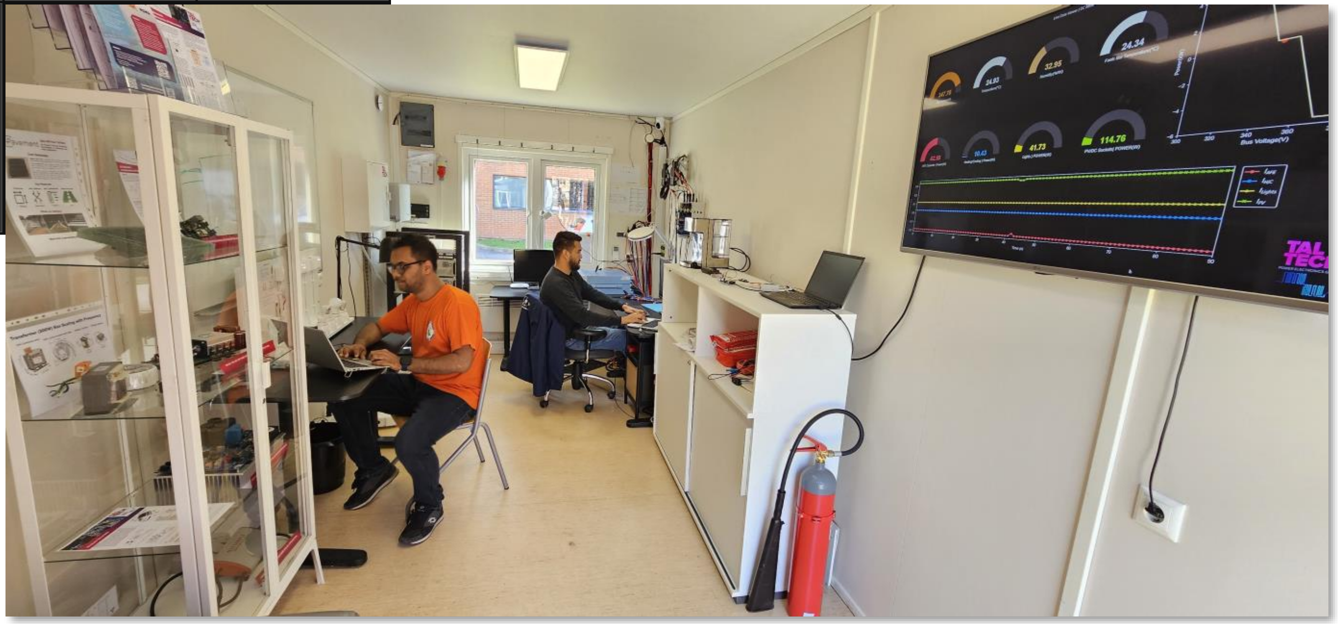


On-site PV capacity:
5 × PV Façade Modules
3 × PV Rooftop South facing Modules
3 × PV Rooftop North facing Modules

i³ DC
Accelerates Energy Transition

2035 TAL TECH JÕUELEKTROONIKA UURIMISRÜHM POWER ELECTRONICS RESEARCH GROUP

Live telemetry



- Data logging and visualization

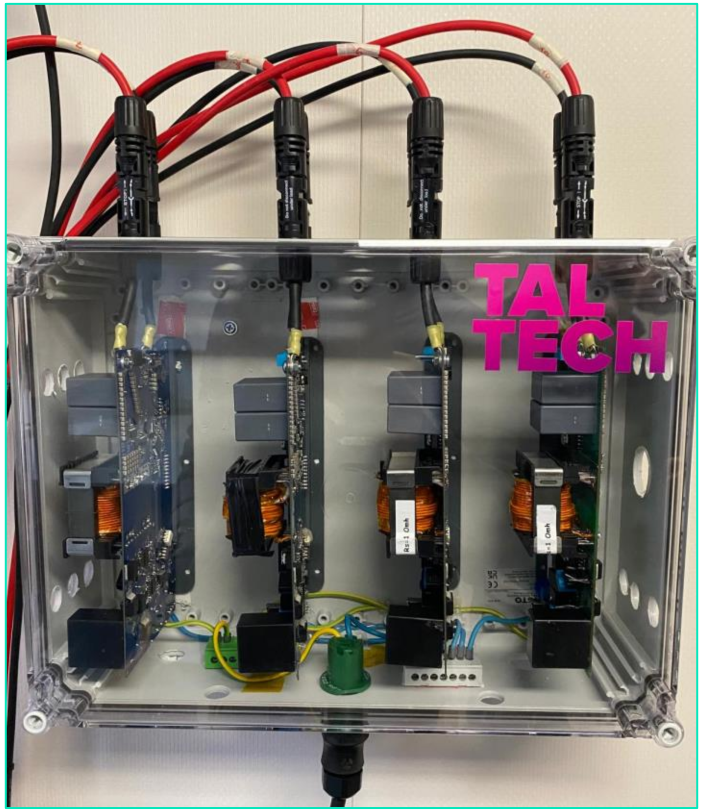
Undergoing concepts

FLEXIVERTER – FLEXIble ConVERTER

- Novel power electronic building block for fast deployment of residential DC systems:
  - Aimed at nano-producers (<800W)
  - Universal compatibility:

    - any residential PV module and 24V or 48V batteries at the input

    - standard 350±30V or 700±60V microgrid at the output
  - Efficiency 98% for both operation modes
  - Integrated soft-start and solid-state protection for compatibility with Current/OS protocols



PC: Andrii Chub

R: Salman Kahan

V. Sidorov, et al. "Novel Universal Power Electronic Interface for Integration of PV Modules and Battery Energy Storages in Residential DC Microgrids," in **IEEE Access**

Undergoing concepts

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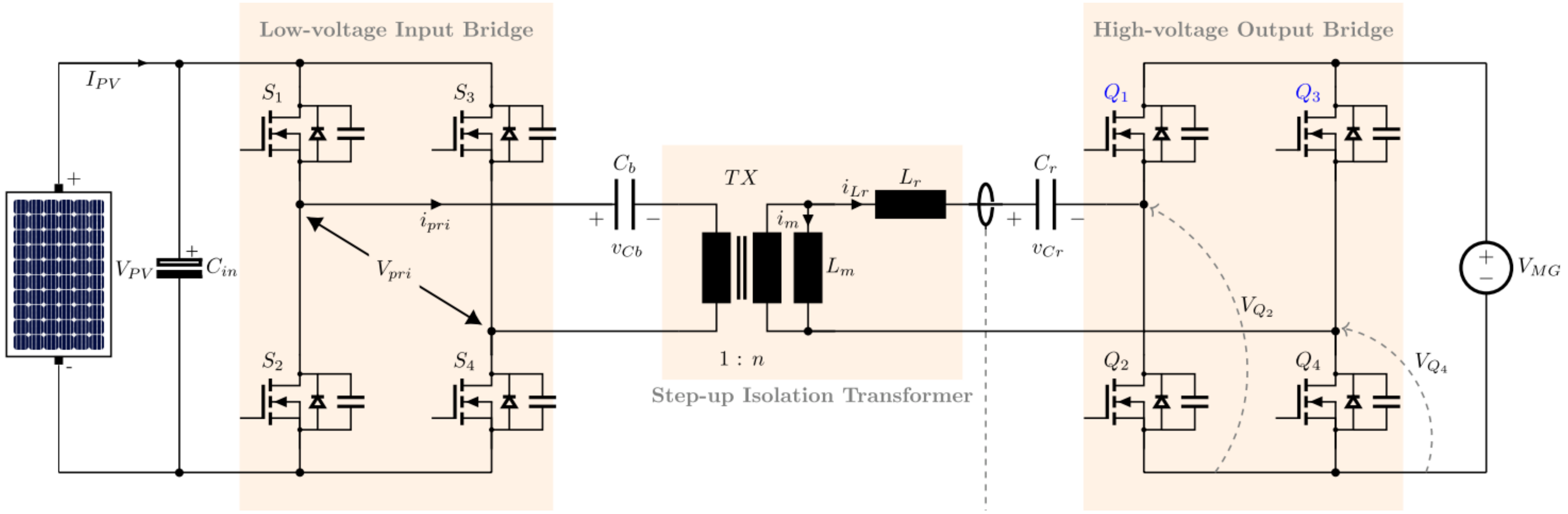

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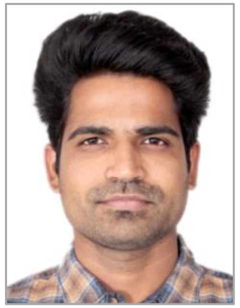
Undergoing concepts

FORCE – Fractional POweR ConvErter

- Ultra-efficient – over 99% for 25%+ load
- Optimized for 350±30V residential DC microgrids
- Designed for second-life LFP battery stack of 109 cells, approx. capacity ~8 kWh (depends on degradation)
- Patented control with soft-switching in the entire range
- Soft-start and embedded solid-state protection for compatibility with Current/OS DC microgrid protocol
- Ready for emerging bidirectional monolithic GaN switches (by Infineon)

PC: Andrii Chub



R: Neelesh Yadav

N. Hassanpour et al. "High-Efficiency Partial Power Converter for Integration of Second-Life Battery Energy Storage Systems in DC Microgrids," in **IEEE Open Journal of the Industrial Electronics Society**

Undergoing concepts

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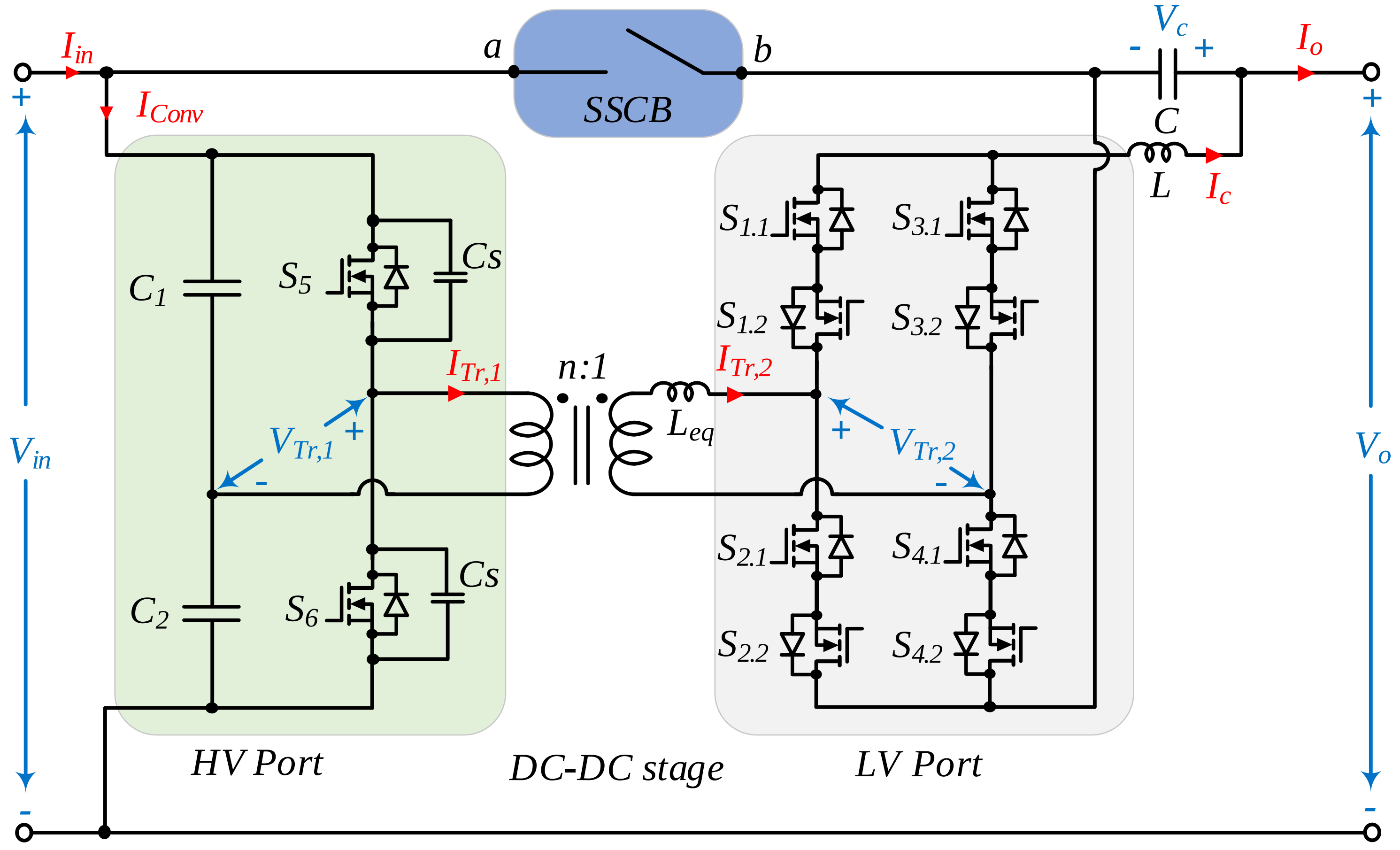

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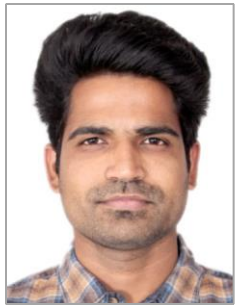

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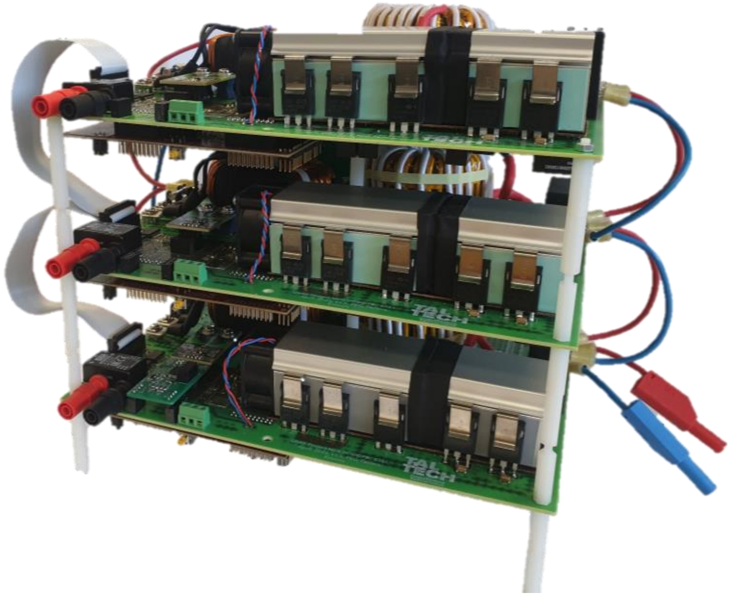
Undergoing concepts

UBICHARGER – low-power EV opportunity Charger

- Charges EV and employs energy stored in it for the emergency backup power supply of ZEB
- High-frequency galvanic isolation
- Power 3…7.4 kVA, universal EV-side range of 200…800 VDC
- Droop controlled according to Current/OS (in emergency bands)
- High weighted efficiency of >97%
- Low-cost single-stage design

PC: Andrei Blinov



PC: Sachin Chauhan

D. Zinchenko et al. "High-Efficiency Single-Stage On-Board Charger for Electrical Vehicles," **in IEEE Transactions on Vehicular Technology**

Undergoing concepts

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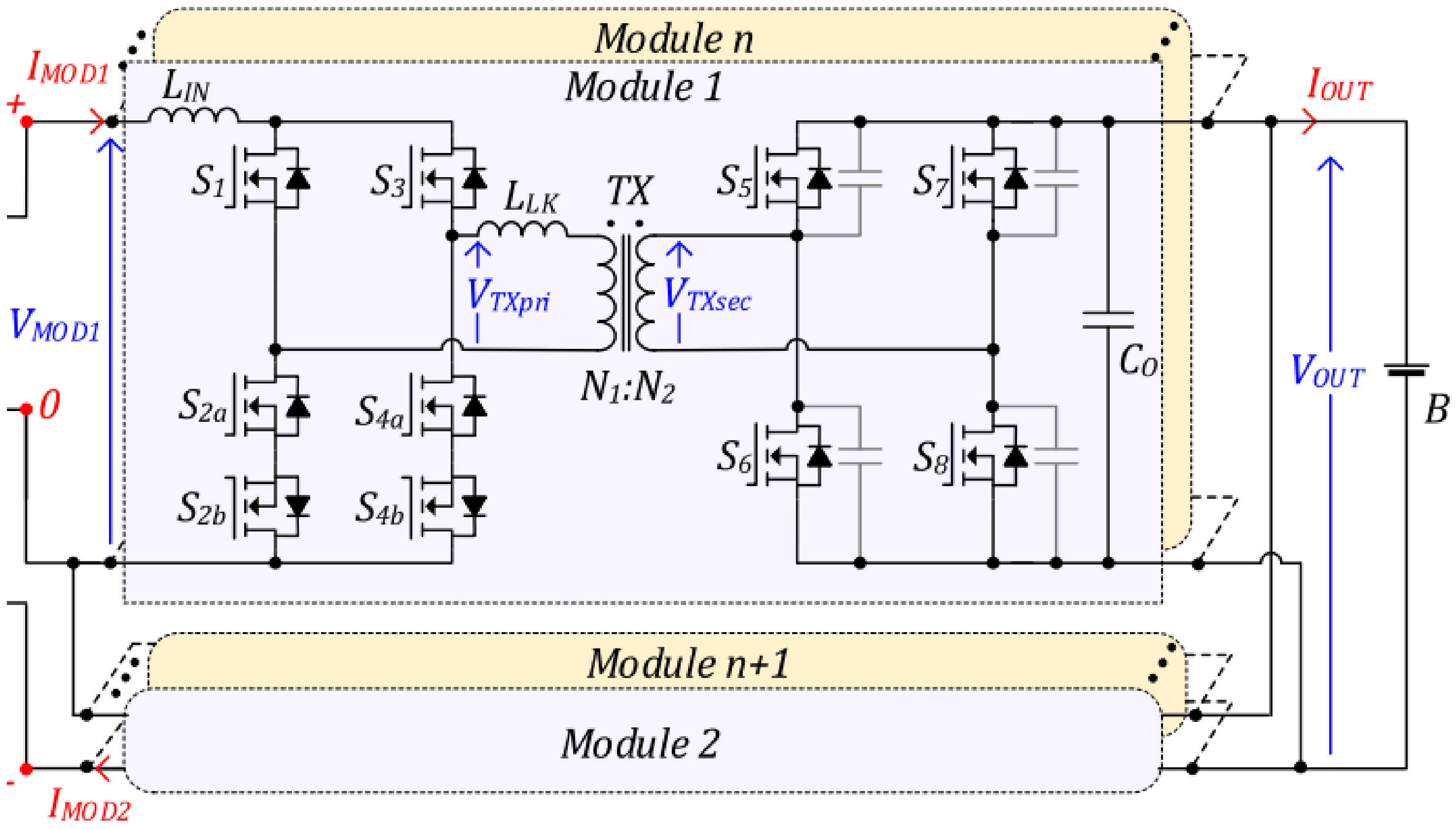


PC: Andrei Blinov

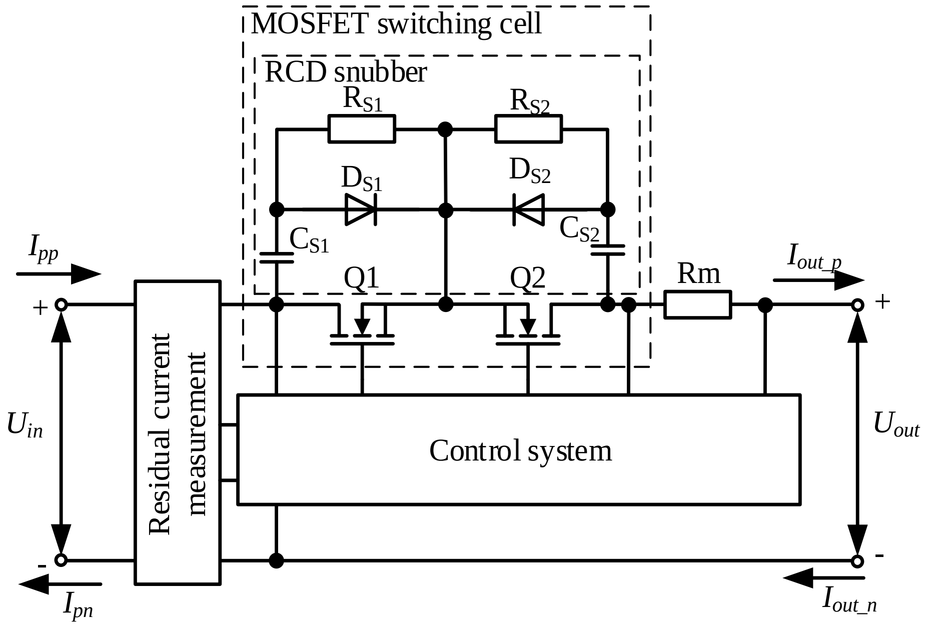
PC: Sachin Chauhan

D. Zinchenko et al. "High-Efficiency Single-Stage On-Board Charger for Electrical Vehicles," **in IEEE Transactions on Vehicular Technology**

Undergoing concepts

SAFEBREAKER – SAfe and Fast DC Electronic BREAKER

- Optimized for 350 VDC/16A residential applications
- Utilizes SiC JFETs for low RDSon, efficiency 99.8% @ 16A
- Contains residual current sensor for ultimate safety
- Fast speed – short circuit detected within 10 µs
- MQTT smart connection to Energy Management System



Main challenges of DC today

- Lack of public awareness
- Lack of international standardization and mature technology
- Lack of market-ready technologies:
  - PV converters
  - energy storage interfaces
  - EV chargers
  - energy routers, etc.

*i*³ DC Initiative: *i*nform, *i*nspire & *i*nnovate (est. 2020)

- organization of national and international seminars and workshops on residential DC nanogrids, DC buildings and districts
- research, development and showcasing of innovative technologies
- development of public policies and standards for DC buildings
- creation of new cleantech ventures and joint seeking for funds

i³ DC
Accelerates Energy Transition

SEPOC 2024

UFSM IEEE

ACKNOWLEDGEMENT

Centre of Excellence in Energy Efficiency

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imperix

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OPAL-RT TECHNOLOGIES

Study English!

Chroma Systems Solutions

WEG

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Tektronix

KEITHLEY