EPE'20 ECCE EUROPE

EPE'20 ECCE Europe
Keynote 1

Roadmap to DC: “From DC building to a DC distribution”

Prof. Dr. Ir. P.Bauer
TU Delft, The Netherlands

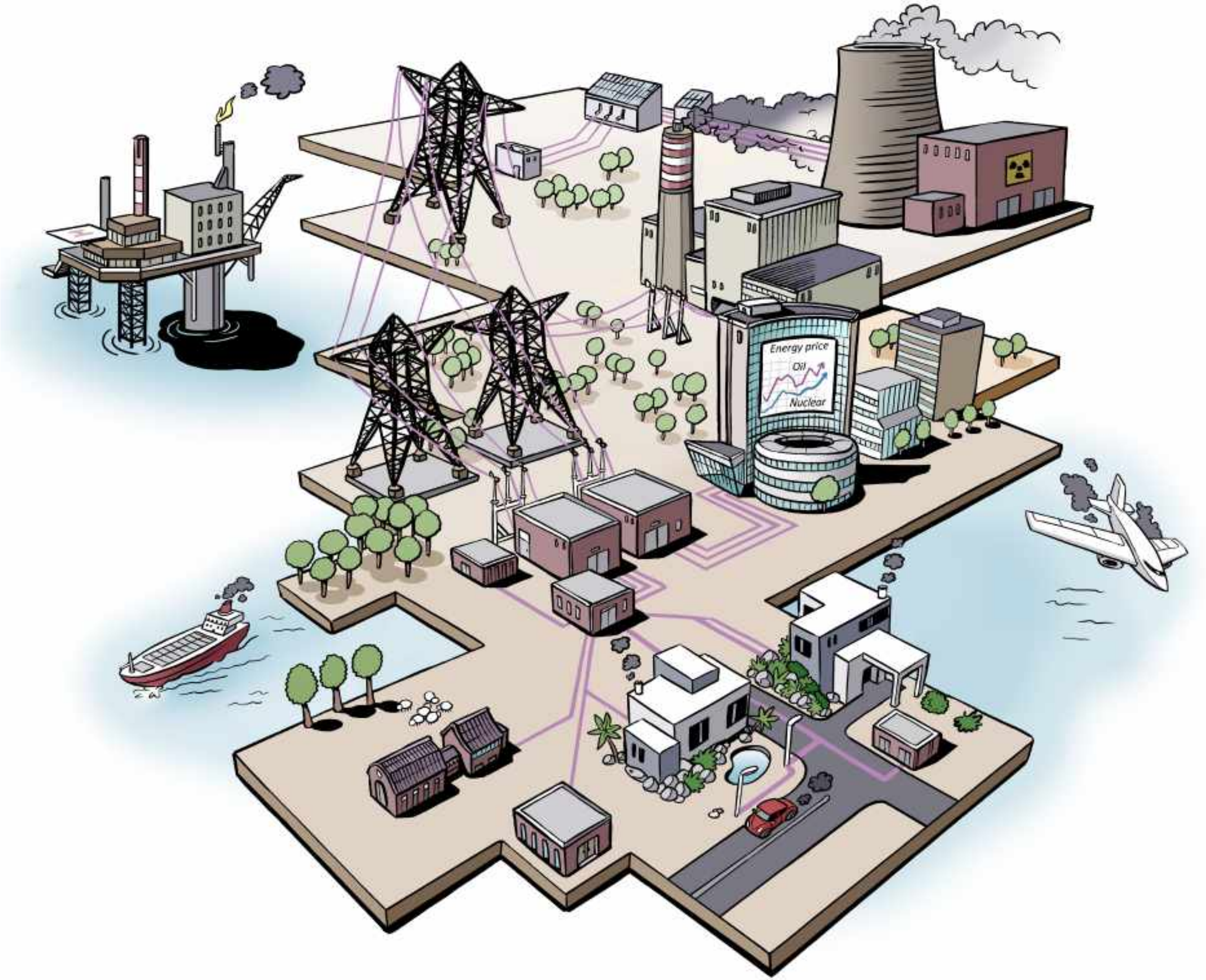
Tuesday 08 September 2020

Roadmap to DC

“From DC building to a DC distribution”

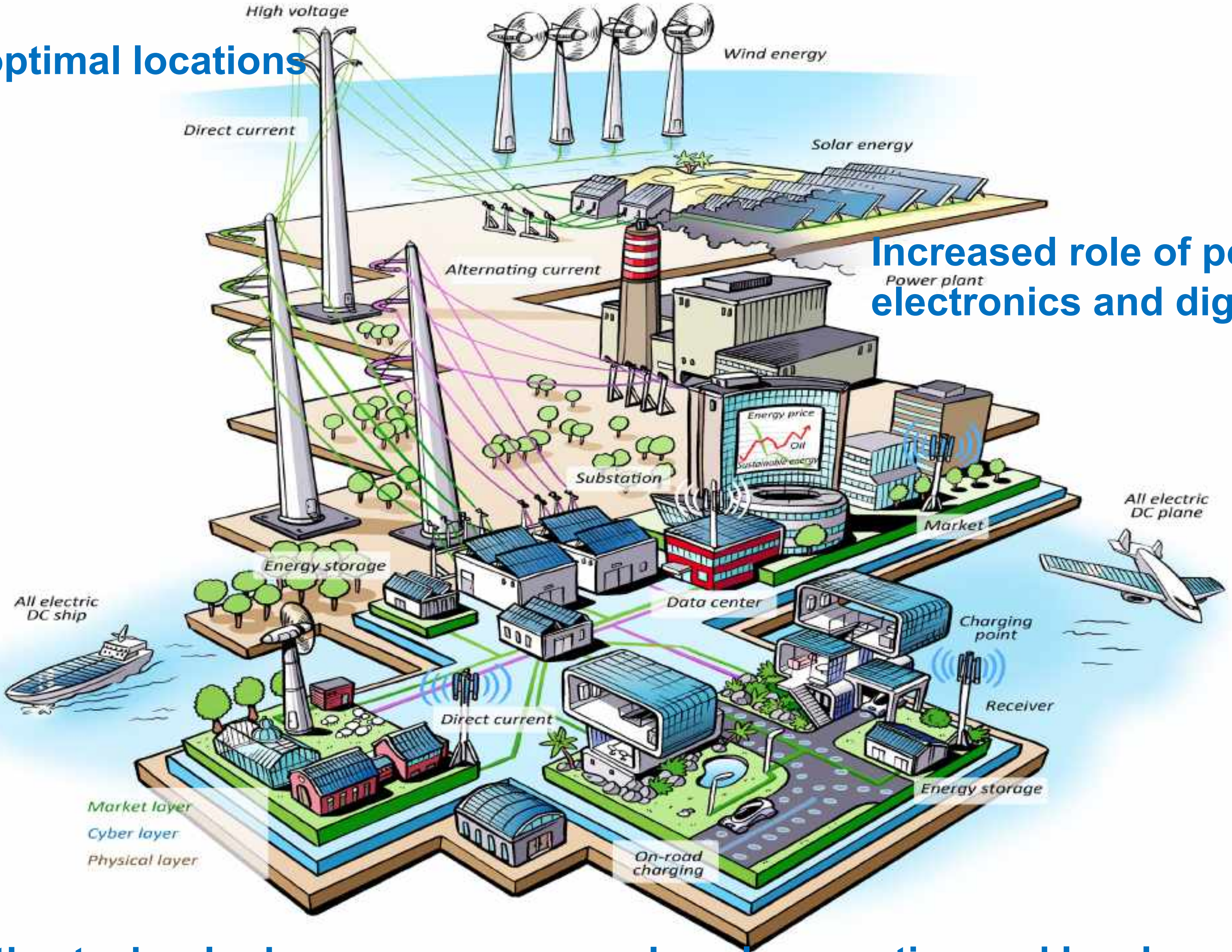
prof.dr.ir. P.Bauer
DC Systems, Energy Conversion & Storage

TUDelft


Energy price
Oil
Nuclear

RE at optimal locations

Increased role of power electronics and digitalization



Disruptive technologies

Local generation and local consumption

TU Delft

Smart grid – chance for revival of DC

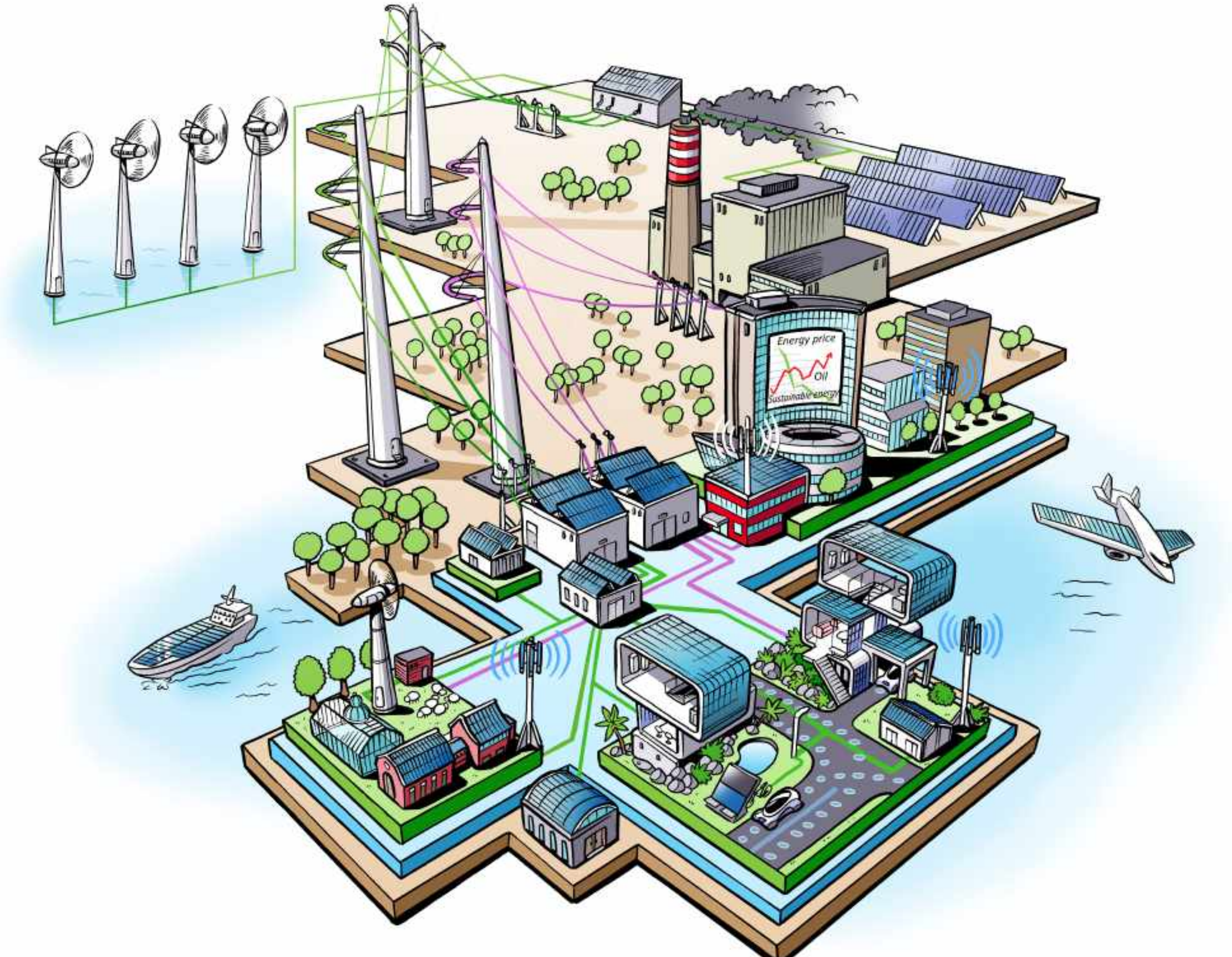
Status now?
AC grid
Control, stability, production follows demand

Impetus?
Renewables & & Electric Vehicles
Aging infrastructure

Uncertainty
- Grid Innovation
- Regulation and Policy
- Climate change
- Geo-political issues
- Public support
  - license to operate
  - customer preference

How?
- Redesign the system for (partially) DC
- Integrate storage
- System of Systems approach (social, ecological & technological)
- Interface, interaction, integration

Where we want to be?
- Sustainable, reliable high efficient, low cost distribution grid
- Grid (DC) with Renewable energy, Electric Vehicles
- Demand follows production
- Towards flexibility and modularity
- De-centralized control
- New distribution of costs & market structures
- System integration (gas&elec.)



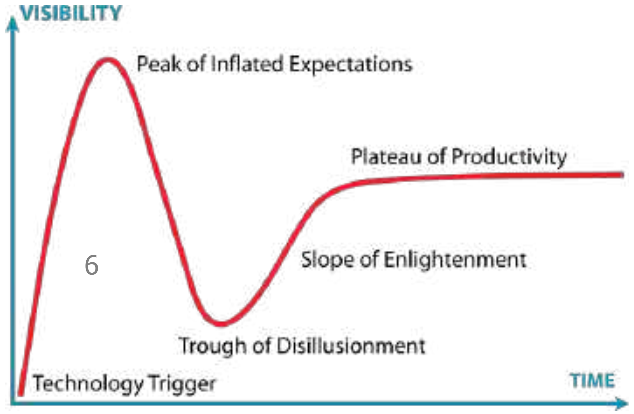
TUDelft

Why DC distribution ?

- All Renewable Energy and Storage essentially DC
- Higher system efficiency
- Lower overall investment costs

What about the transformer

- Higher System controllability (stability, resonances)
- Potential for long distance transmission
- Higher reliability
- Greater power per conductor
- Higher voltages possible



Roadmap for DC Systems

DC Nanogrids
- Radial DC feeders (lighting,trolley)
- Devices, protection, stability

DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

DC microgrids / DC links
- Towards local generation local use (storage, EVs)
- Cellular concept
- Sizing (optimization)
- Protection, grounding
- Stability of DC grids
- Optimal power flow
- Power flow controller
- Demand side management
- Data over power line
- Power management
- Markets
- harmonics

Radial DC grids
- Connecting DC microgrids
- Refurbishing the system for (partially) DC infra
- Modular converters with integrated protection
- Integrated control market approach
- Integrating cells/microgrids
- Interface, interact, integrate

Meshed DC distribution grids
- Sustainable, reliable, high efficient, low cost DC distribution grid with renewable energy, and electric vehicles
- Fexibility and modularity
- Decentralized control
- New distribution of costs, market and usage structures
- Integration of multiple energy carriers (gas&elec.)

Roadmap for DC Systems

DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

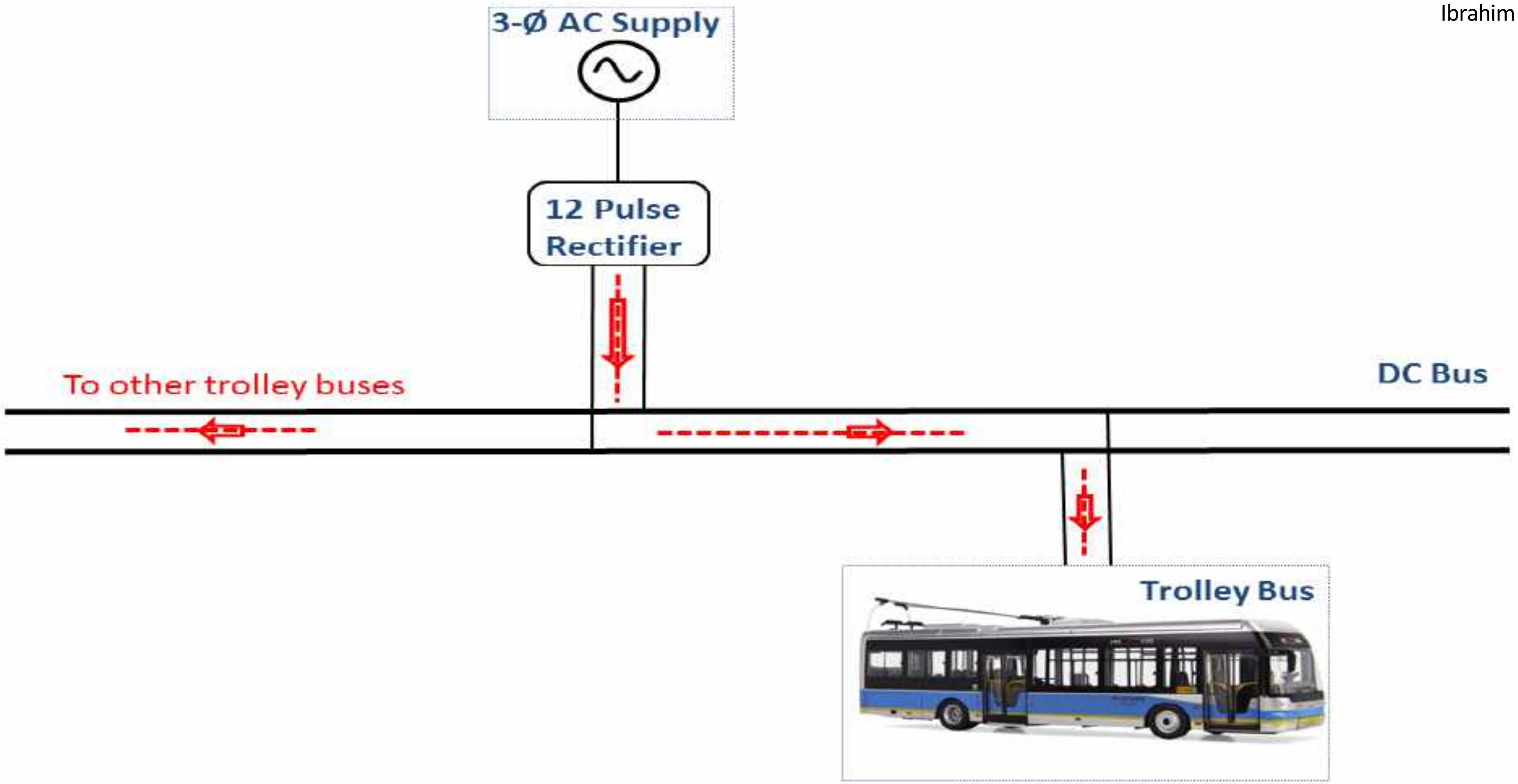
DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

Roadmap for DC Systems

DC Nanogrids
- Radial DC feeders (lighting, trolley)
- Devices, protection, stability

DC Nanogrids V2.0
- **Bidirectional power flow**
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

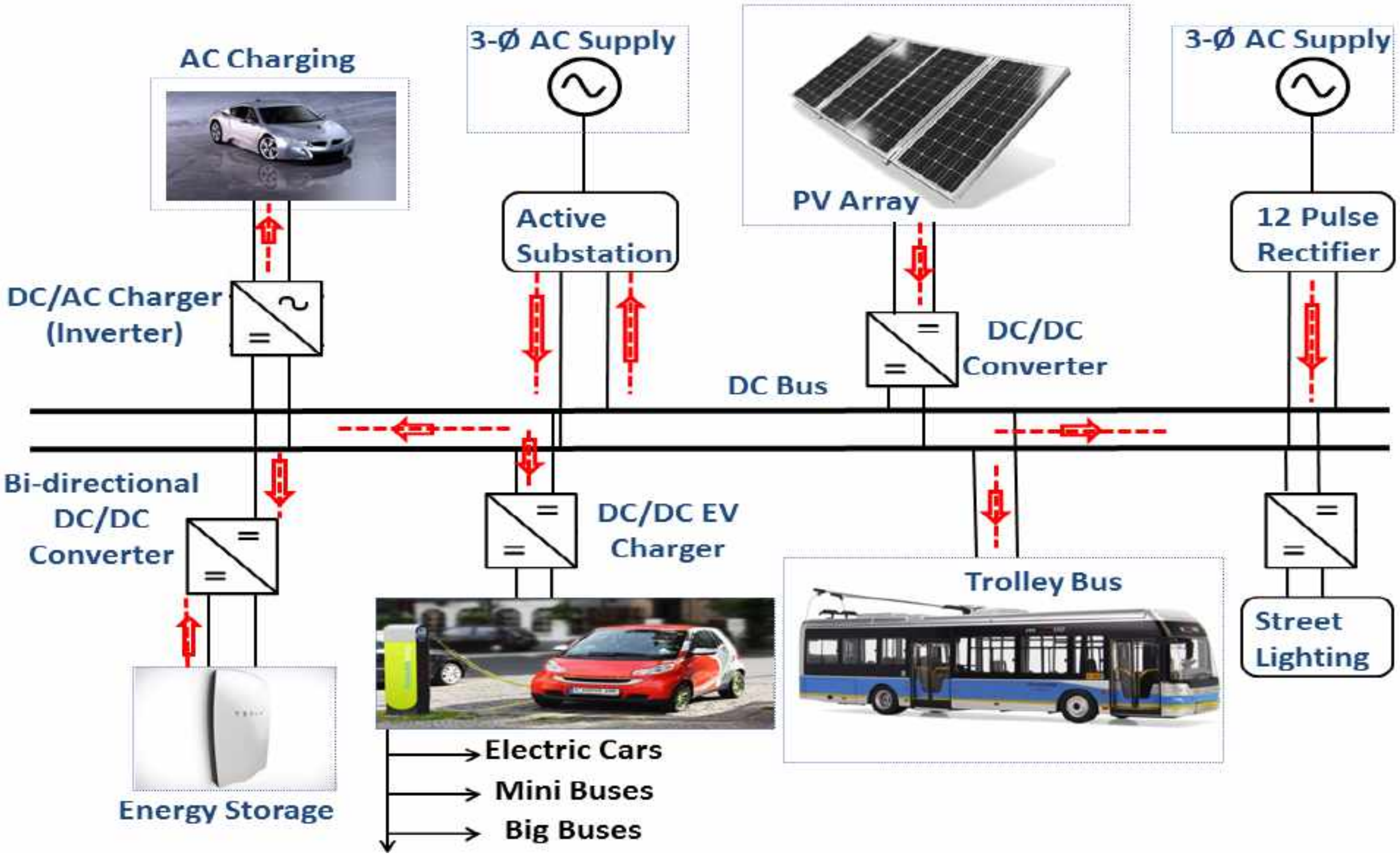
Trolley Bus Charging



Ibrahim Diab

TU Delft

Trolley Bus Charging



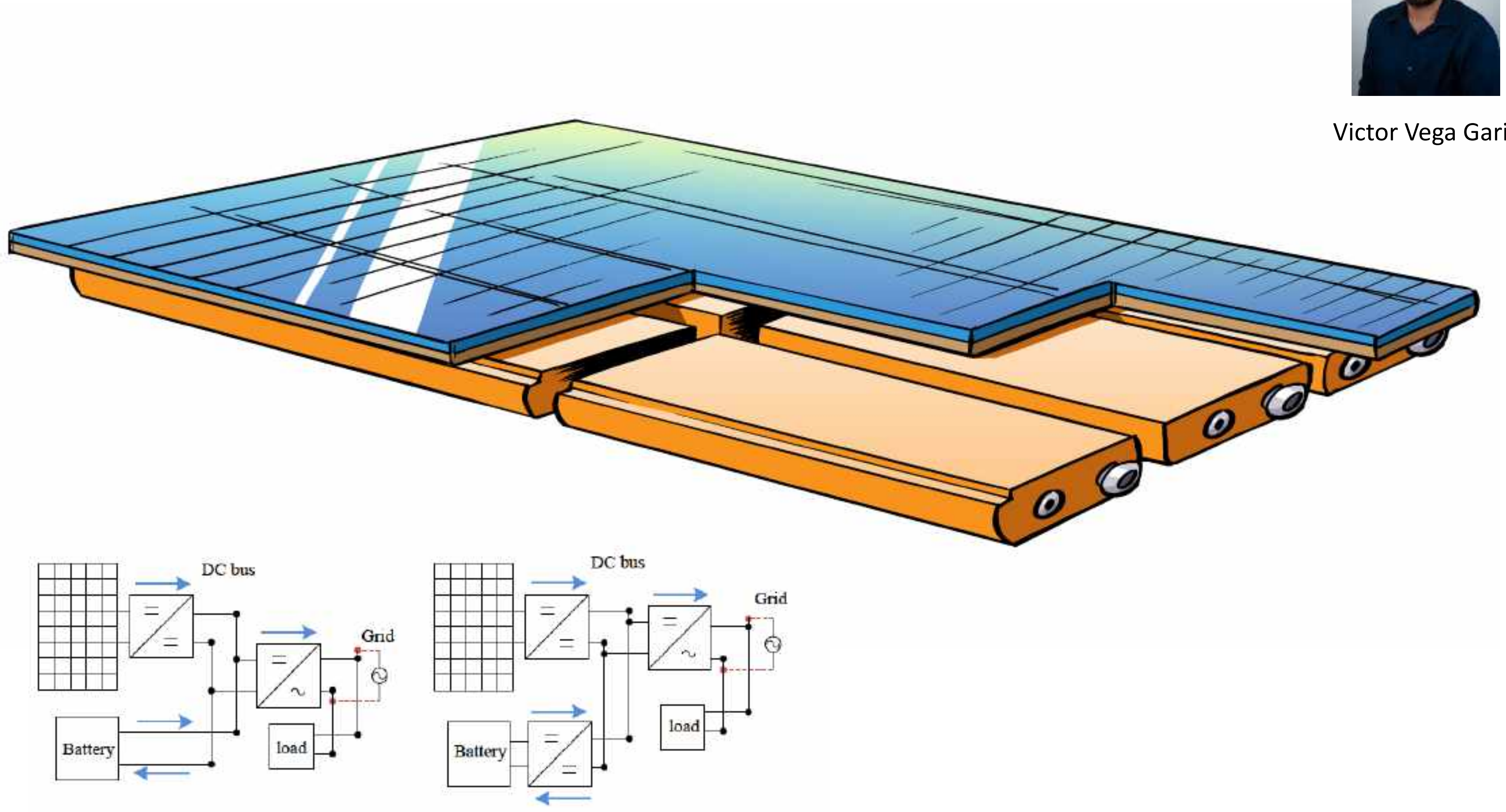
Roadmap for DC Systems

DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

DC Nanogrids V2.0
- Bidirectional power flow
- **PV and storage**
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

Integrated PV – Battery Module

Victor Vega Garita



Integrating a Photovoltaic Panel and a Battery Pack in One repository.tudelft.nl › datastream › OBJ › download

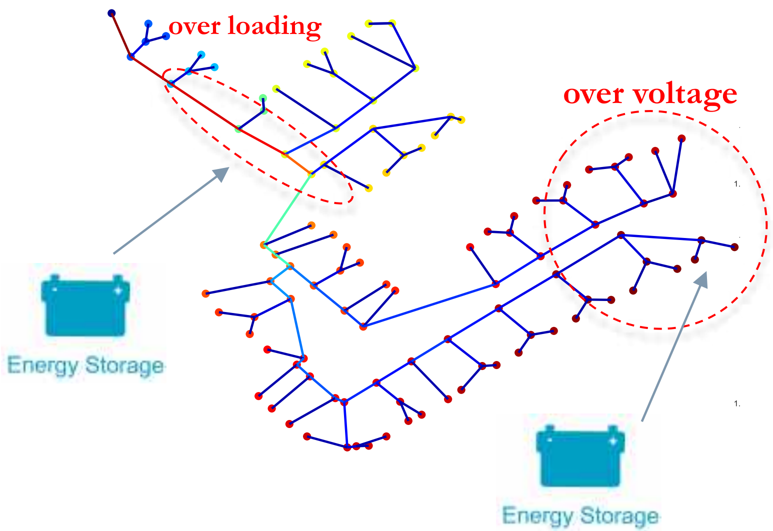
TU Delft

Battery energy Storage System Integration (Distribution Grids)

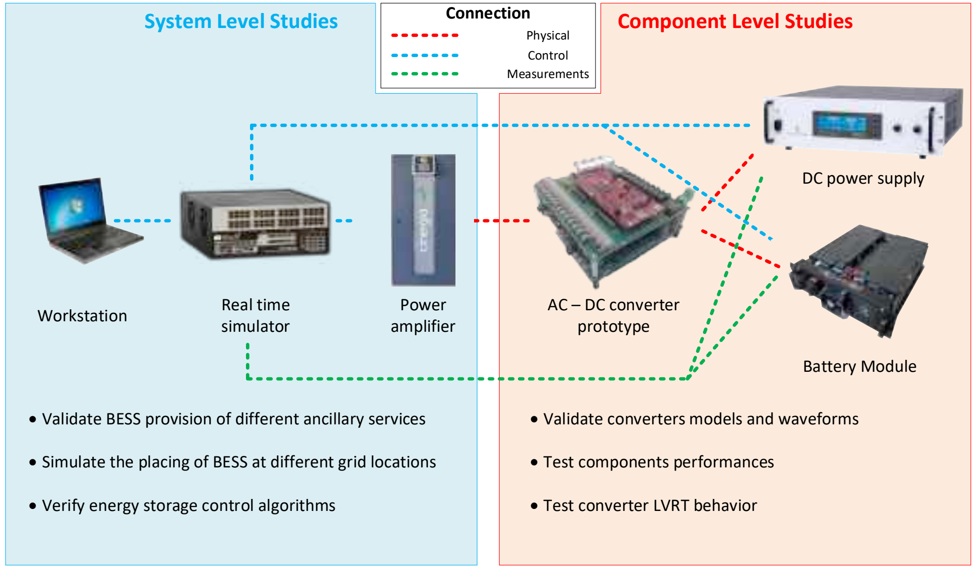
- Develop techniques for the optimal size, location and control of battery storage systems in distribution network with high penetration of Renewable Energy Sources
- Design of the energy storage power electronics converter and optimization according to the battery functionality

PhD Topic of Marco Stecca

Distribution Network Overloaded by high PV Production



Set up for the testing and validation of the storage behavior in distribution networks



TU Delft

Roadmap for DC Systems

DC Nanogrids
• Radial DC feeders (lighting)
• Devices, protection, stability

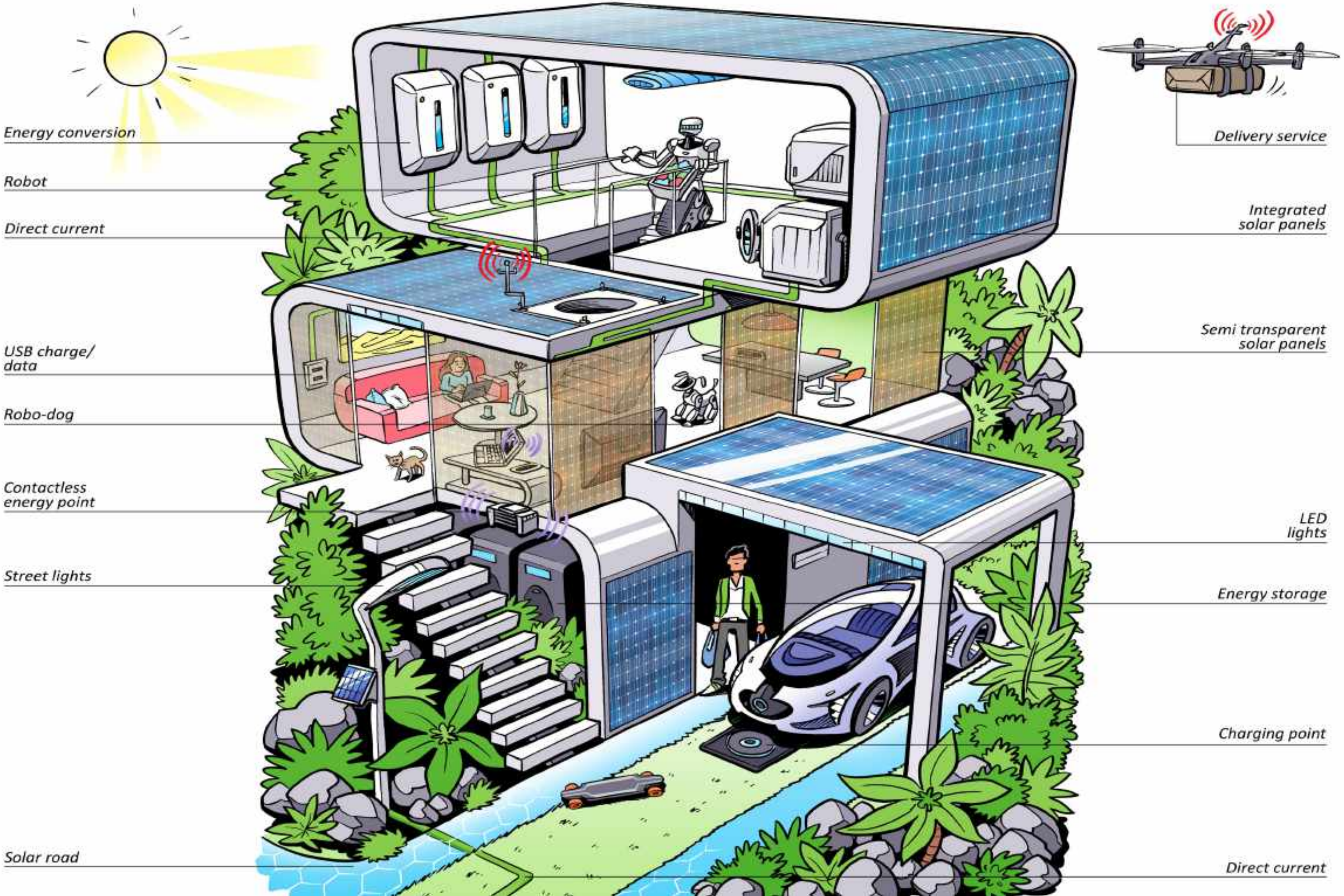
DC Nanogrids V2.0
• Bidirectional power flow
• PV and storage
• DC house nanogrid
• PV charging systems of EVs
• DC ready devices and USB power delivery
• Enable demand response

TU Delft

Roadmap for DC Systems

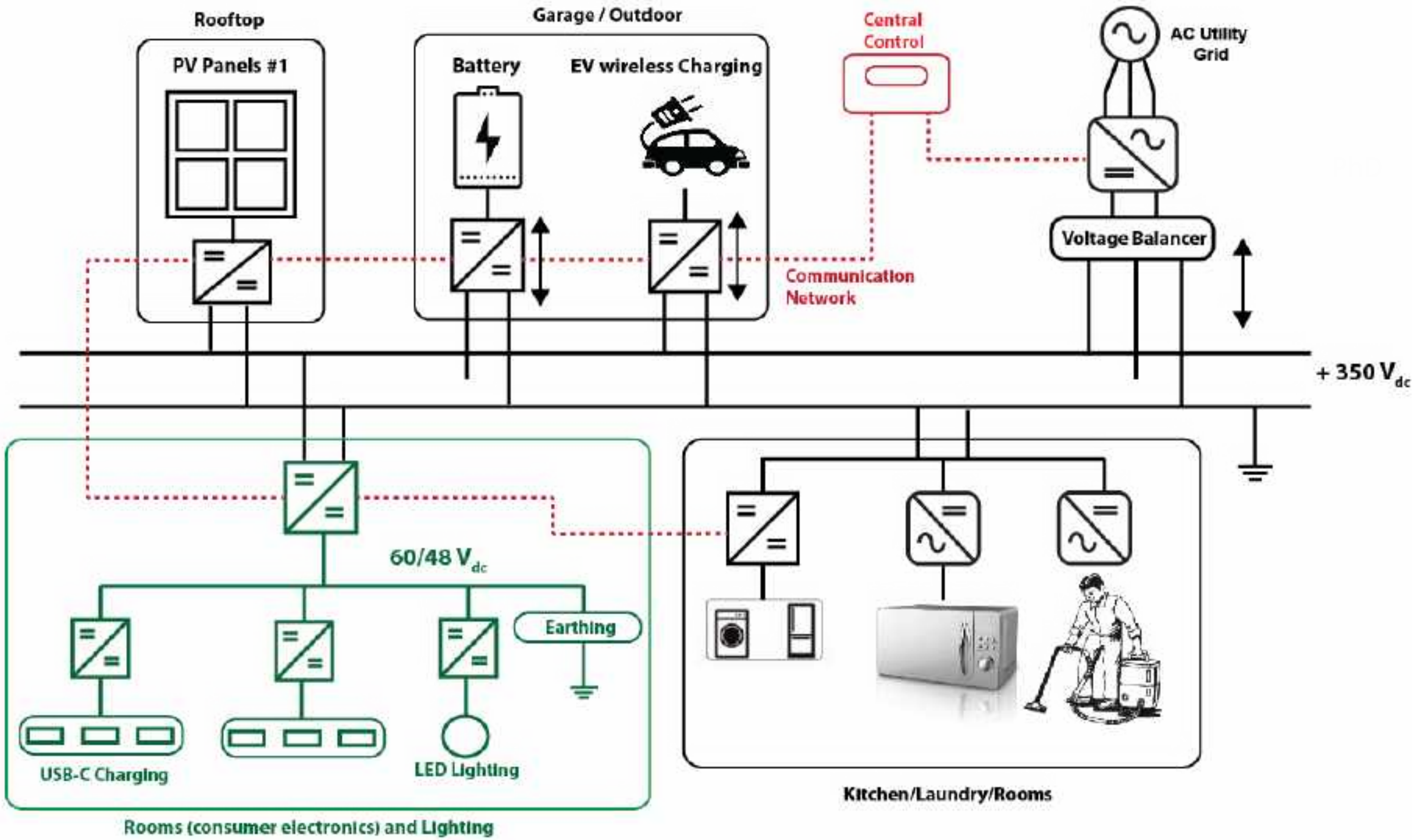
DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- **DC house nanogrid**
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response


Energy conversion
Robot
Direct current
USB charge/
data
Robo-dog
Contactless
energy point
Street lights
Solar road
Delivery service
Integrated
solar panels
Semi transparent
solar panels
LED
lights
Energy storage
Charging point
Direct current

TU Delft

'DC House Nanogrid

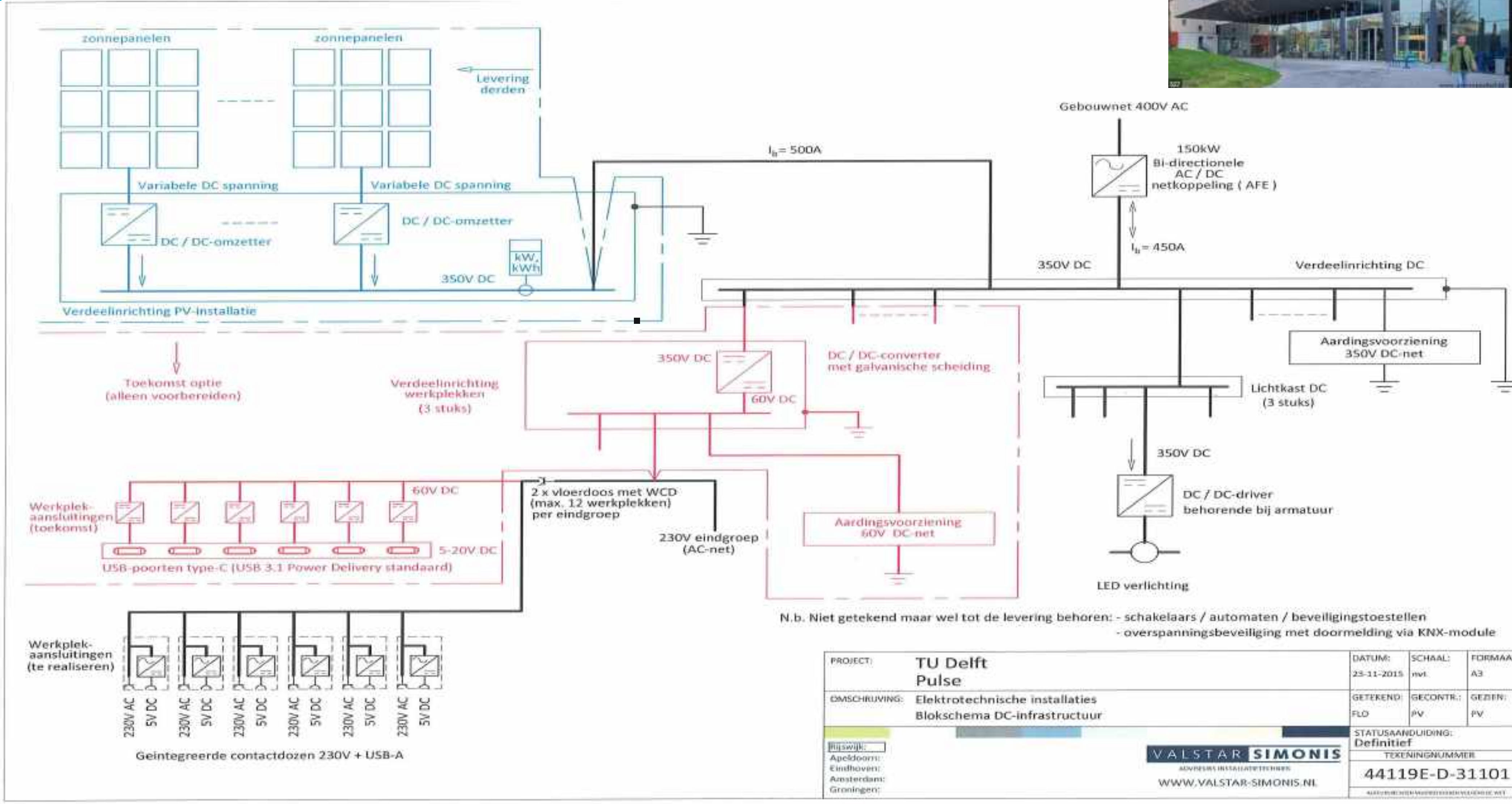


Soumya Bandyopadhyay

"To Develop Efficient and Intelligent Residential Nanogrids Suitable for Future Smart Grid Integration"

TU Delft

Pulse Building TU Delft



Current AC System Layout

Functions

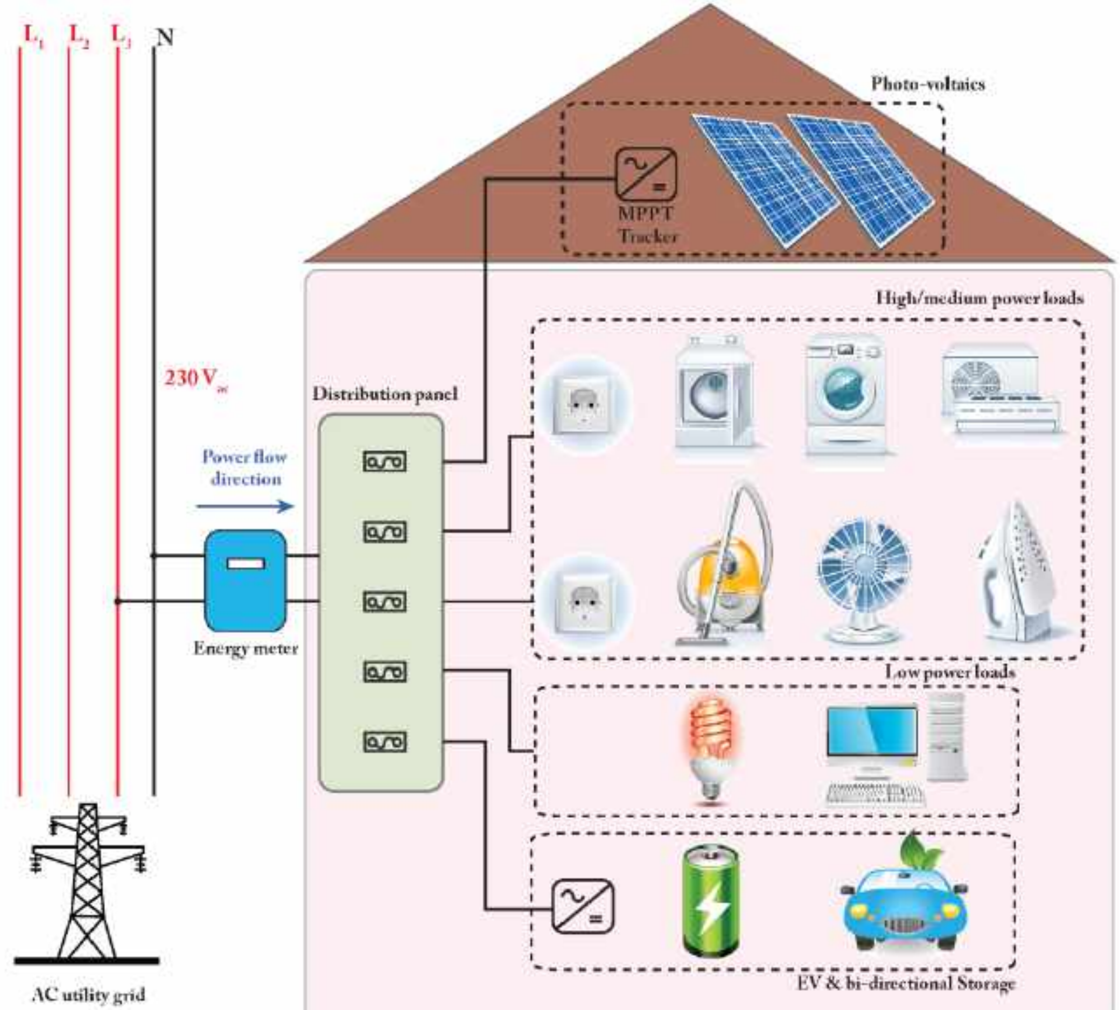
Energy efficiency

Availability and reliability

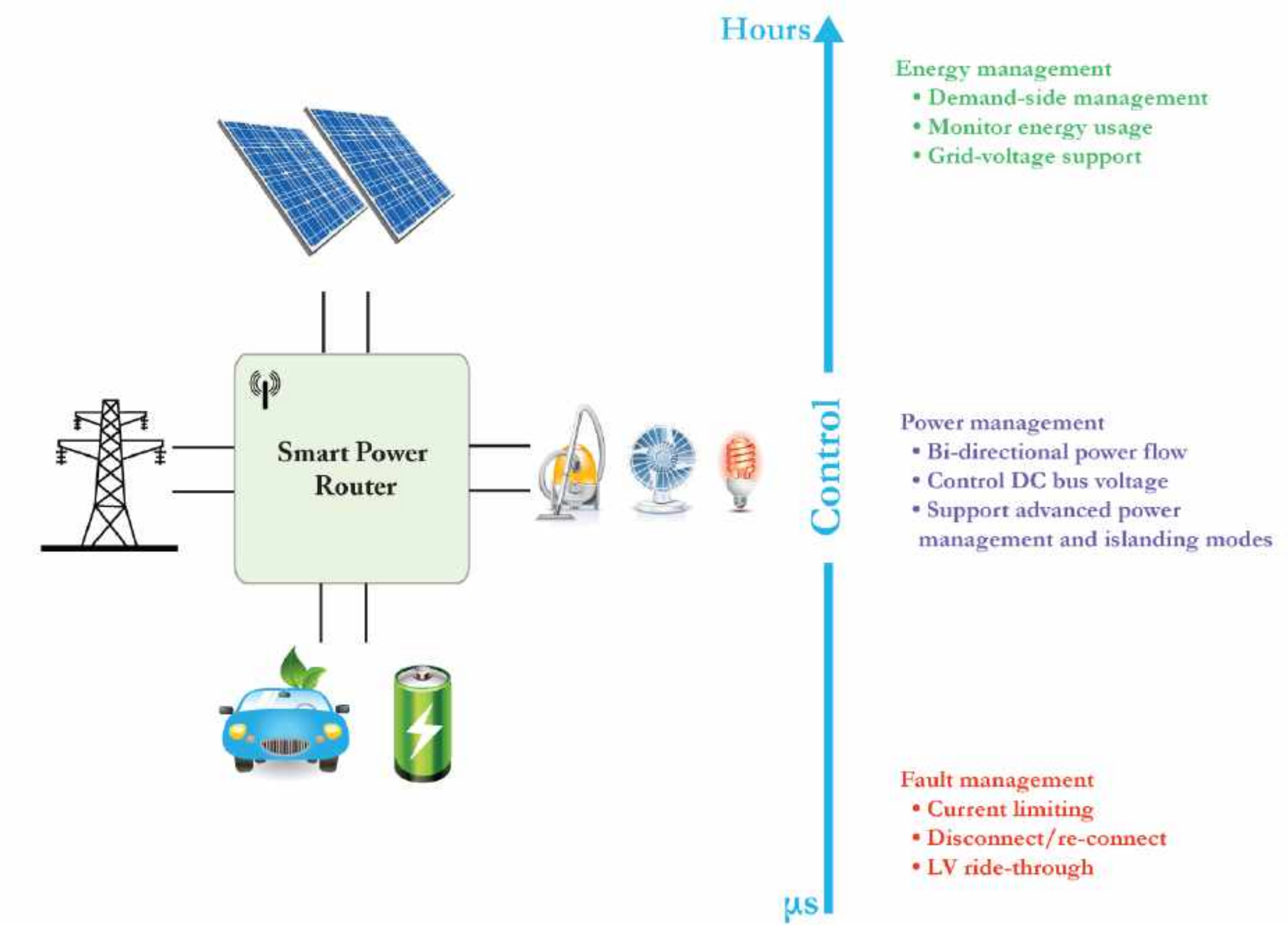
Co-ordinated control

Grid-support capability

Scalability



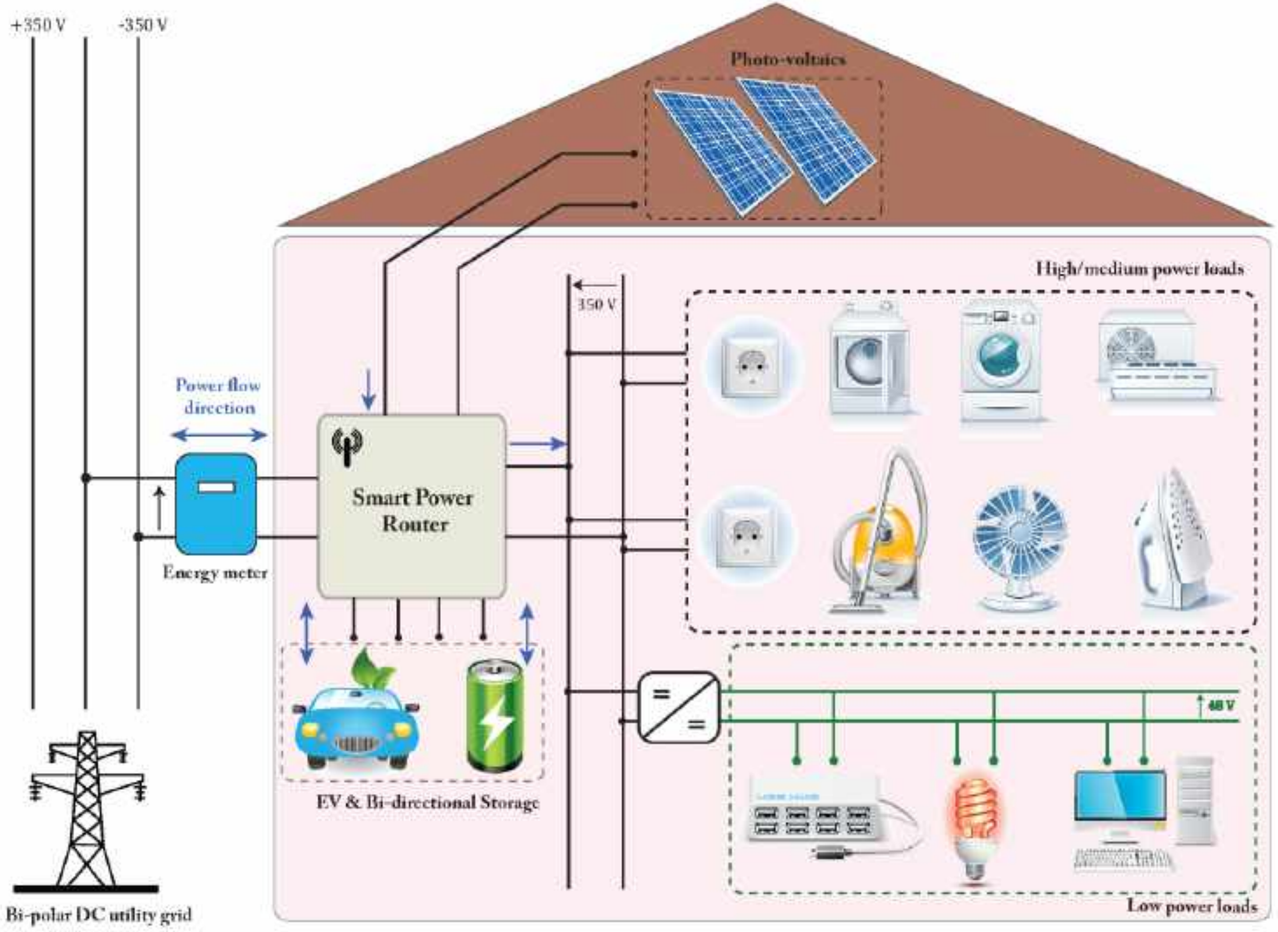
Solution: Smart Power Router



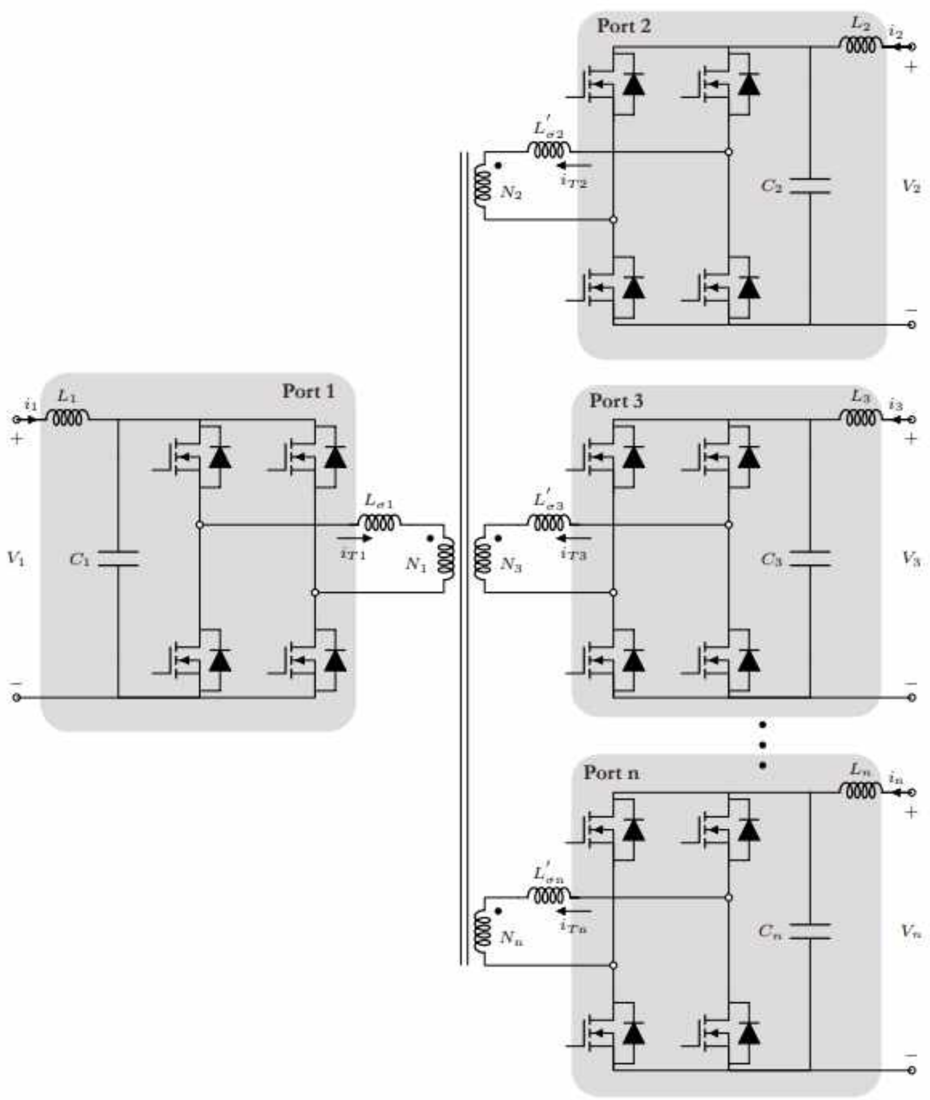
Novel DC House Architecture

Functions

- Energy efficiency
- Availability and reliability
- Co-ordinated control
- Grid-support capability
- Scalability

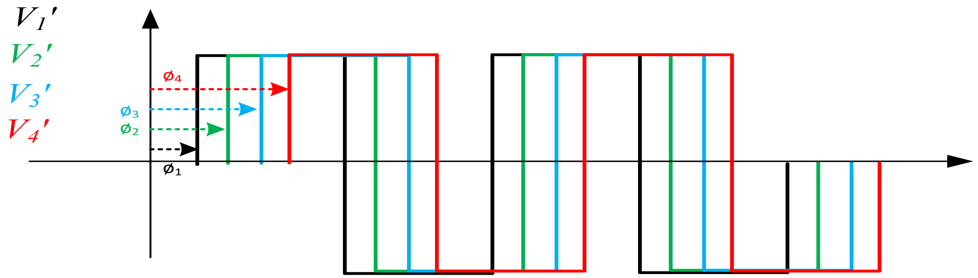


Multi-active bridge (MAB) converter



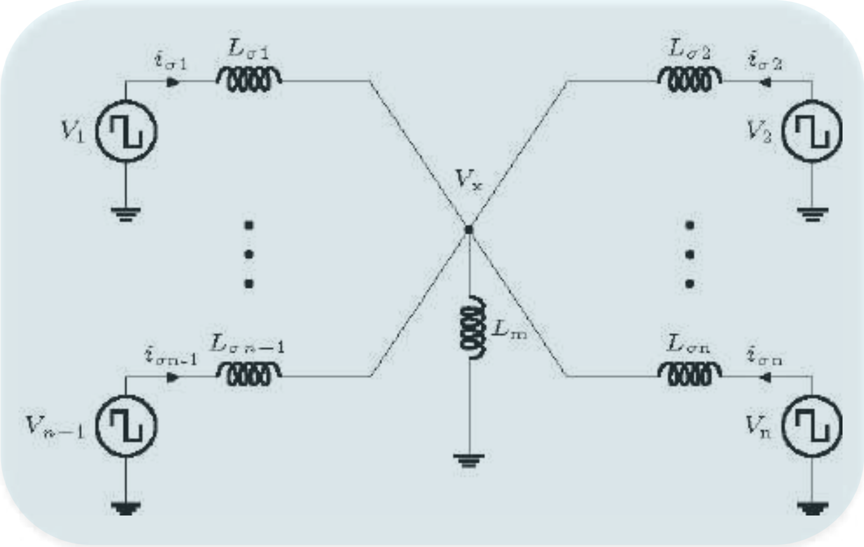
- **Features:**

1. Immune to grid outages or faults
2. Low footprint on the grid
3. Possibility to support the grid
4. Decentralized grid ready

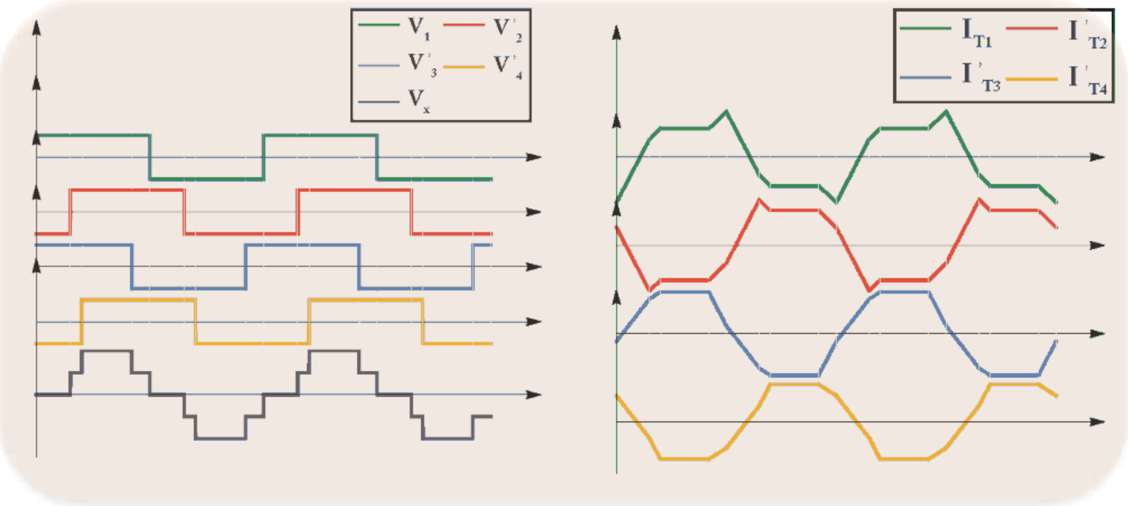


MAB Converter Operation

Equivalent circuit



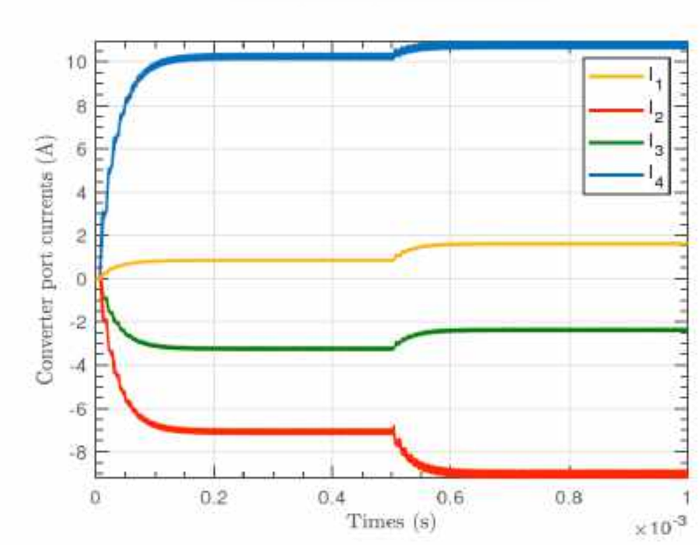
Switching waveforms



Power Flow Equation

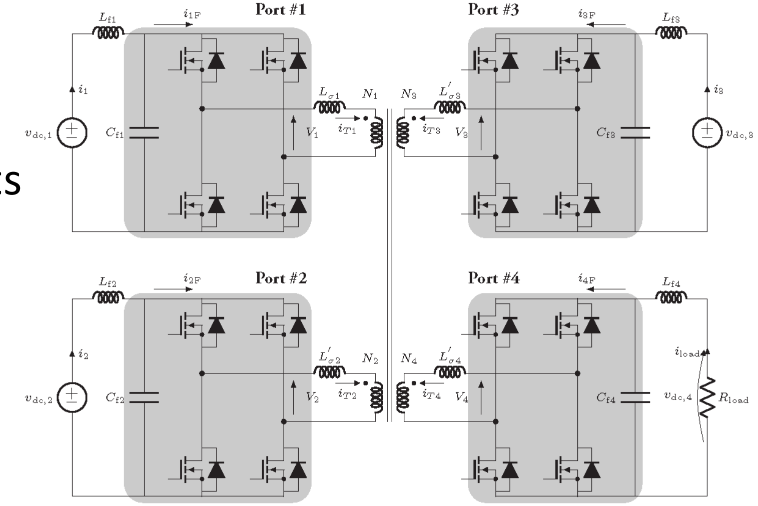
$$P_{ij} = \frac{V_i' V_j'}{2\pi f_s L_{ij}} \phi_{ij} \left(1 - \frac{|\phi_{ij}|}{\pi}\right), \qquad \phi_{ij} = \phi_i - \phi_j$$

Coupled power flows



Critical Review of State of the Art

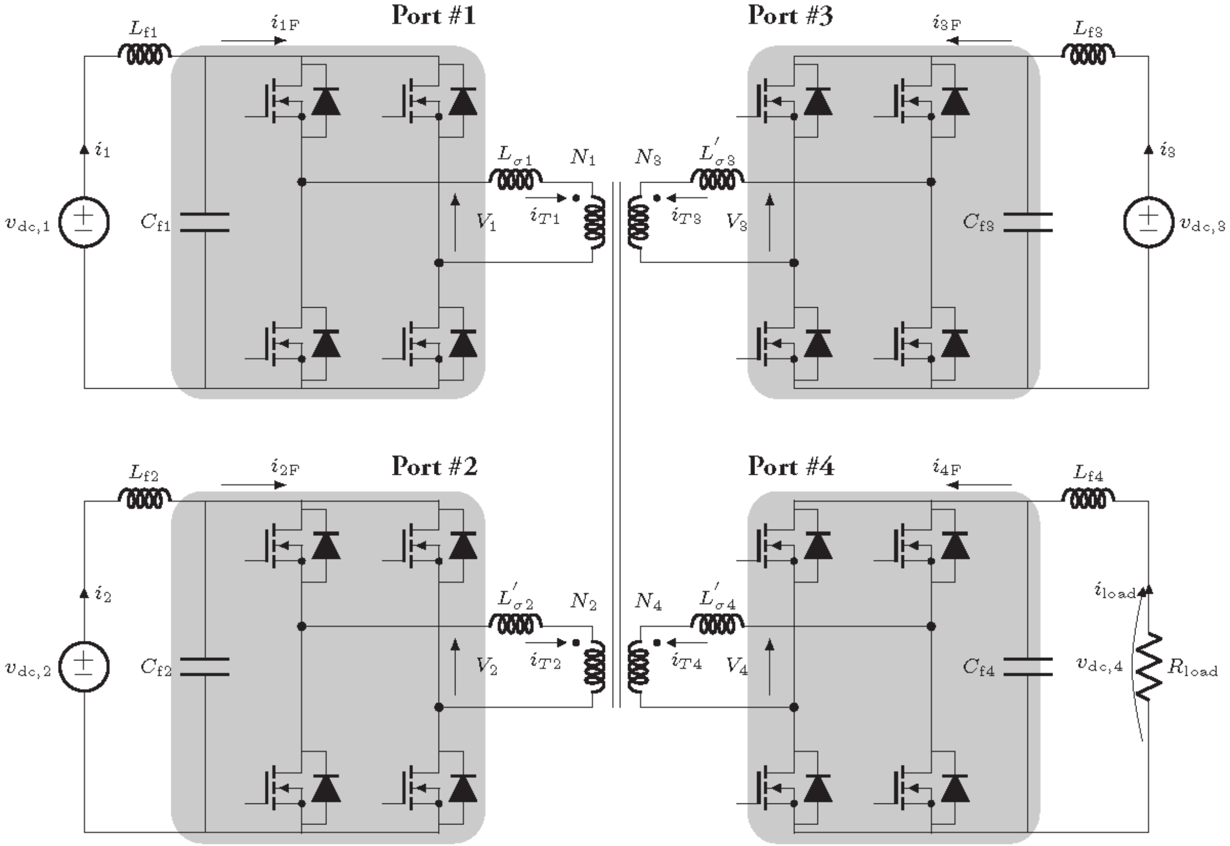
- Power flow complexity increases with number of ports
- High computational requirement for control
- Transformer design is challenging



Number of Ports	Possible Power Flows
2	2
3	12
4	26

TU Delft

Coupling problem in MAB Converter



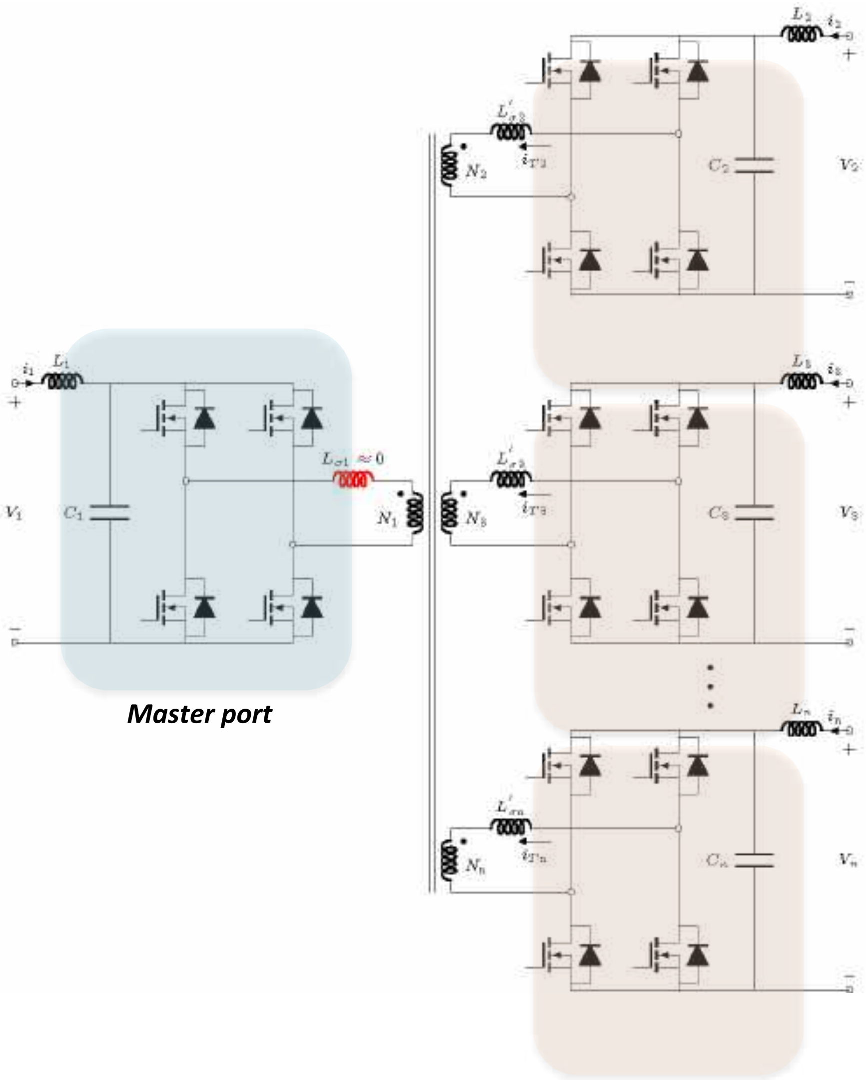
$$\begin{bmatrix} i_{2F} \\ i_{3F} \\ i_{4F} \end{bmatrix} = \begin{bmatrix} G_{22} & G_{23} & G_{23} \\ G_{32} & G_{33} & G_{34} \\ G_{42} & G_{43} & G_{44} \end{bmatrix} \begin{bmatrix} \phi_2 \\ \phi_3 \\ \phi_4 \end{bmatrix}$$

$$\begin{aligned} G_{ij} &= \sum_{p \neq i}^{n} \frac{V_{p,A}}{2\pi f_s L_{ip}} \left(1 - \frac{2|\phi_{i,A} - \phi_{p,A}|}{\pi}\right) && \forall [i = j] \\ &= -\frac{V_{j,A}}{2\pi f_s L_{ij}} \left(1 - \frac{2|\phi_{j,A} - \phi_{i,A}|}{\pi}\right) && \forall [i \neq j] \end{aligned}$$

$$L_{ij} = \begin{cases} 0, & \forall i = j \\ L'_{\sigma i} + L'_{\sigma j} + L'_{\sigma i} L'_{\sigma j} \left(\sum_{k \neq i,j}^{n} \frac{1}{L'_{\sigma k}} \right), & \forall i \neq j \end{cases}$$

S BANDYOPADHYAY, P Purgat, Z Qin, P Bauer: A Multi-Active Bridge Converter with Inherently Decoupled Power Flows
IEEE Transactions on Power Electronics

Decoupling Solution



Master port

Slave port

$$L_{ij} = \begin{cases} 0, & \forall i = j \\ L'_{\sigma i} + L'_{\sigma j} + L'_{\sigma i} L'_{\sigma j} \left(\sum_{k \neq i,j}^{n} \frac{1}{L'_{\sigma k}} \right), & \forall i \neq j \end{cases}$$

$$L_{ij} = \begin{cases} 0, & i = j \\ L'_{\sigma j}, & i = 1, j \neq 1 \\ L'_{\sigma i}, & i \neq 1, j = 1 \\ \infty, & i \neq 1, j \neq 1, i \neq j \end{cases}$$

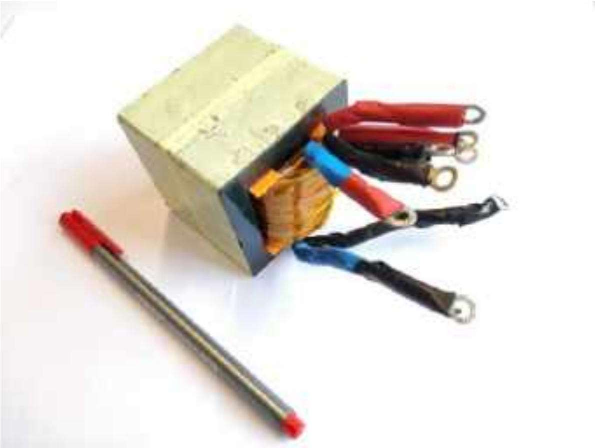
Master - Slave

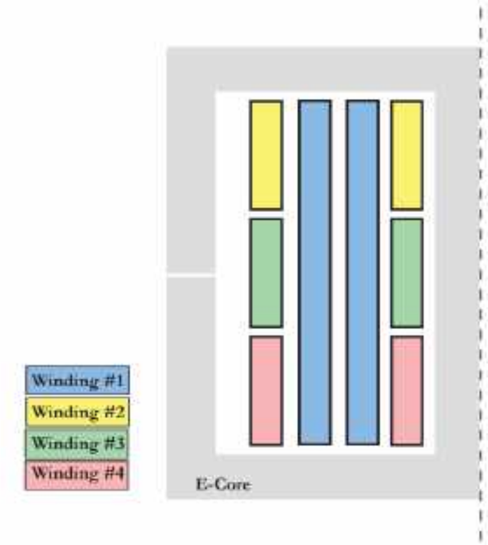
Slave - Slave

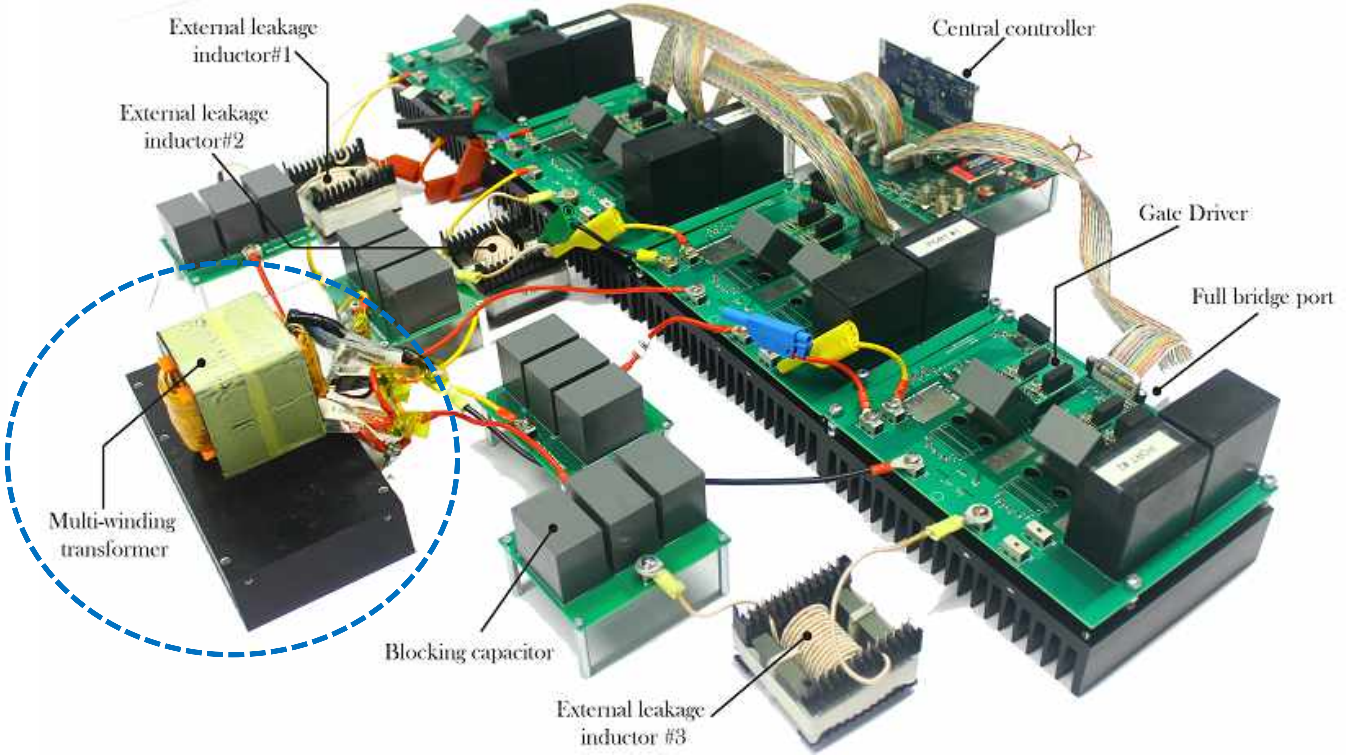
$$\begin{bmatrix} i_{2F} \\ i_{3F} \\ i_{4F} \end{bmatrix} = \begin{bmatrix} G_{22} & 0 & 0 \\ 0 & G_{33} & 0 \\ 0 & 0 & G_{44} \end{bmatrix} \begin{bmatrix} \phi_2 \\ \phi_3 \\ \phi_4 \end{bmatrix}$$

S.Bandyopadhyay, P. Purgat, Z. Qin and P. Bauer, "A Multi-Active Bridge Converter with Inherently Decoupled Power Flows," in *IEEE Transactions on Power Electronics*,

Experimental prototype





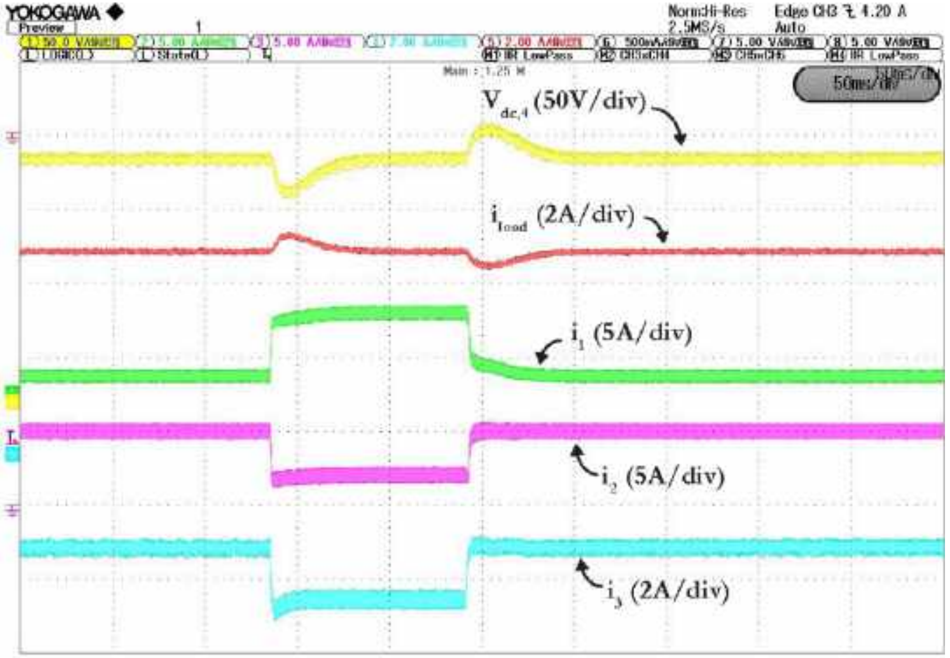


- **Features:**

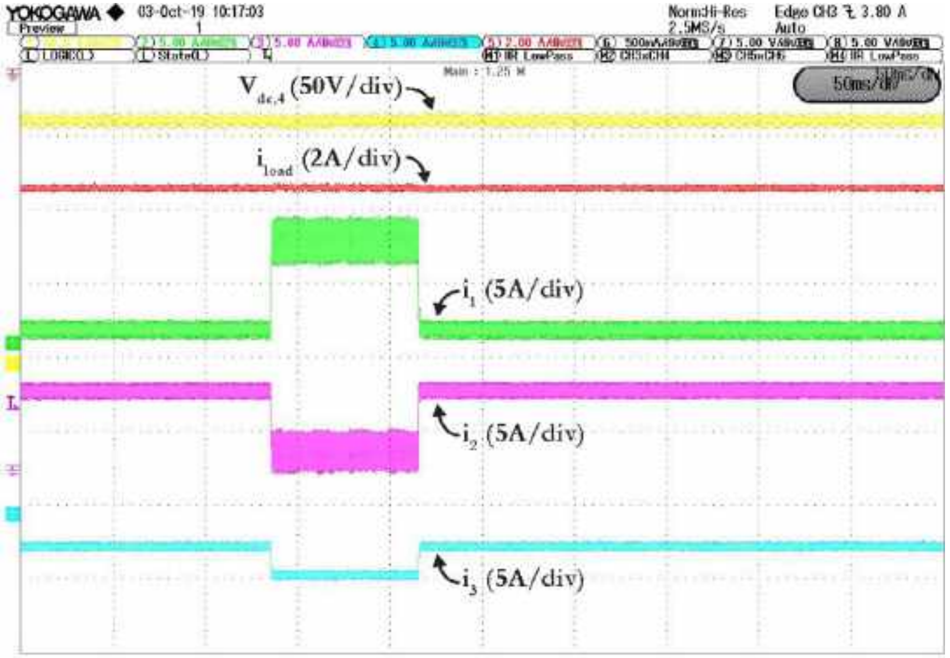
1. 5 kW, 350 V, 100 kHz
2. In house gate-driver design
3. Si-C modules
4. Four bi-directional ports

TUDelft

Decoupling performance



Conventional MAB converter dynamics



Proposed MAB converter dynamics

Roadmap for DC Systems

DC Nanogrids
• Radial DC feeders (lighting)
• Devices, protection, stability

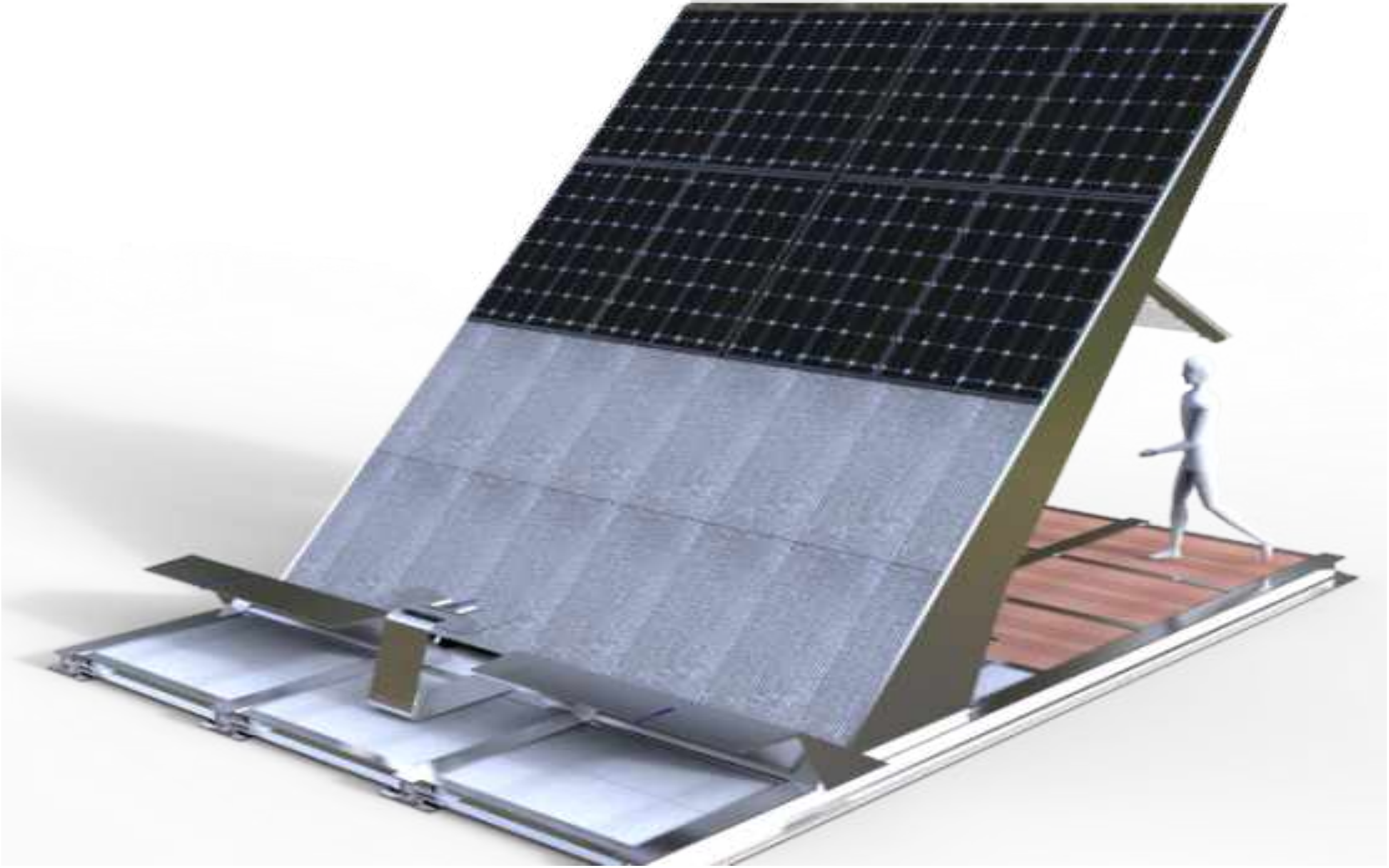
DC Nanogrids V2.0

• Bidirectional power flow
• PV and storage
• DC house nanogrid
• **PV charging systems of EVs**
• DC ready devices and USB power delivery
• Enable demand response

TU Delft

PV for smart cities applications

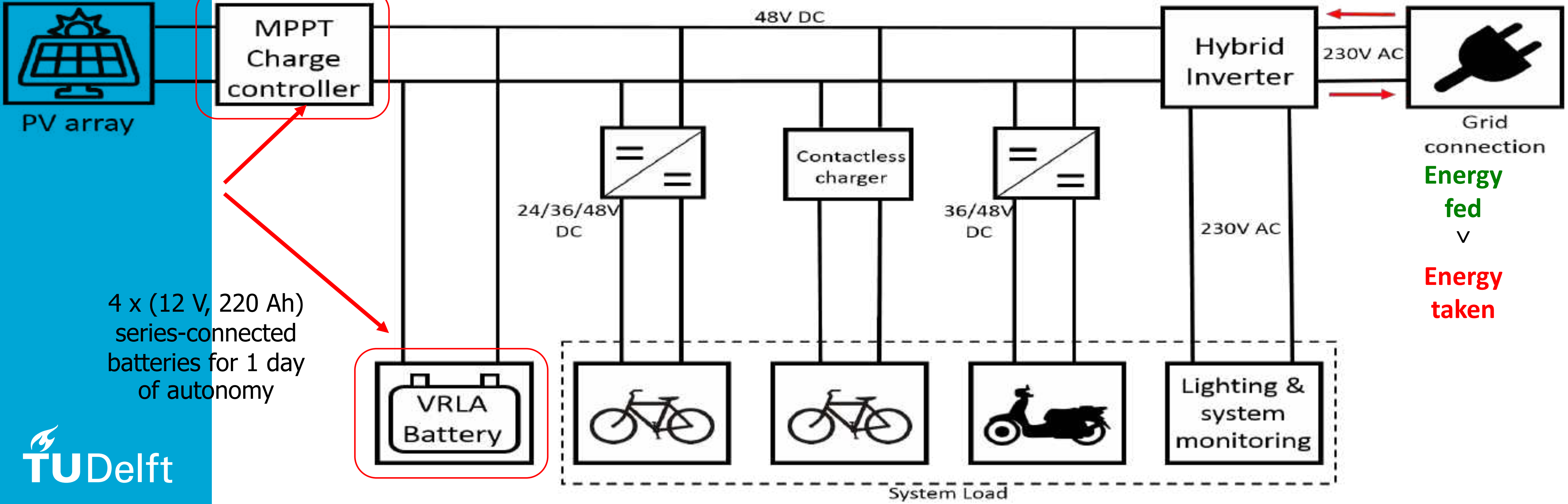
Solar Powered Electrical Bike and Scooter Charging Station



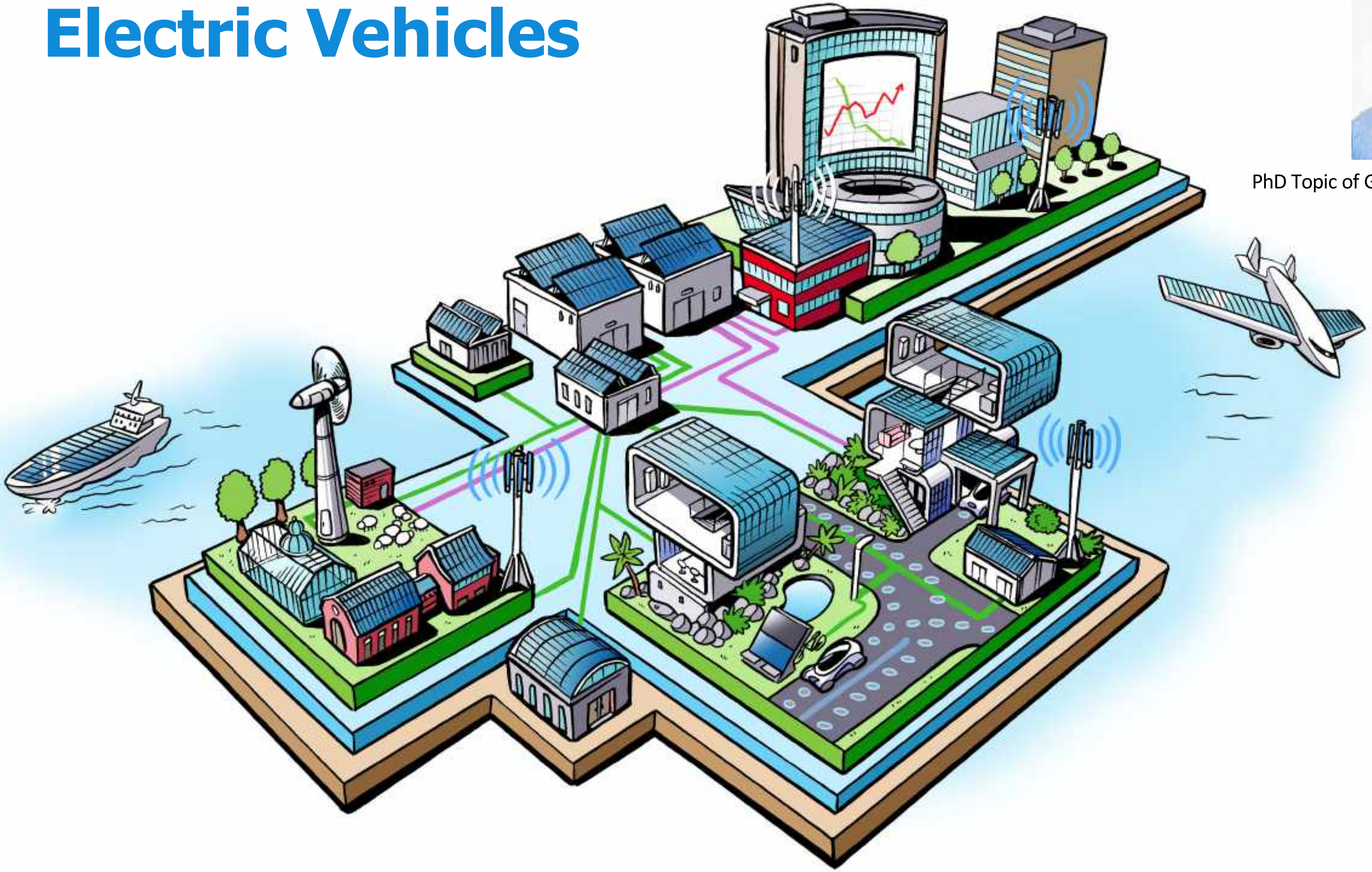
PV for smart cities applications

Solar Powered Electrical Bike and Scooter Charging Station

System topology



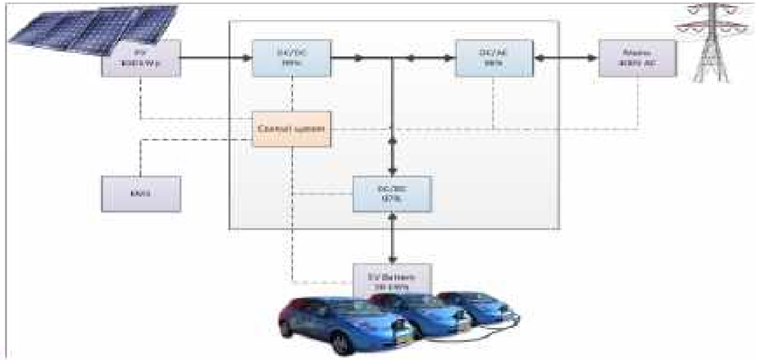
Electric Vehicles

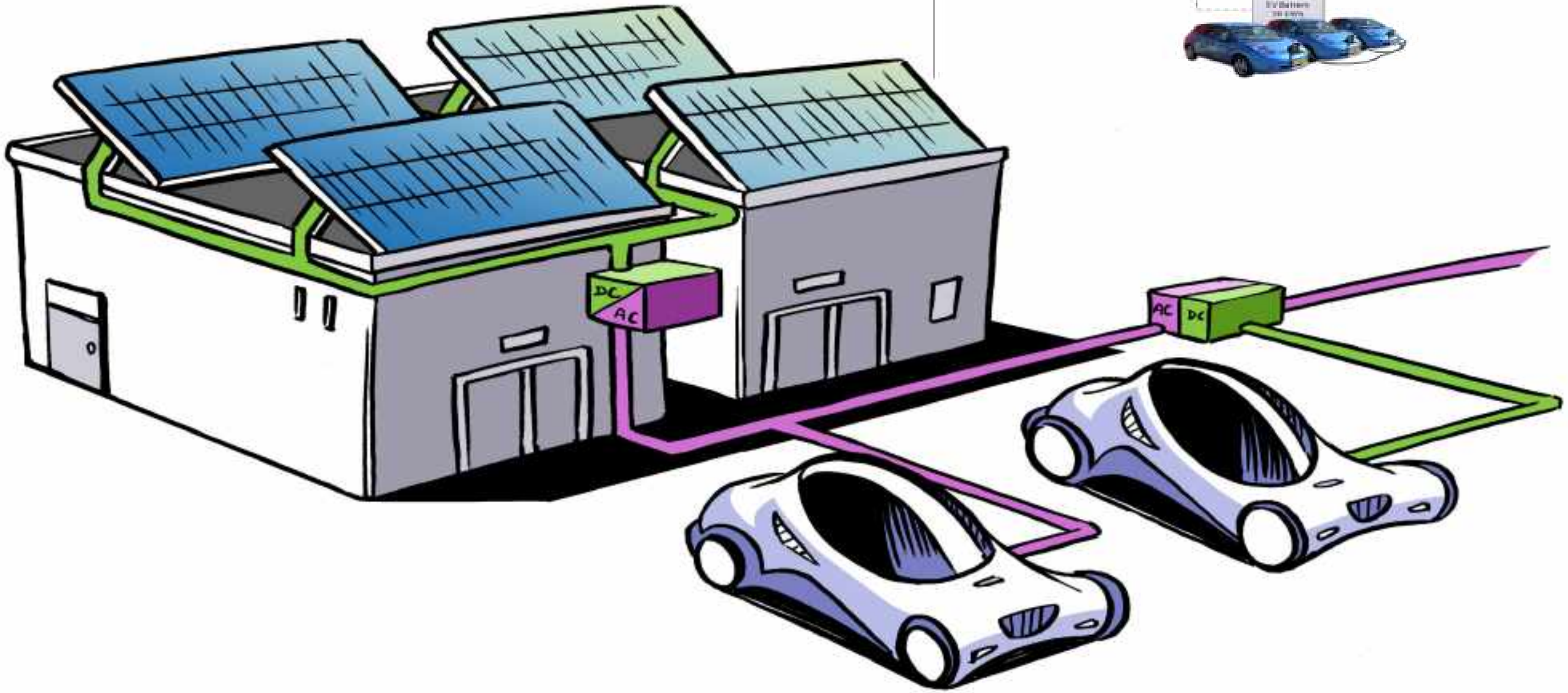


PhD Topic of Gautham Mouli

TUDelft

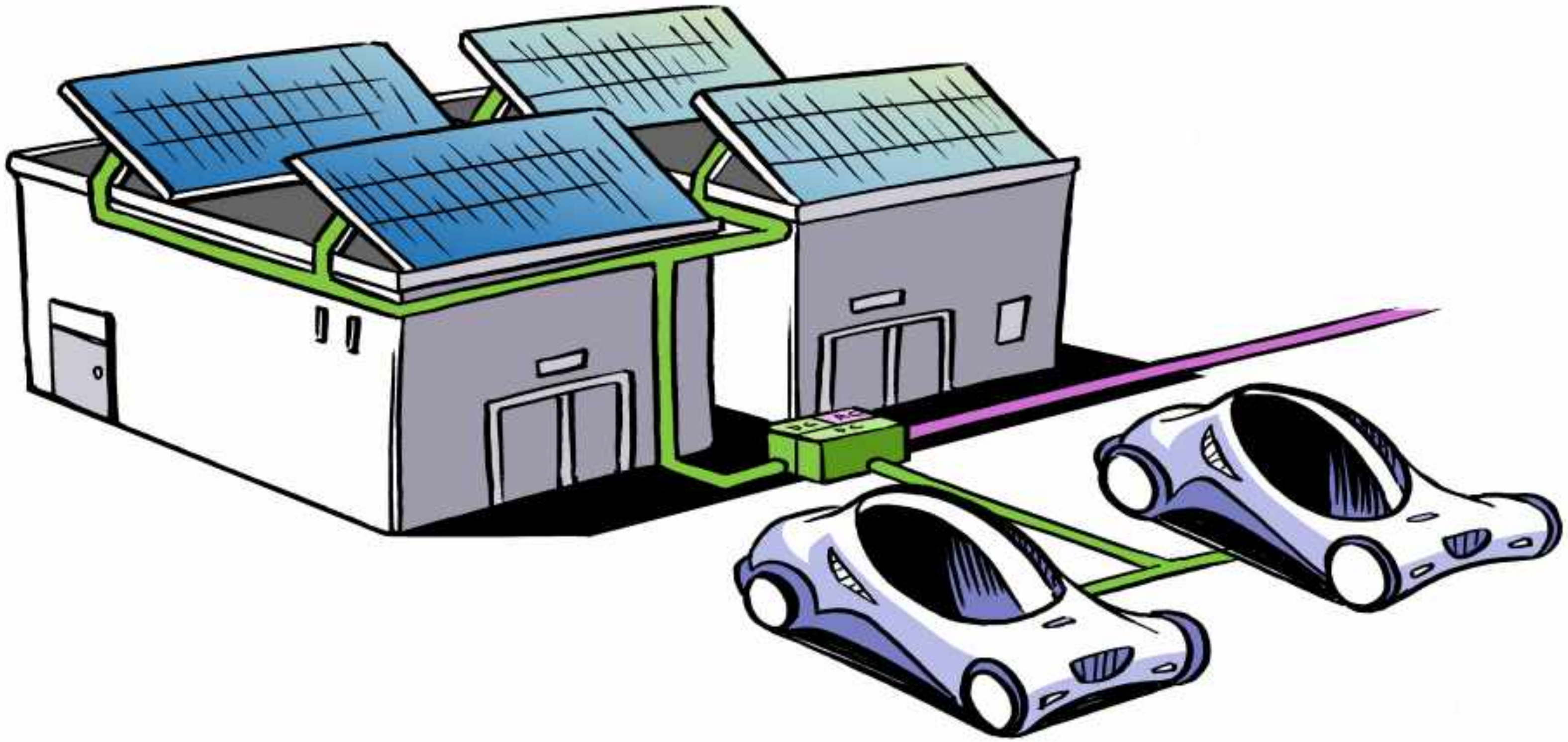
PV Charging of Electric Vehicles





PhD Gautam Ram

PV Charging of Electric Vehicles



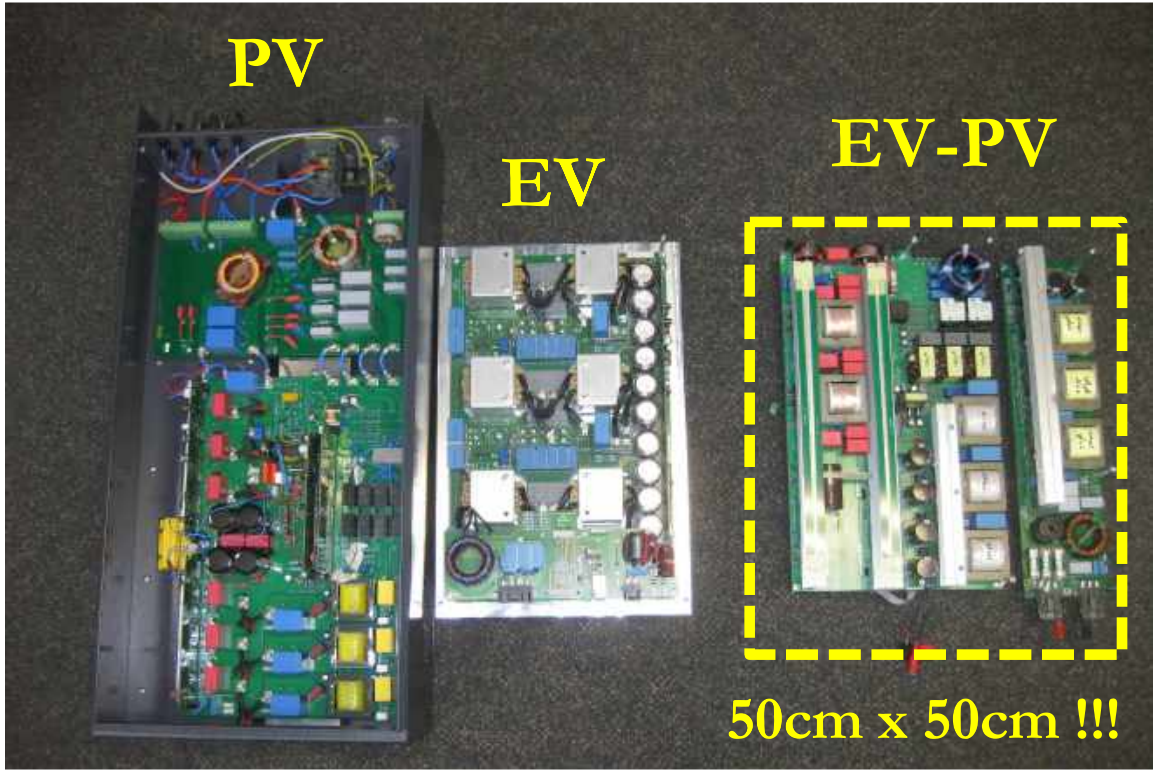
PhD Gautam Ram

TU Delft

10kW EV-PV power converter

- Higher power density
- Higher efficiency
- Bidirectional EV charging

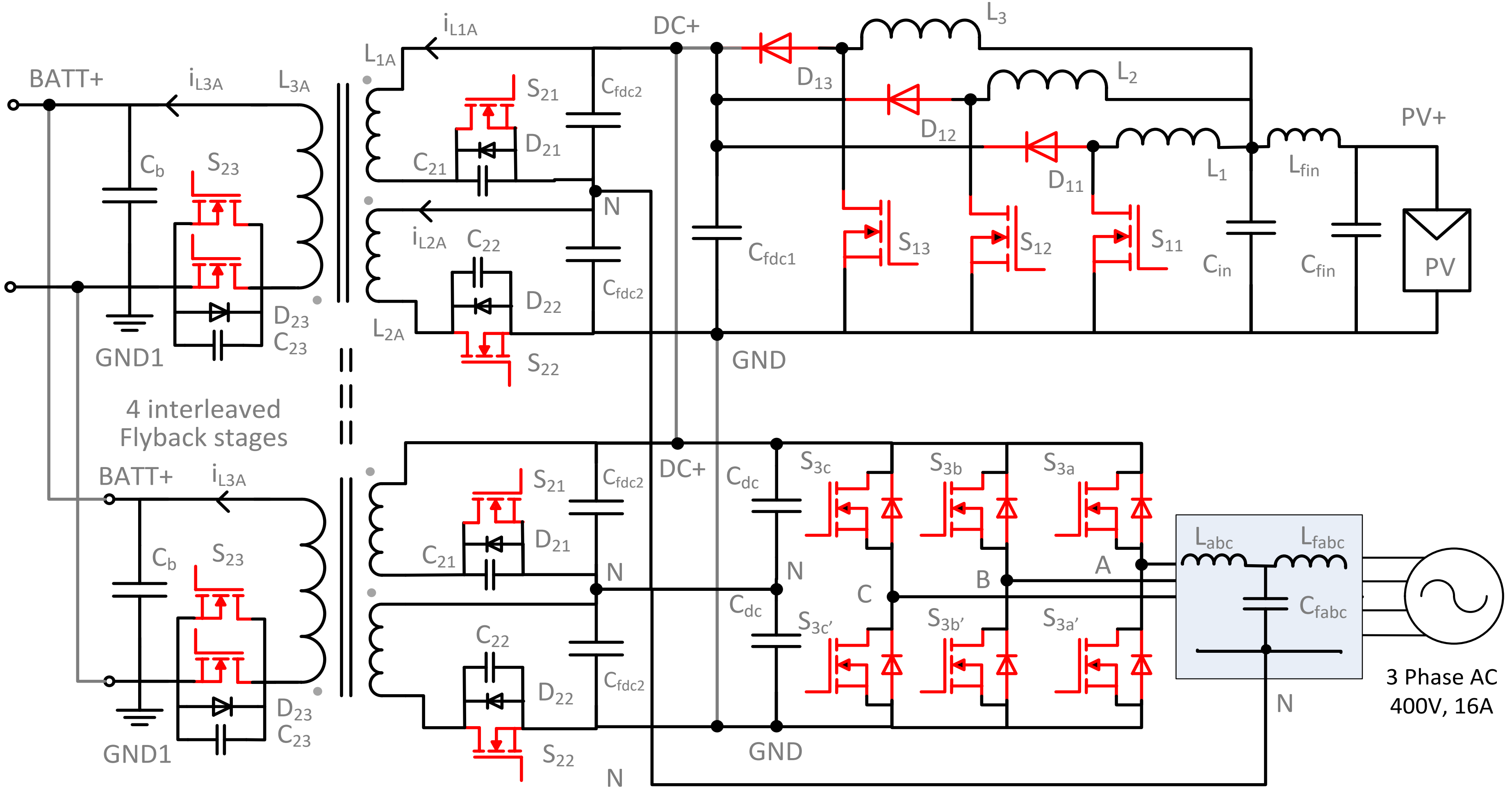
- SiC MOSFET
- SiC diode
- Powdered alloy inductors



TU Delft

EV-PV power converter

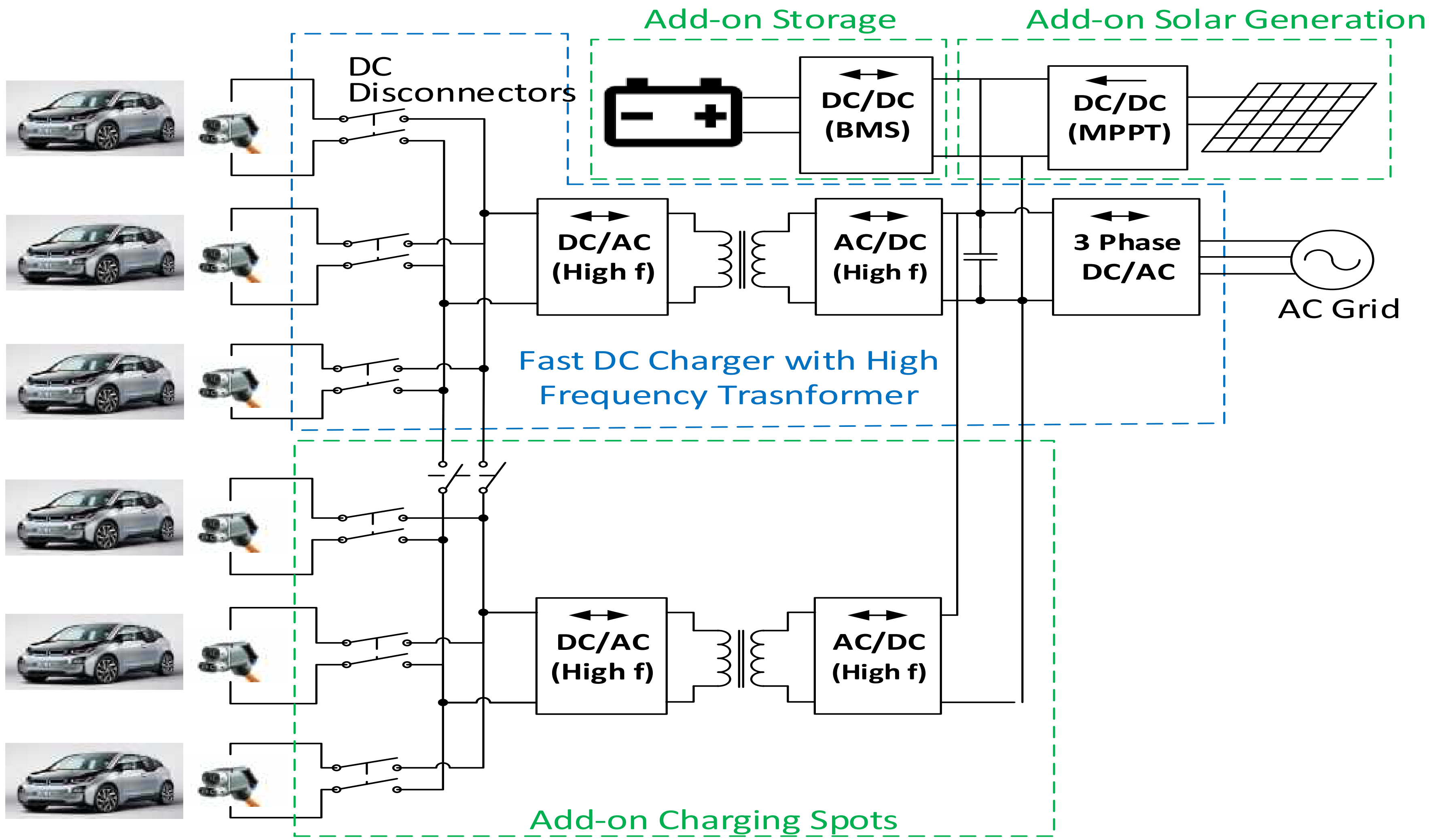
Interleaved boost converter (IBC)



TUDelft

Winners of the EV Award Presented at the IDTechEx Show! Berlin

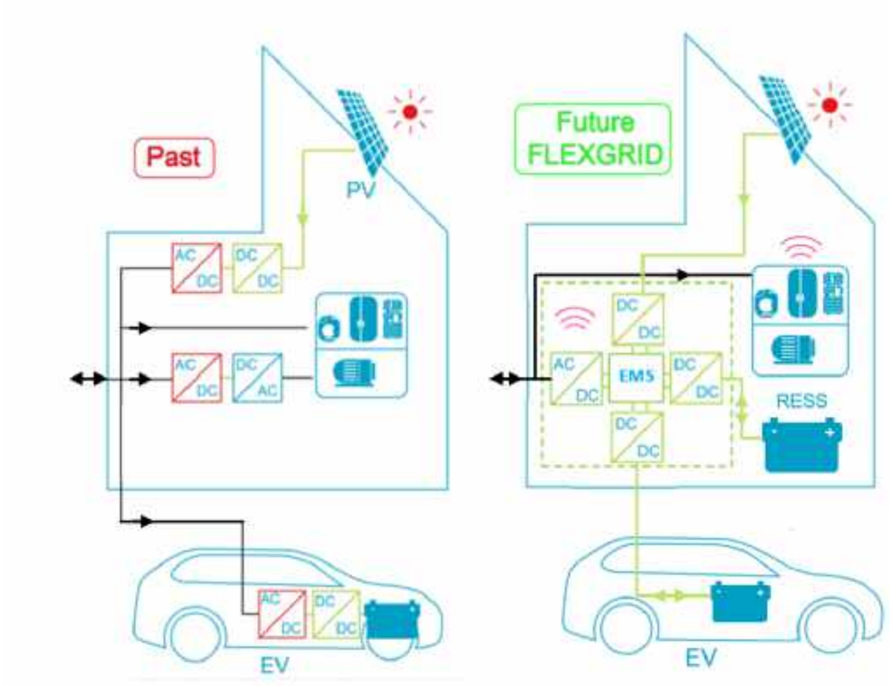
DC Charging

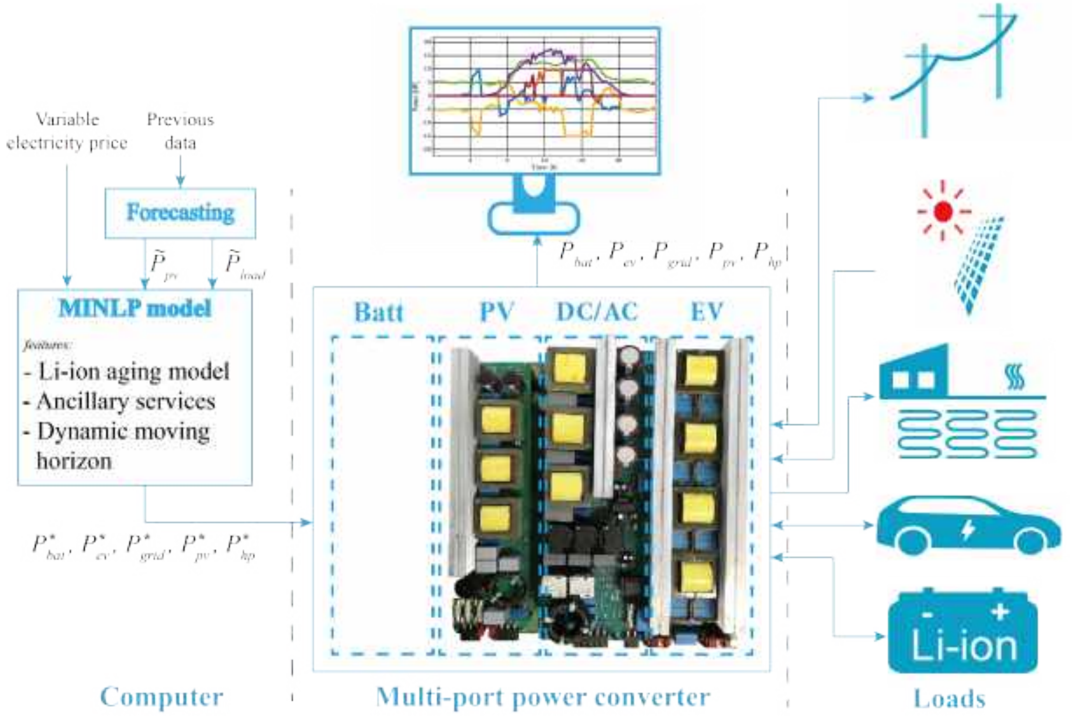

Add-on Storage
Add-on Solar Generation
DC
Disconnectors
DC/DC
(BMS)
DC/DC
(MPPT)
DC/AC
(High f)
AC/DC
(High f)
3 Phase
DC/AC
AC Grid
Fast DC Charger with High
Frequency Trasnformer
DC/AC
(High f)
AC/DC
(High f)
Add-on Charging Spots

Smart Building Power / Energy Management

PhD Topic of Wiljan Vermeer

- Developing smart energy management algorithms for future buildings based on PV & load forecasting
- Develop novel bidirectional battery charger
- Integrate energy management algorithm and novel battery charger on existing multi-port modular DC/DC converter





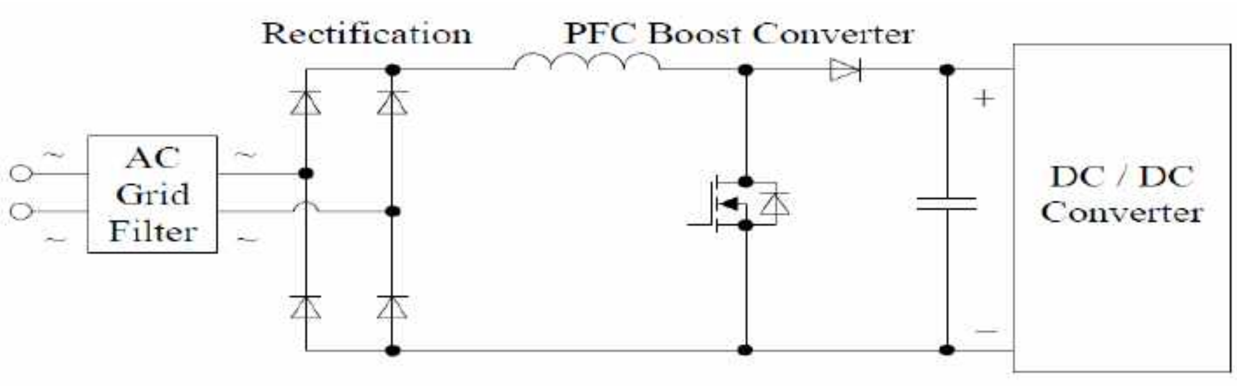
TU Delft

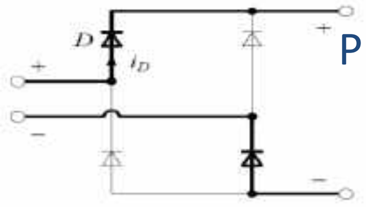
Roadmap for DC Systems

DC Nanogrids
• Radial DC feeders (lighting, Trolley)
• Devices, protection, stability

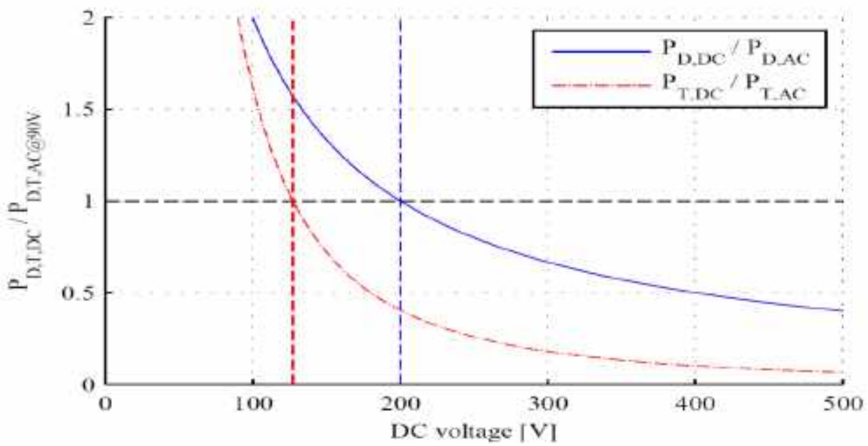
DC Nanogrids V2.0
• Bidirectional power flow
• PV and storage
• DC house nanogrid
• PV charging systems of EVs
• **DC ready devices and USB power delivery**
• Enable demand response

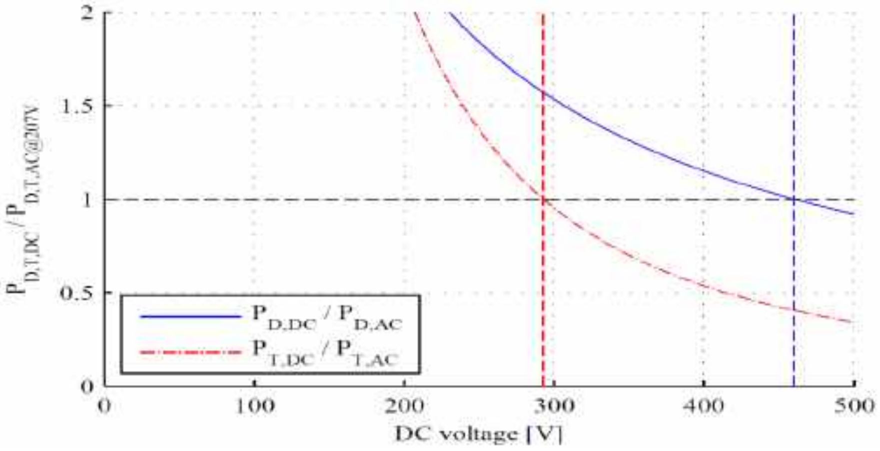
DC READY DEVICES





PhD Laurens Mackay





Laurens Mackay; Laura Ramirez-Elizondo; Pavol Bauer: DC ready devices - Is redimensioning of the rectification components necessary?
Proceedings of the 16th International Conference on Mechatronics - Mechatronika 2014

Roadmap for DC Systems

DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

DC microgrids / DC links
- Towards local generation local use (storage, EVs)
- Cellular concept
- Sizing (optimization)
- Protection, grounding
- Stability of DC grids
- Optimal power flow
- Power flow controller
- Demand side management
- Data over power line
- Power management
- Markets
- Harmonics

TU Delft

Roadmap for DC Systems

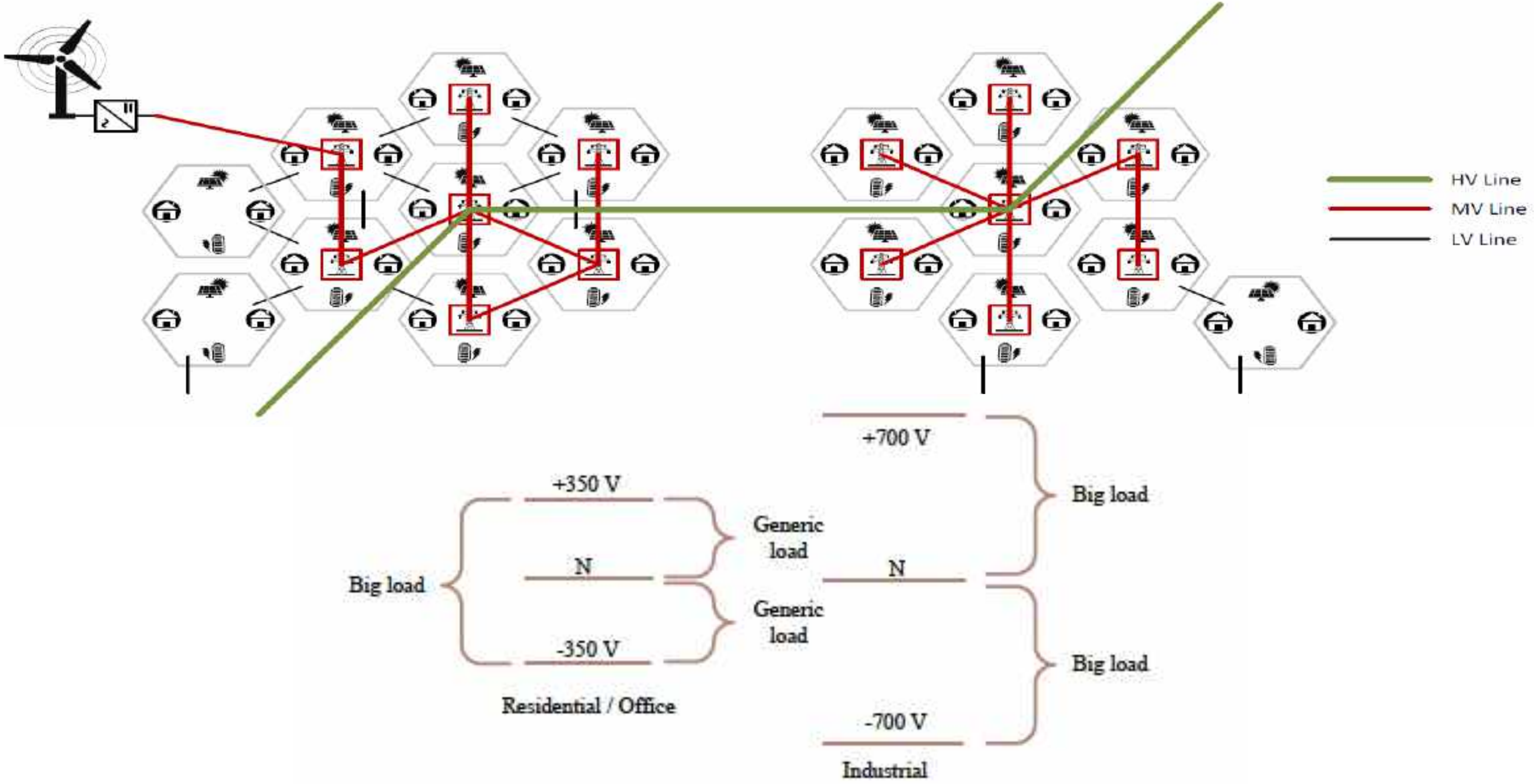
DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

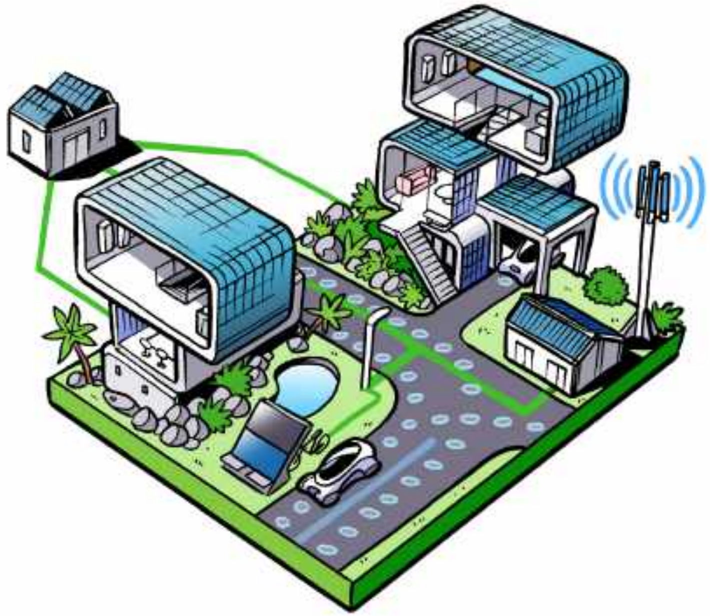
DC microgrids / DC links
- Towards local generation local use (storage, EVs)
- **Cellular concept**
- Sizing (optimization)
- Protection, grounding
- Stability of DC grids
- Optimal power flow
- Power flow controller
- Demand side management
- Data over power line
- Power management
- Markets
- Harmonics

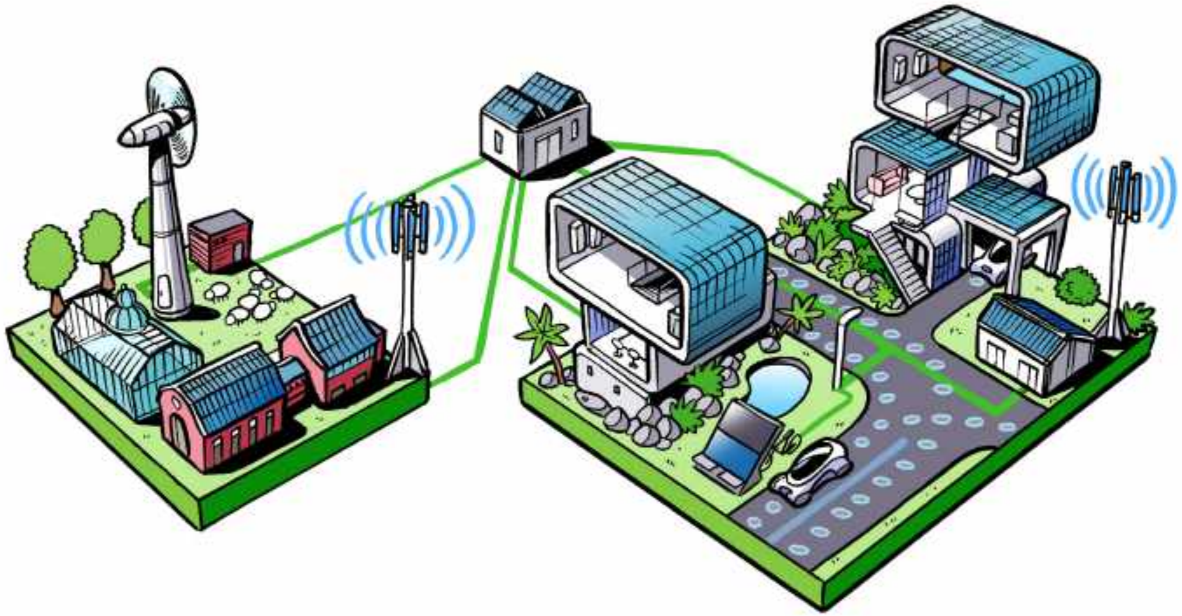
TU Delft

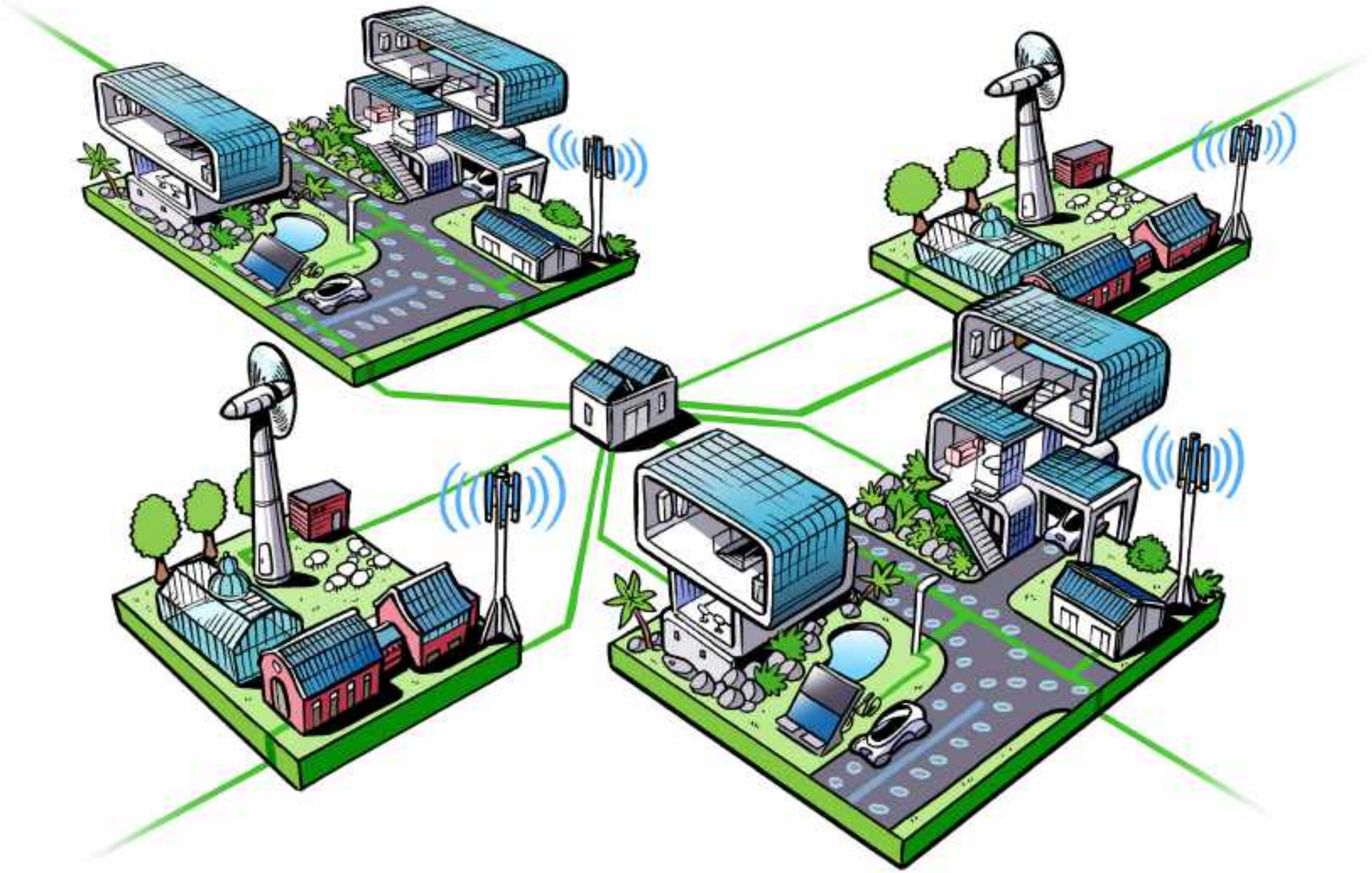
Cellular Concept



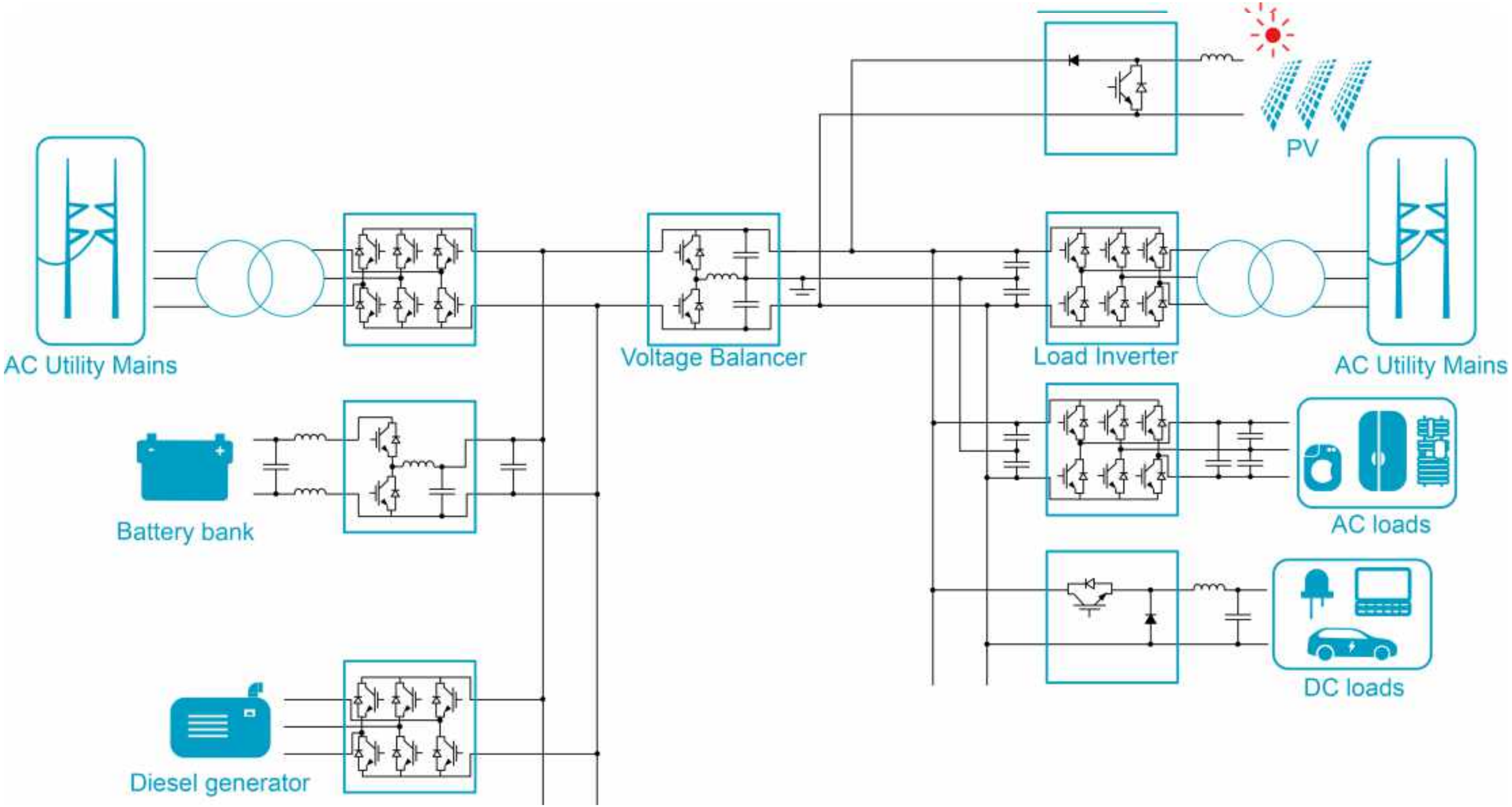
L. Mackay, N. H. van der Blij, L. M. Ramirez-Elizondo and P. Bauer, Toward the Universal DC Distribution System", Electric Power Components and Systems, vol. 45, no. 10, 2017



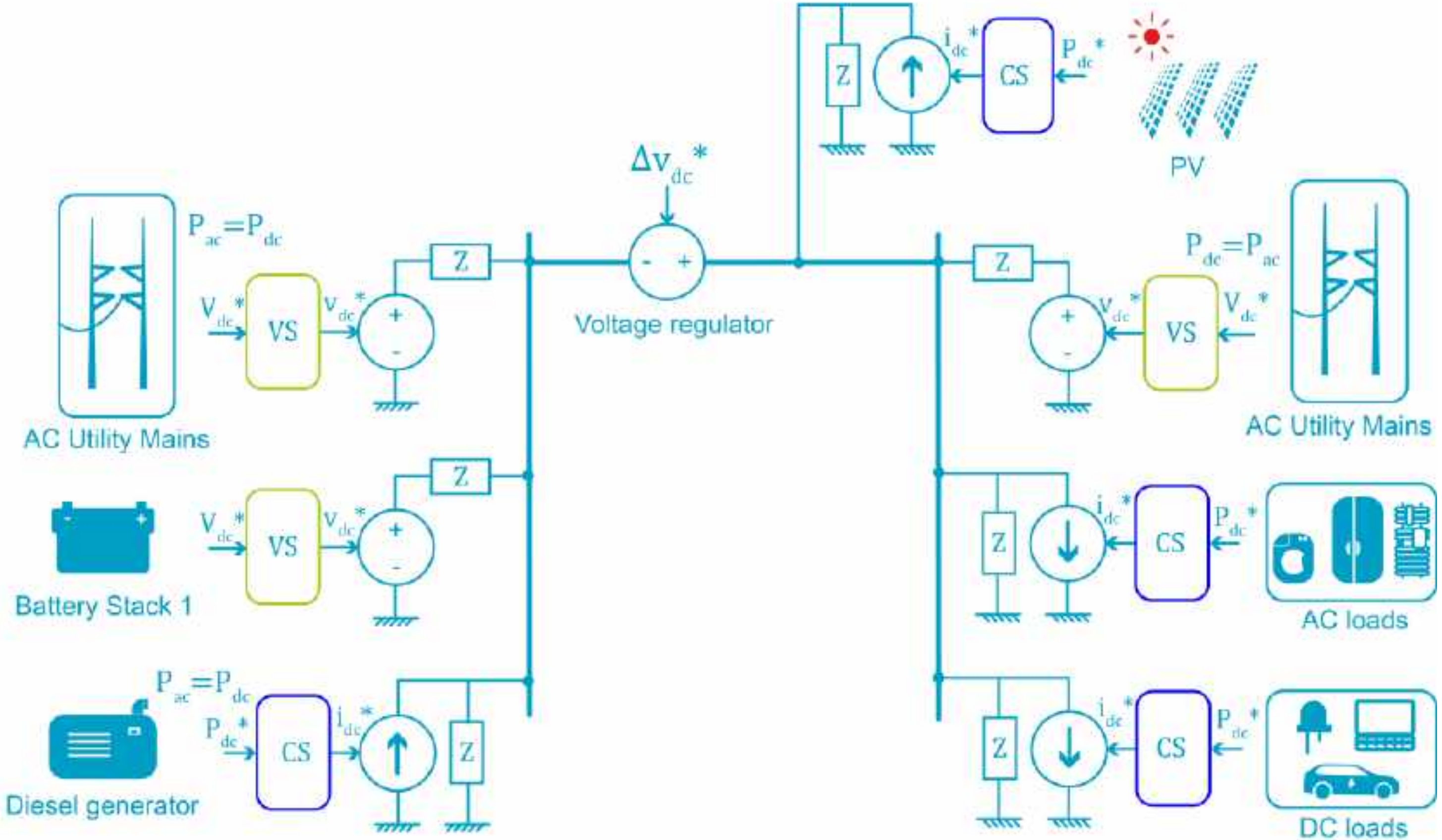




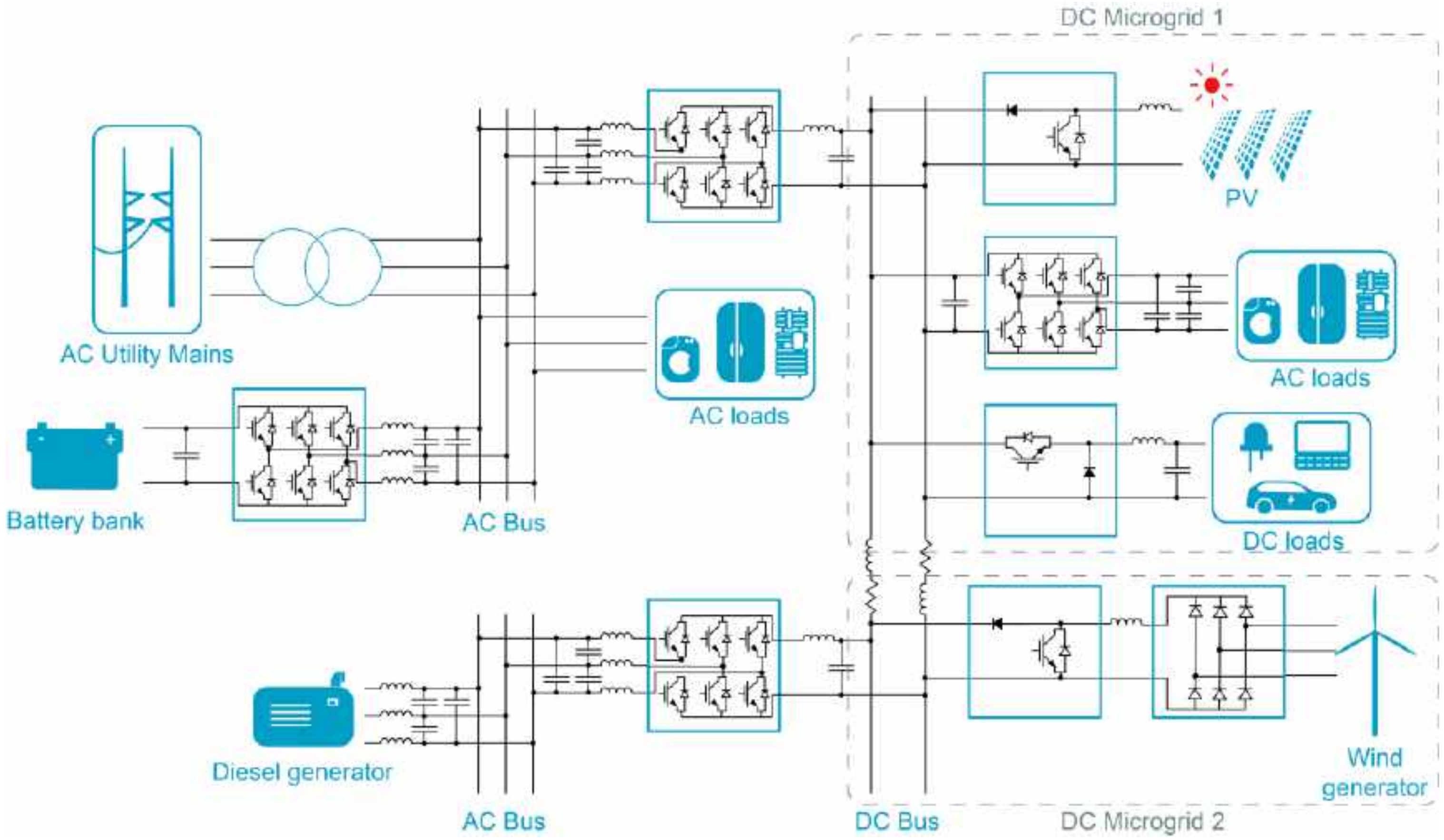
Bipolar Single-Bus



Bipolar Single-Bus

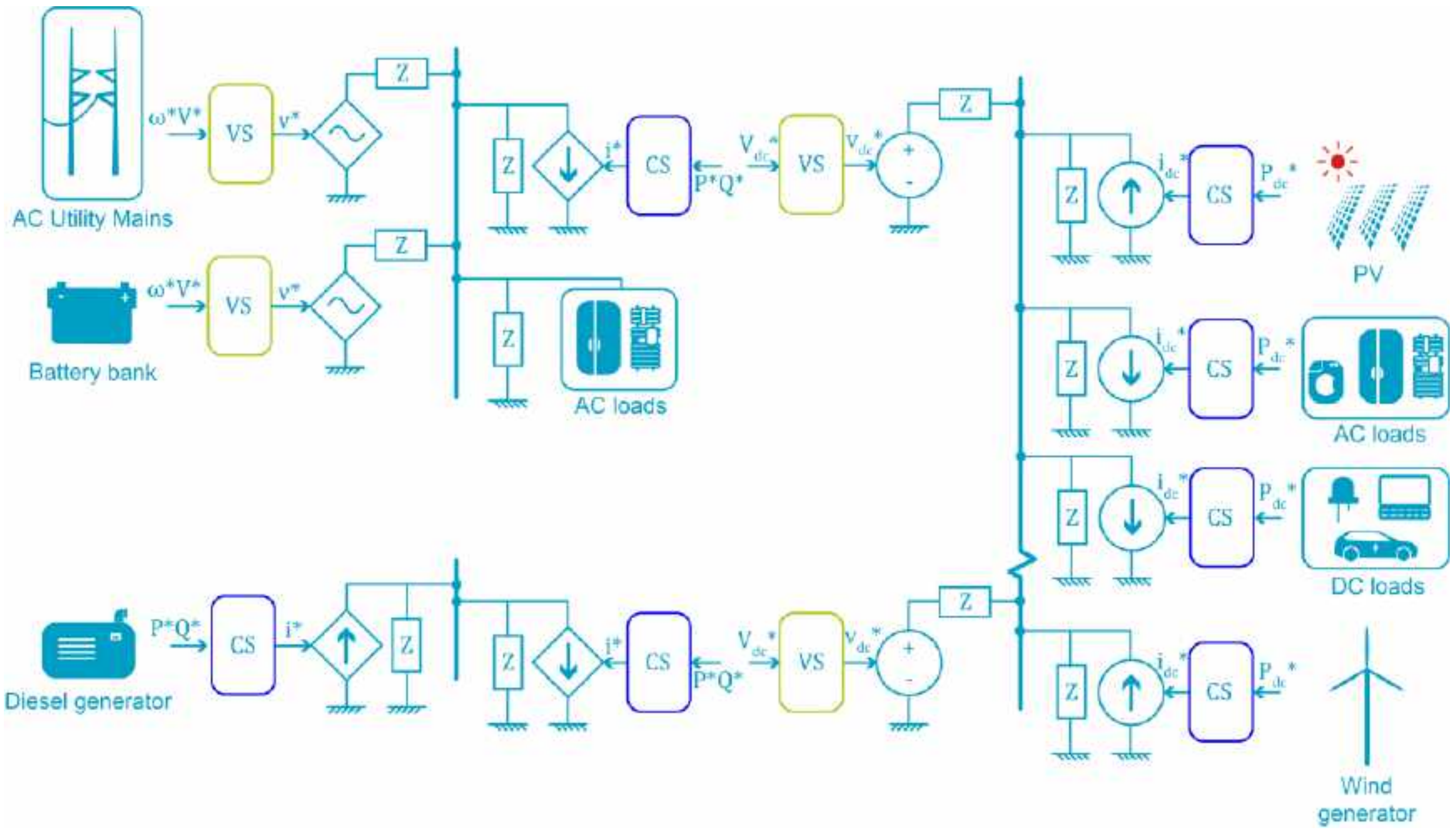


Hybrid AC-DC



DC Microgrid 1
PV
AC Utility Mains
AC loads
AC loads
Battery bank
AC Bus
DC loads
Diesel generator
Wind
generator
AC Bus
DC Bus
DC Microgrid 2

Hybrid AC-DC



Pavol Bauer, Leake E. Weldemariam, Delft University of Technology; Evert Raijen, Exendis, NL; Praveen Kumar, Indian Institute of Technology, ;Connecting Topologies of Stand Alone Micro Hybrid Power Systems.pp. 304-310, PCIM 2011

Roadmap for DC Systems

DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

DC microgrids / DC links
- Towards local generation local use (storage, EVs)
- Cellular concept
- Sizing (optimization)
- Protection, grounding
- Stability of DC grids
- Optimal power flow
- Power flow controller
- Demand side management
- Data over power line
- Power management
- Markets
- Harmonics

TUDelft

Roadmap for DC Systems

DC Nanogrids

- Radial DC feeders (lighting)
- Devices, protection, stability

DC Nanogrids V2.0

- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

DC microgrids / DC links

- Towards local generation local use (storage, EVs)
- Cellular concept
- Sizing (optimization)
- **Protection, grounding**
- Stability of DC grids
- Optimal power flow
- Power flow controller
- Demand side management
- Data over power line
- Power management
- Markets
- Harmonics

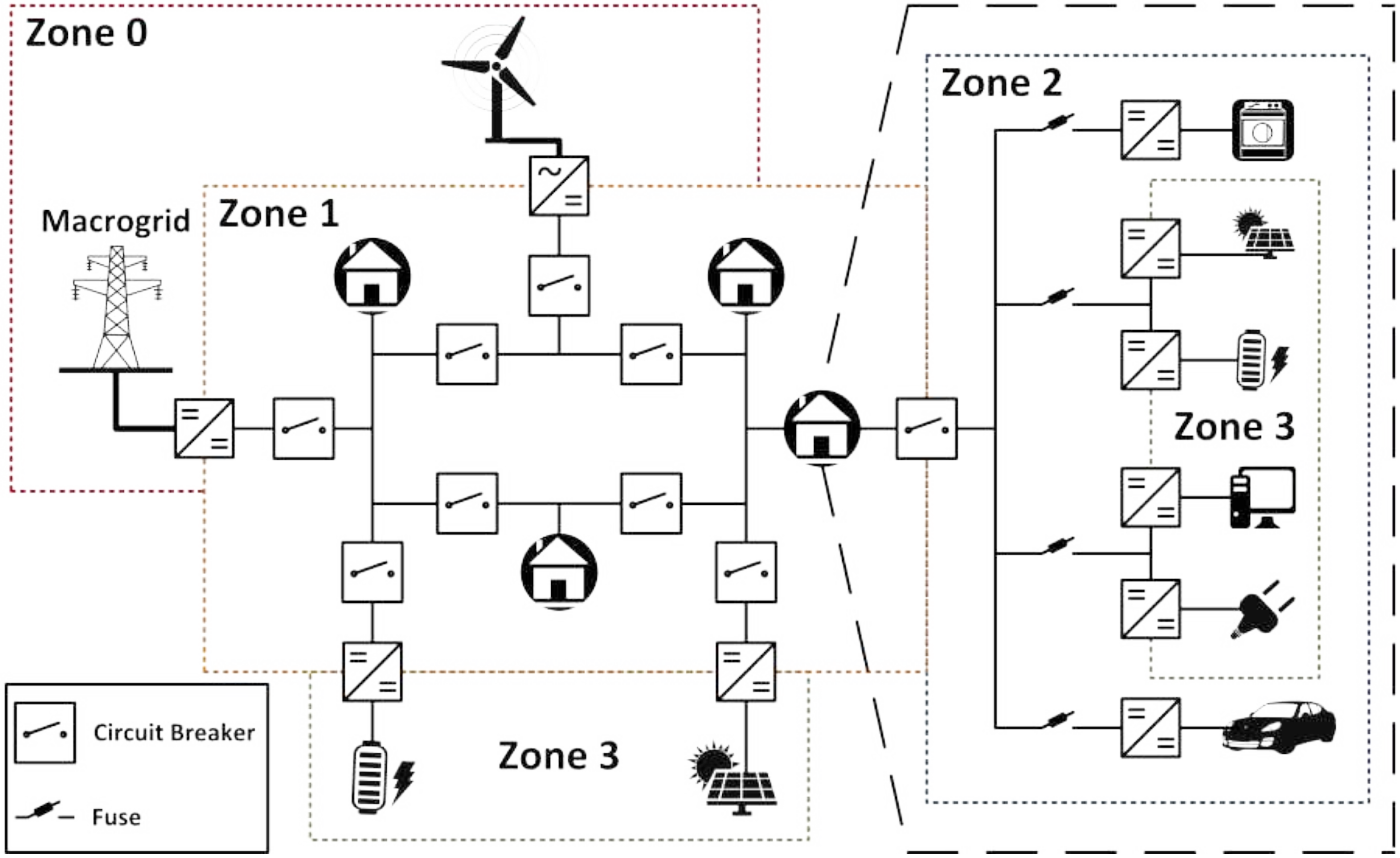
Protection of Low Voltage DC Systems

- System is **safe** for devices and individuals interacting with the grid
- The detection methods are **sensitive** to the different types of faults
- The protection devices are **secure** and do not trip unnecessarily
- The protection scheme is **selective** and isolates the faulted section
- The fault is cleared **fast**, so that blackout and damage is prevented
- The protection of the system is **cost-effective**

Protection of Low Voltage DC Systems

- **Lack of a zero crossing**
- **Fast interruption is required**: low inertia, component design
- **Selectivity**: meshed systems, fast interruption, challenging selectivity

Protection Zones



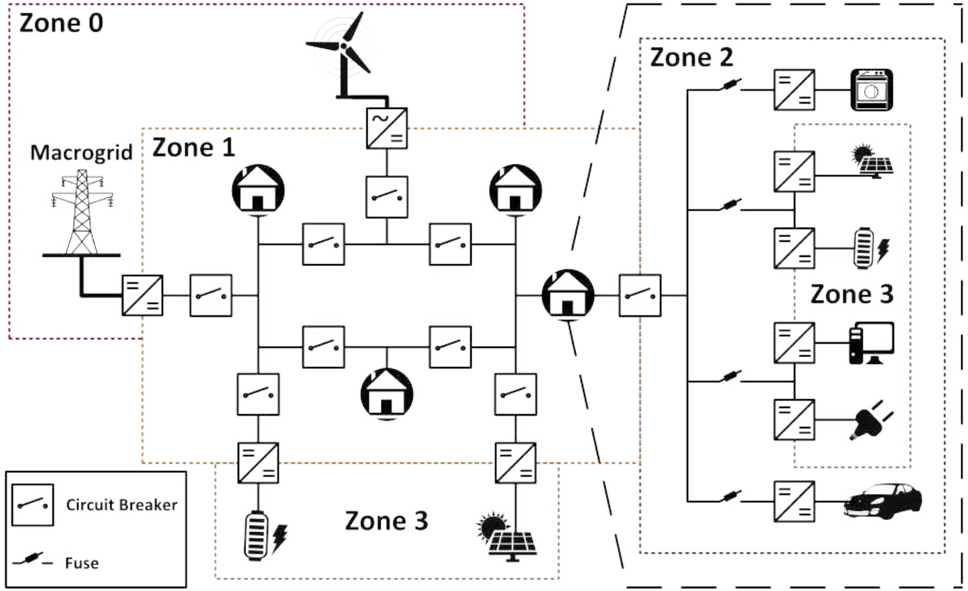
N. H. van der Blij, P. Purgat, T. B. Soeiro, L. M. Ramirez-Elizondo, M. T. J. Spaan and P. Bauer, Decentralized Plug-and-Play Protection Scheme for Low Voltage DC Grids", Energies 2020

TUDelft

Protection Zones

Short-circuit potential

- **Zone 0:** Medium/high voltage (> 1500V) – highest short circuit
- **Zone 1:** Microgrid level (350 – 1500 V) – high short circuit, low inertia
- **Zone 2:** Nanogrid level (42 – 350 V) – low short circuit
- **Zone 3:** Device level (< 42 V)- safe to touch (usb C)

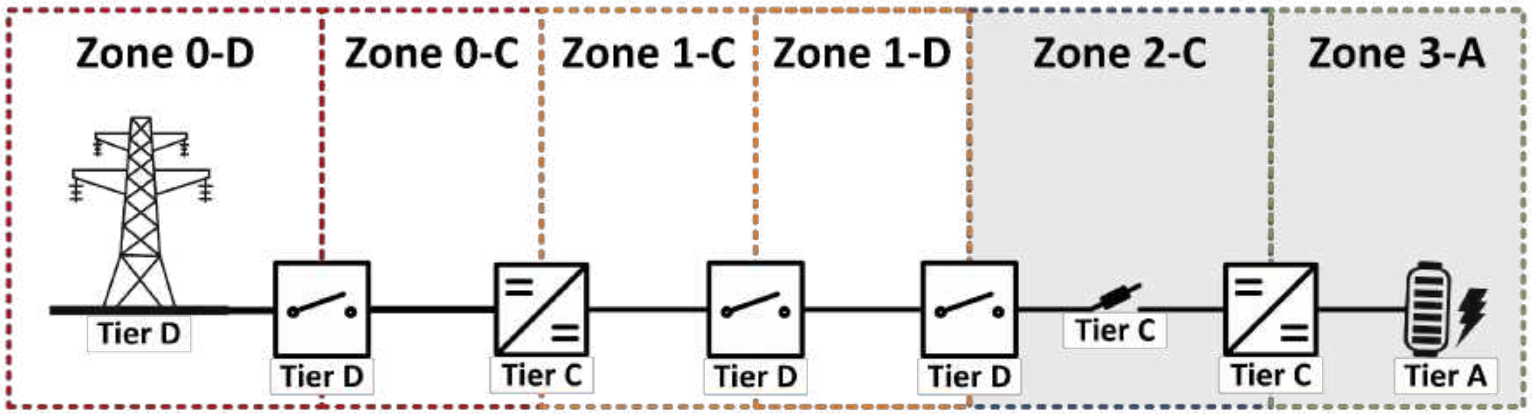


- **Protection – galvanic isolation**

Protection Tiers

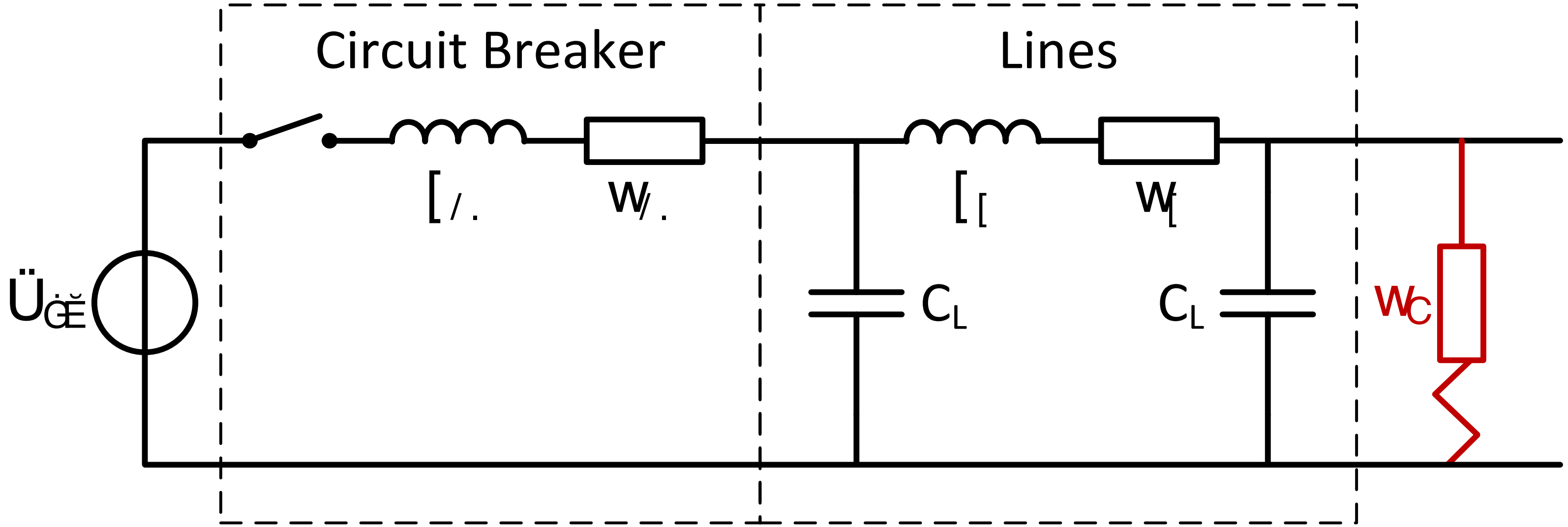
Provided protection:

- **Tier A:** No guaranteed protection
- **Tier B:** Device protection – internal protection
- **Tier C:** Overcurrent protection – interrupted when specified current
- **Tier D:** Current prevention protection



TU Delft

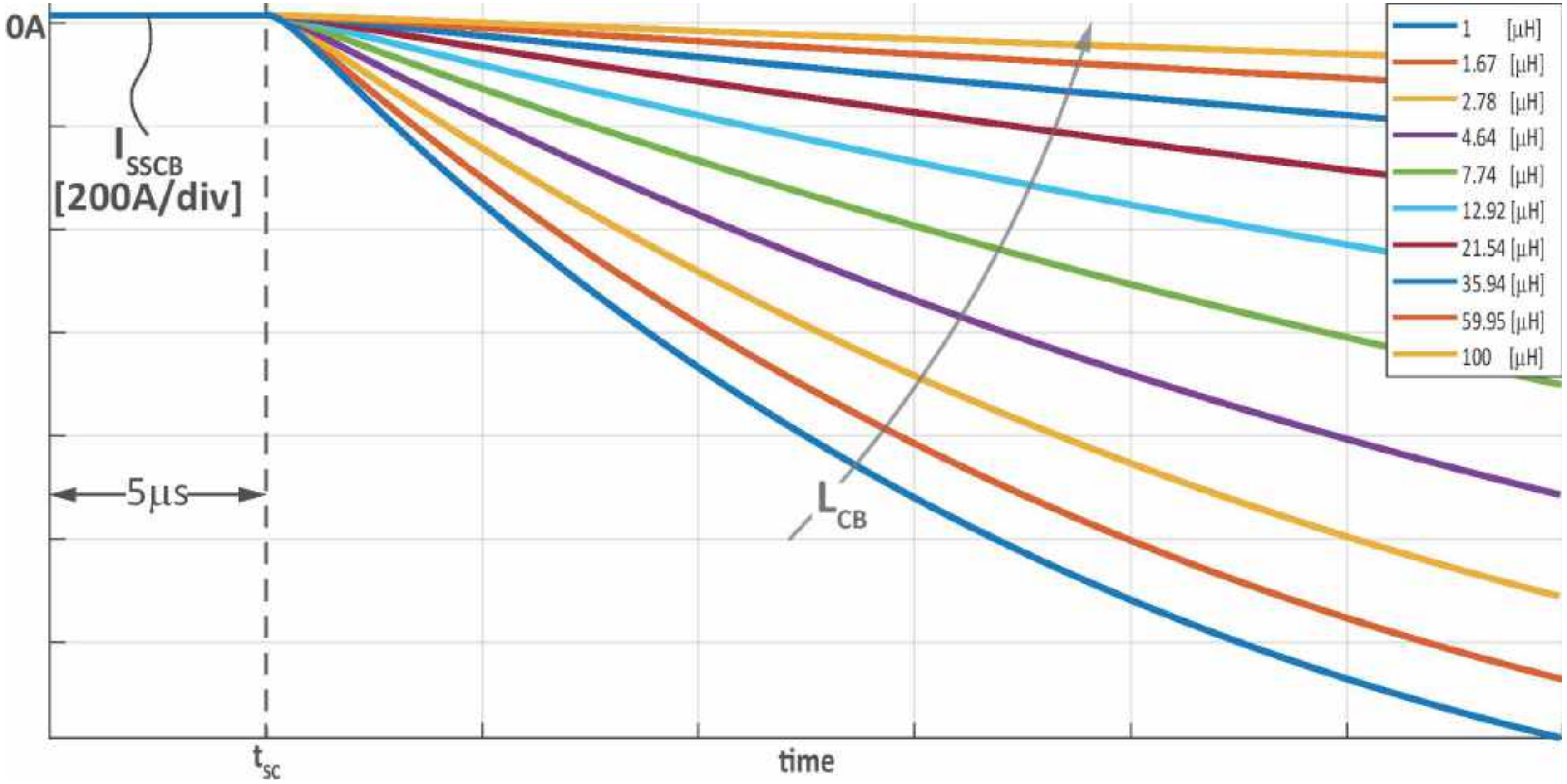
Low Voltage DC Faults



$$I_F(t) = \frac{U_{dc}}{R_{CB} + R_L + R_F}\left(1 - e^{-\frac{R_{CB}+R_L+R_F}{L_{CB}+L_L}t}\right)$$

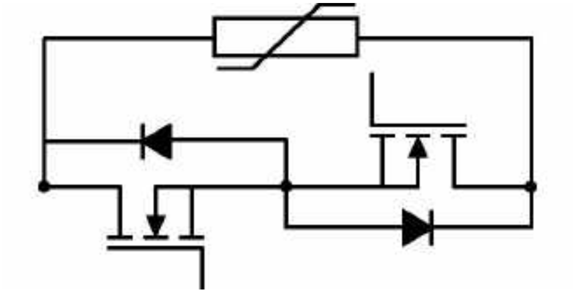
Current limiting inductances and fast fault interruption are required to prevent the system from reaching its large steady-state currents

Low Voltage DC Faults

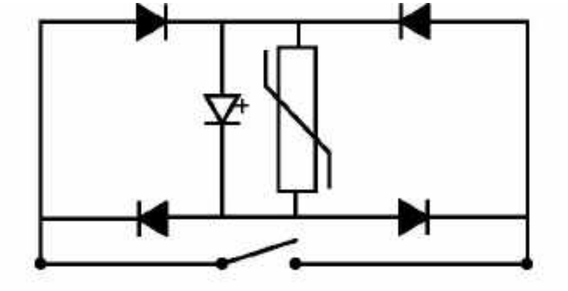


Current limiting inductances and fast fault interruption are required to prevent the system from reaching its large steady-state currents

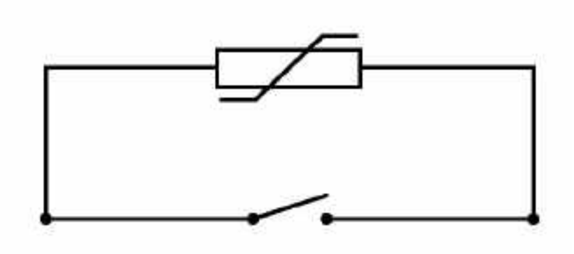
Protection Devices



~ 1 μs



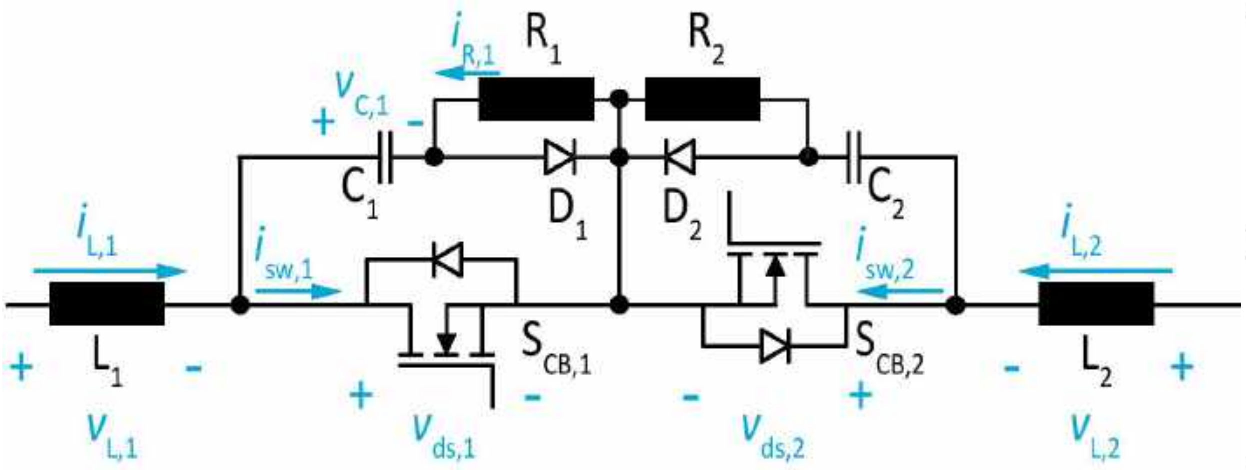
~ 1 ms

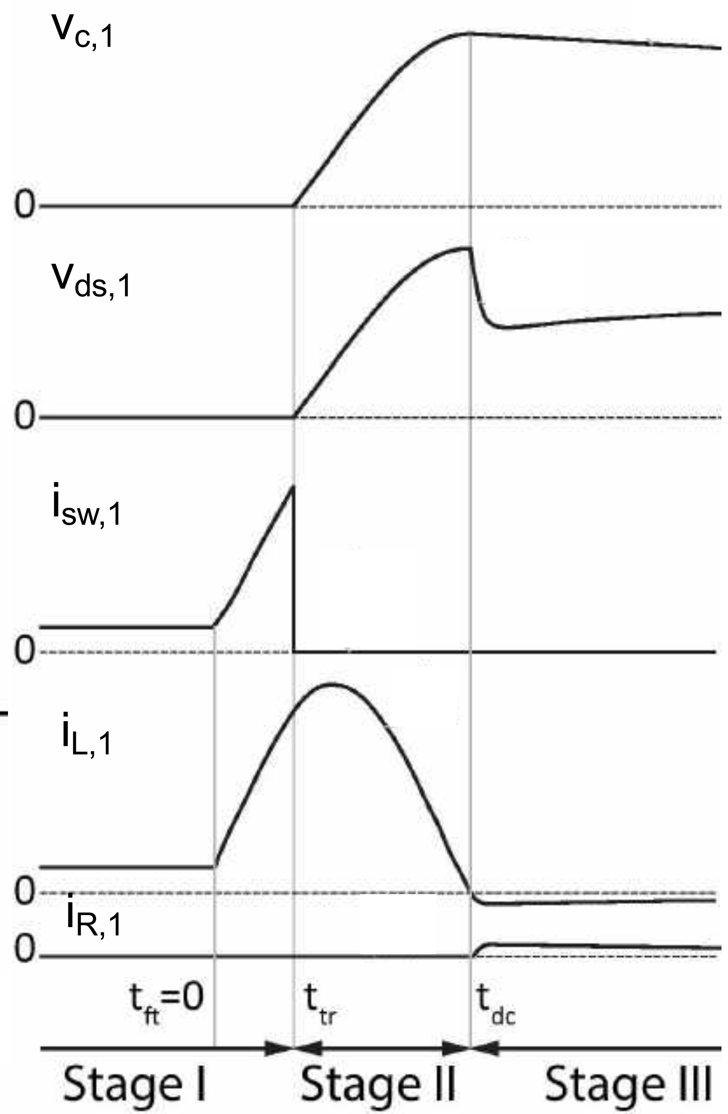


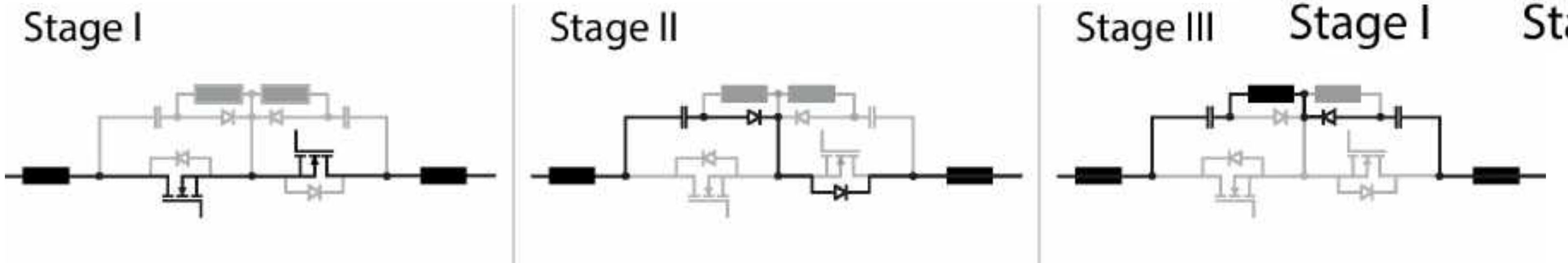
~ 10 ms

Type	Speed	Reliability	TCO
Hybrid CB	-	-	-
Solid-state CB	+	+	+

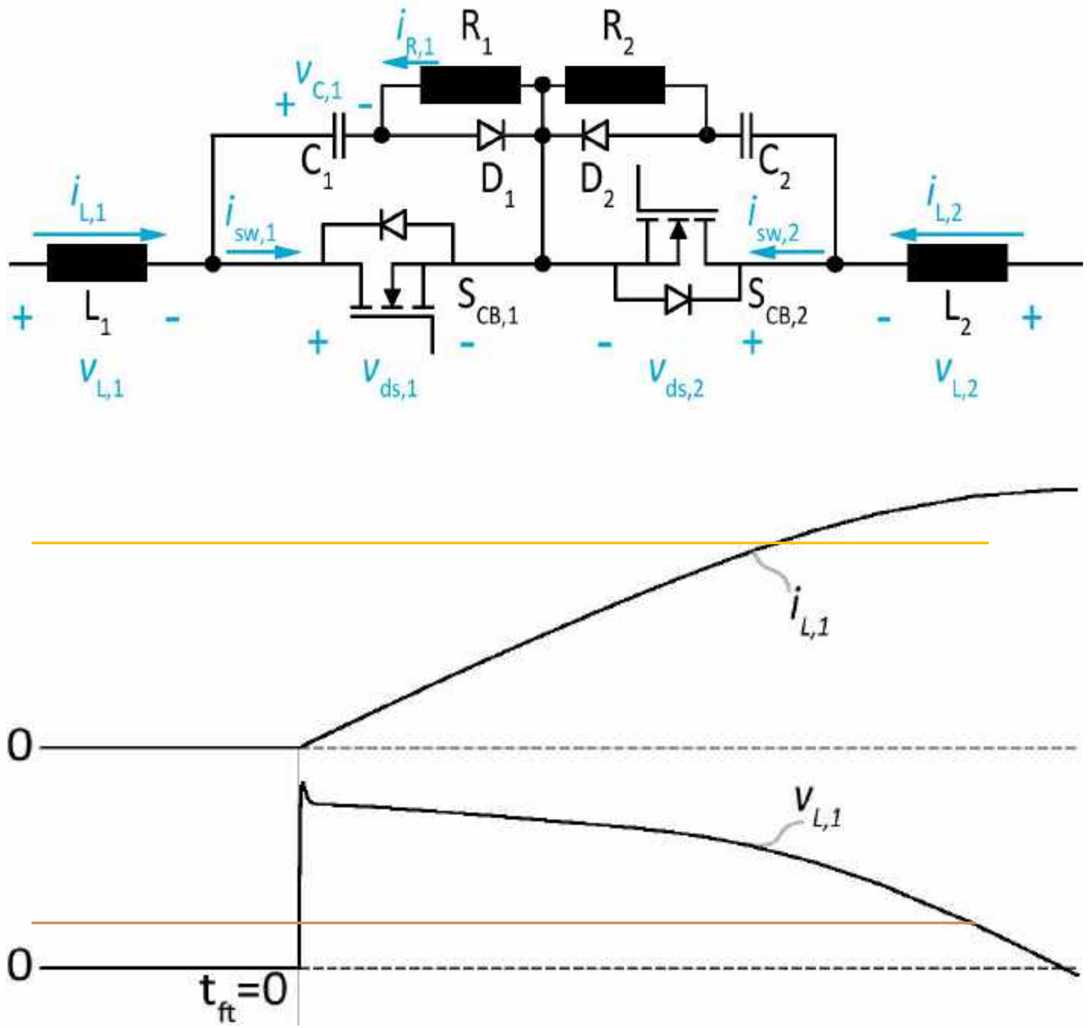
SSCB operation





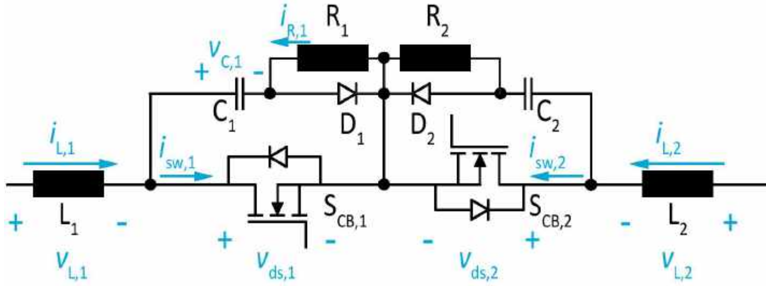


SSCB Detection Methods

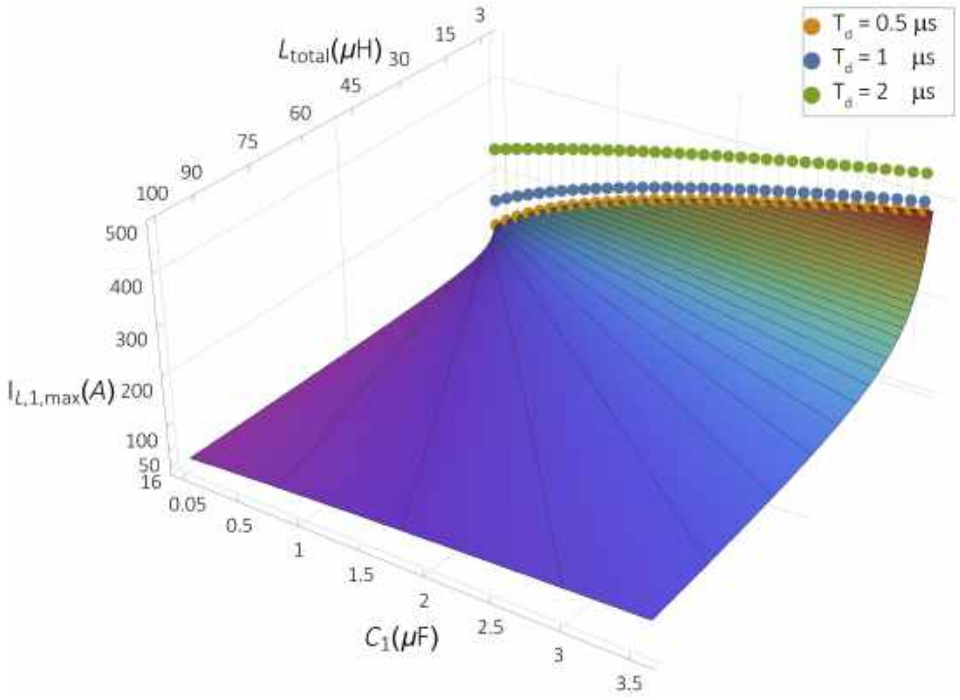


- Overcurrent Detection
- Rate-of-change-of-current Detection

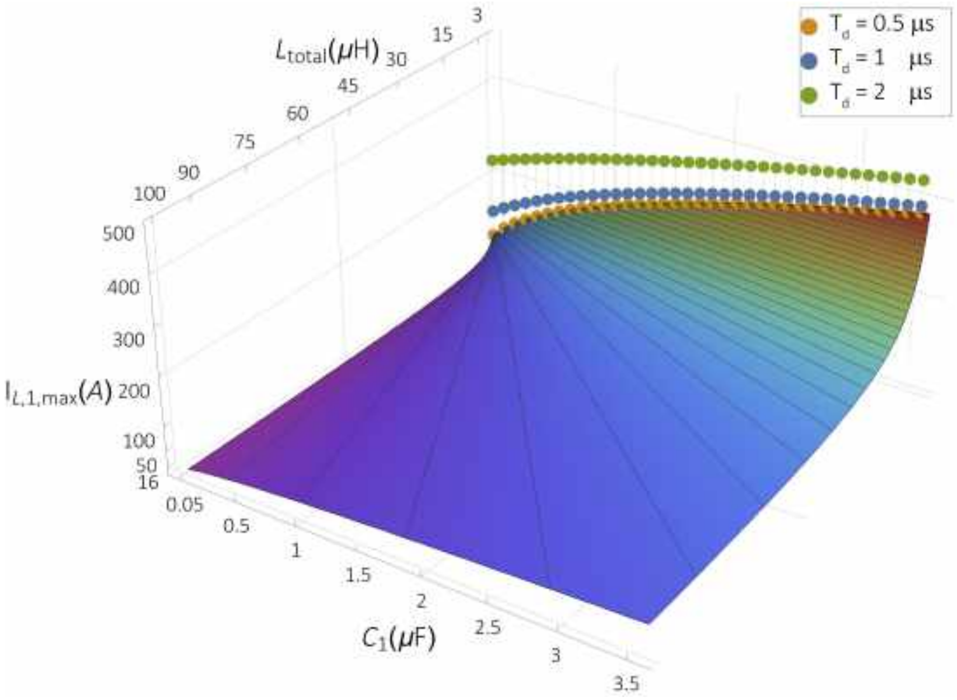
SSCB Design Constraints



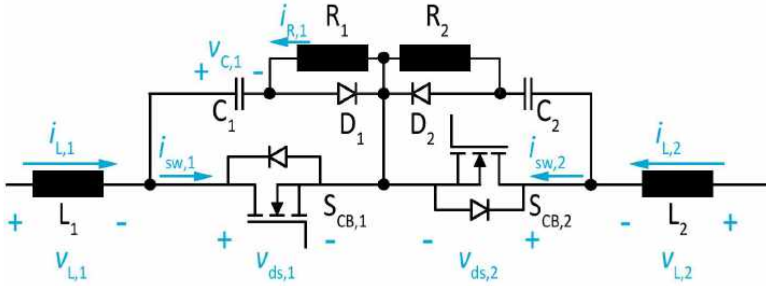
Overcurrent Detection



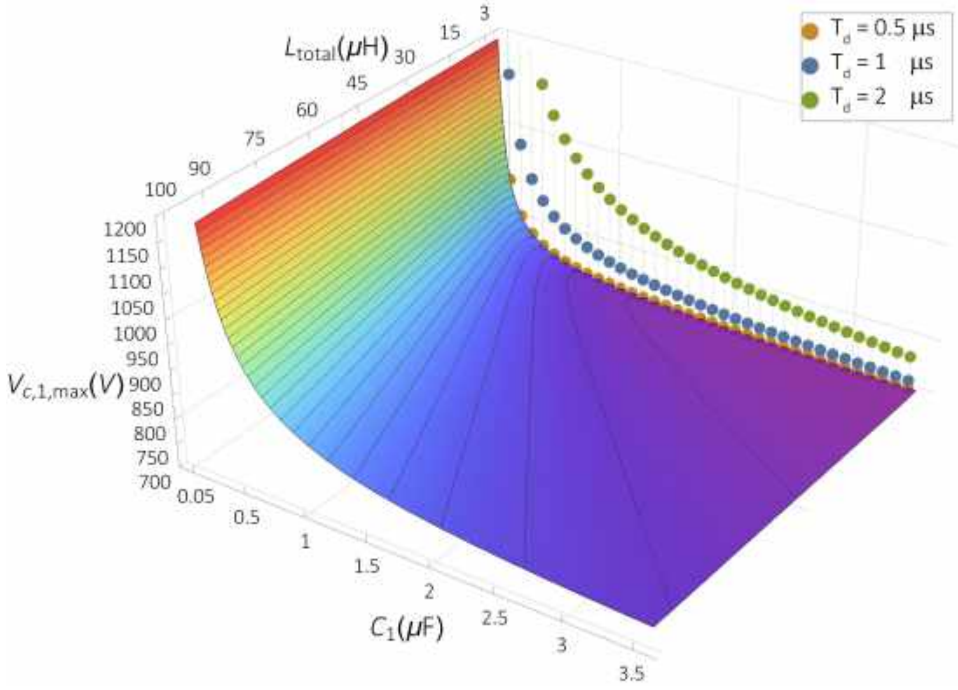
Rate-of-change-of-current Detection



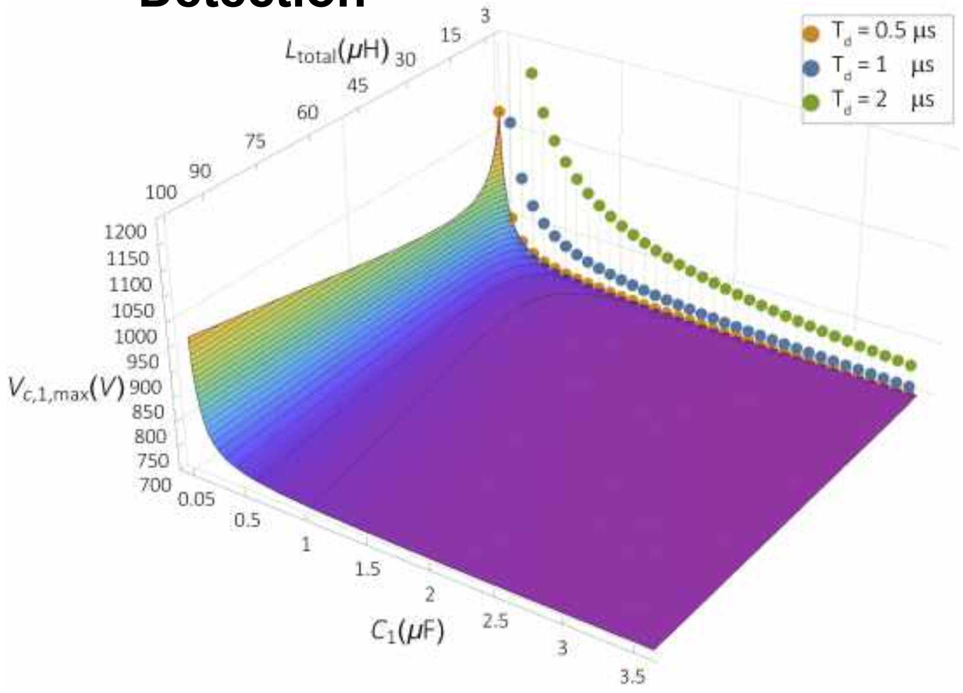
SSCB Design Constraints



Overcurrent Detection

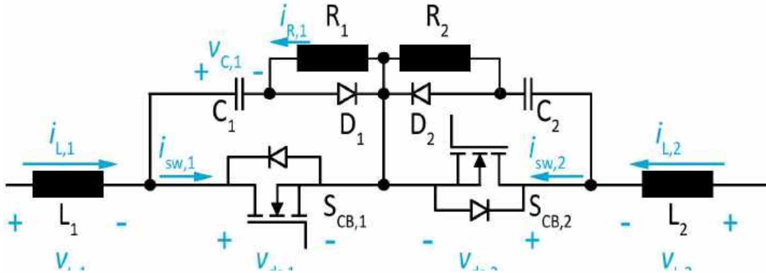


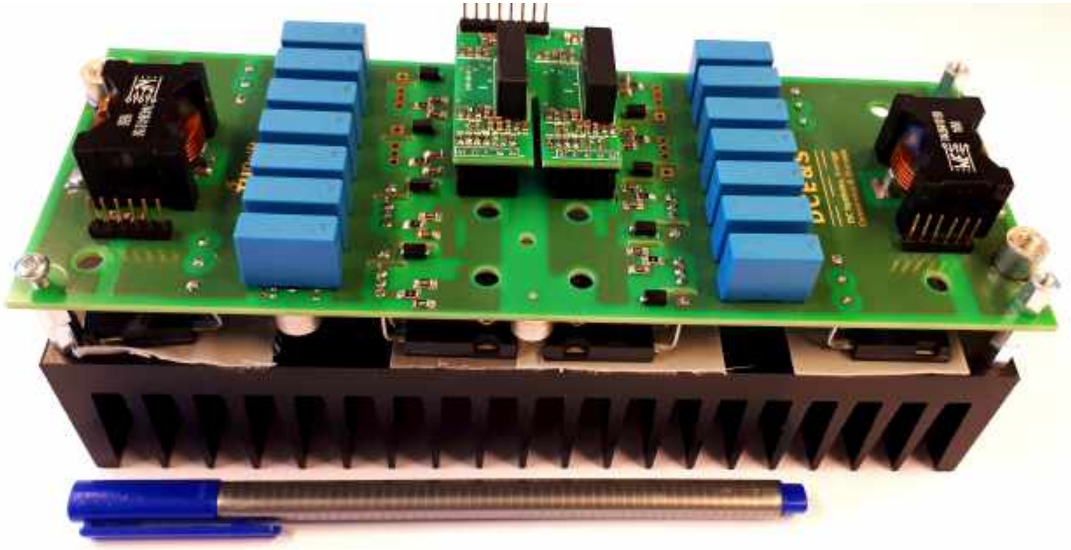
Rate-of-change-of-current Detection



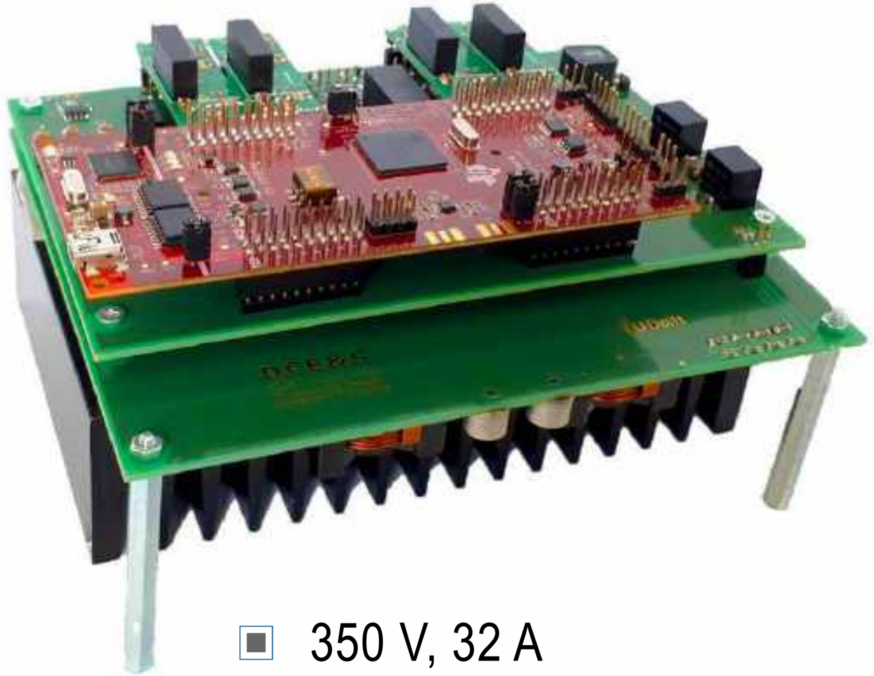
TU Delft

SSCB Prototype 1



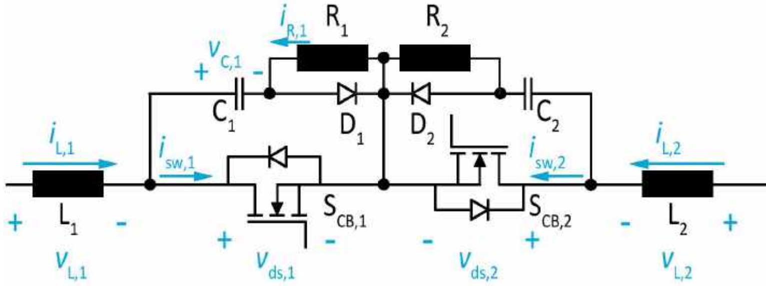


- 350 V, 32 A
- Si Mosfets
- 8 mΩ
- 270x75x60 mm

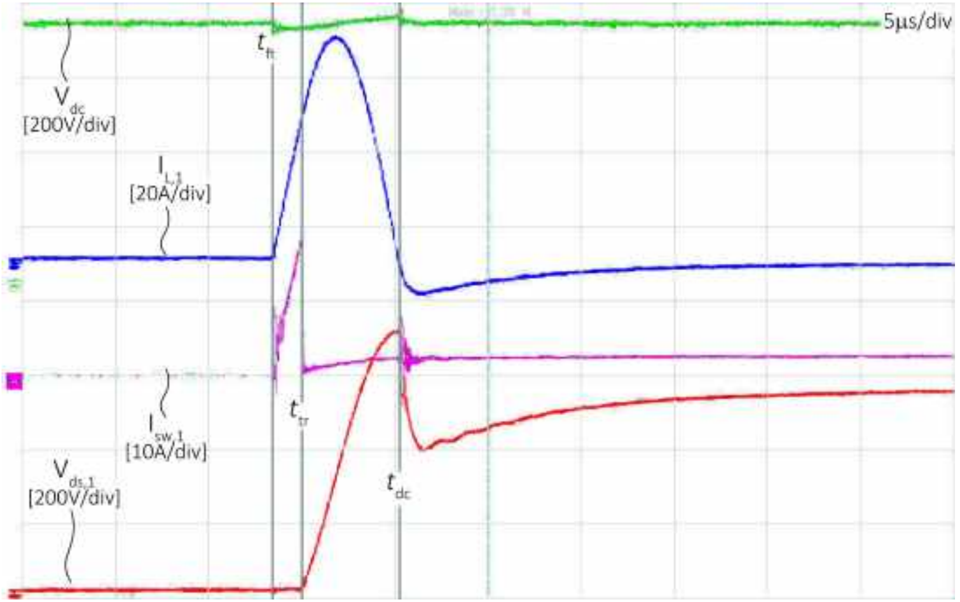


- 350 V, 32 A
- SiC Mosfets
- <100 μH
- Overcurrent (v_{ds})
- ROCOC

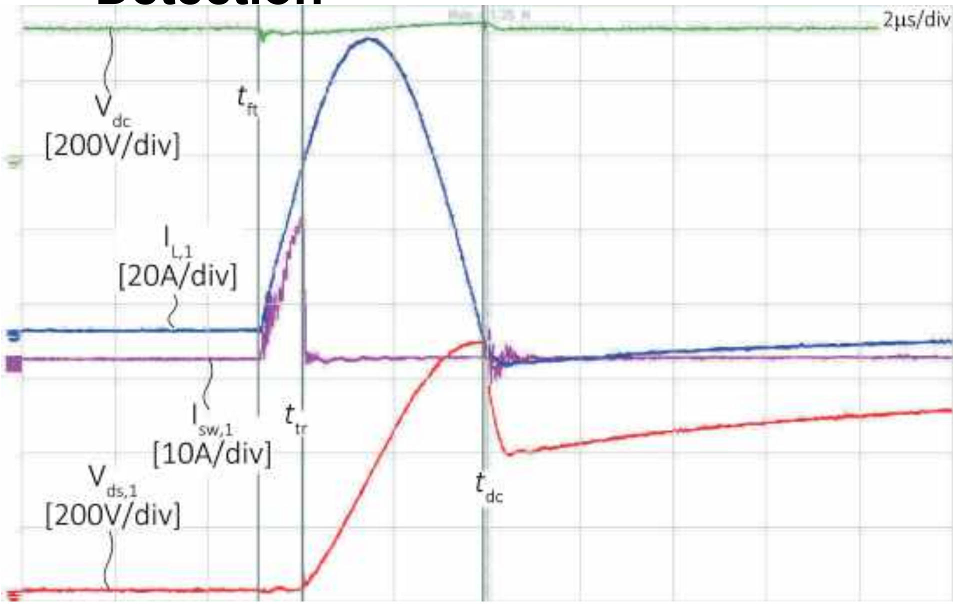
TESTING



Overcurrent Detection



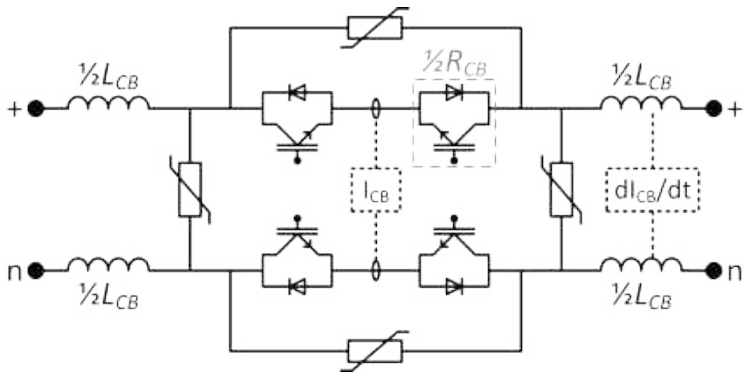
Rate-of-change-of-current Detection



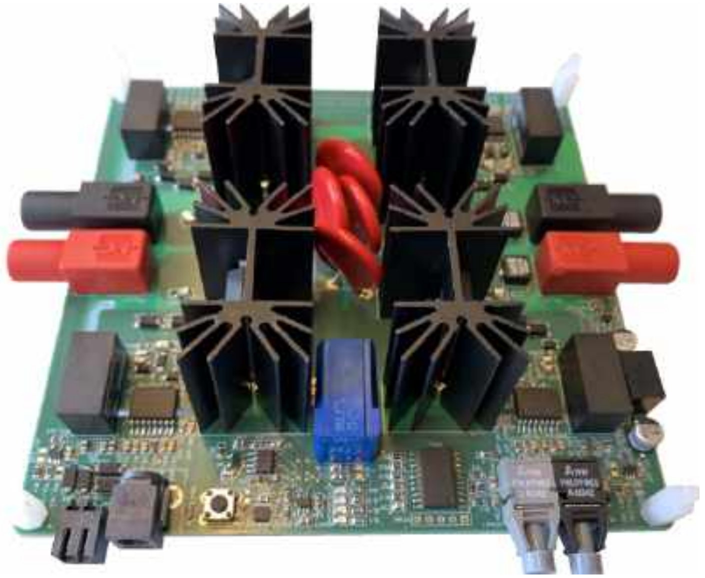
TU Delft

DCE&S
DC Systems, Energy Conversion & Storage

SSCB Prototype 3



Parameter	Acronym	Value
Nominal voltage	U_{nom}	350 [V]
Nominal current	I_{nom}	16 [A]
On-state resistance per pole	R_{CB}	130 [mΩ]
Current limiting inductance	L_{CB}	1.0 [μH]
Fault clearing time	t_{CB}	1.0 [μs]



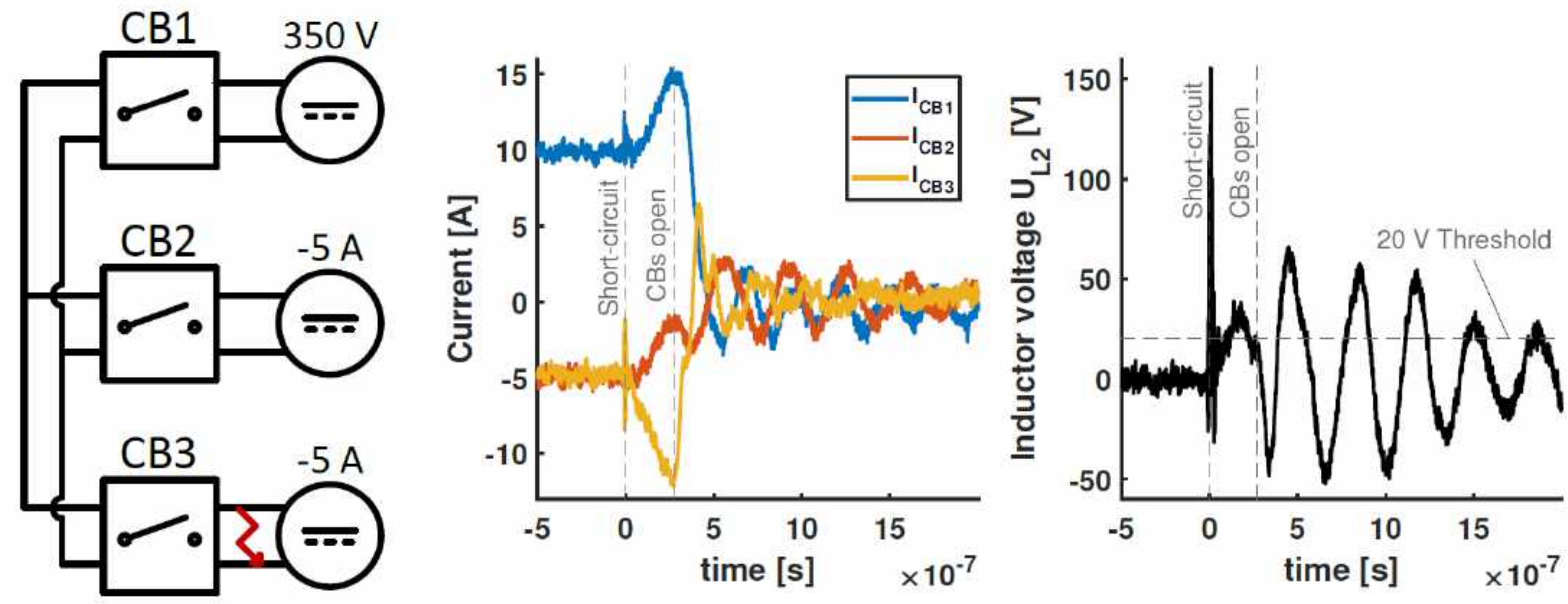
Selectivity in LVDC Systems

Major challenges for selectivity in low voltage DC systems:

- **Fast fault interruption**
- **Radial and meshed structures**
- **Changing grid topology**

The **fast propagation of the fault** throughout the system and the **commutation of inductive currents** encumbers selectivity.

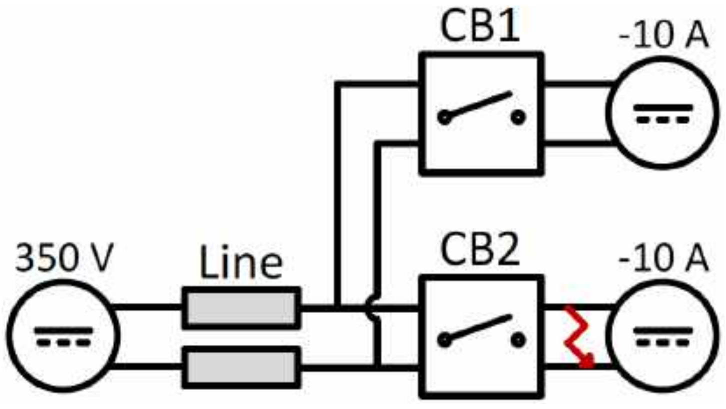
Fast Fault propagation

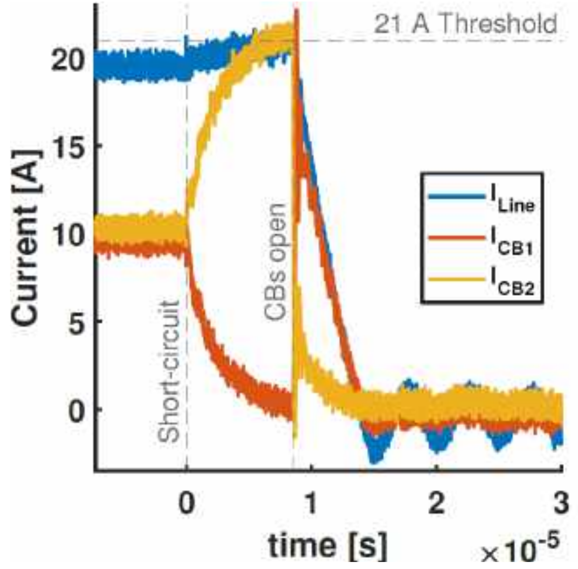


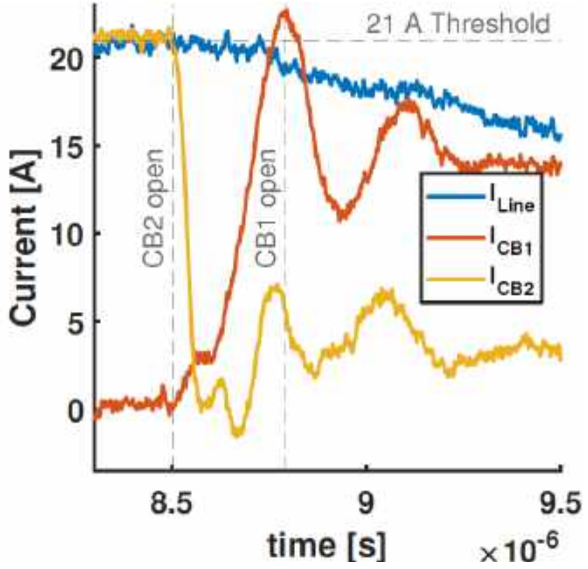
This situation occurs in, for example, an islanded household nanogrid.

In such a system the fault propagates quickly and the set thresholds (in this case the di/dt thresholds) are exceeded in all groups, before the SSCB in the faulted group can react.

Commutation of Inductive Currents







This situation occurs, for example, a connected household nanogrid.

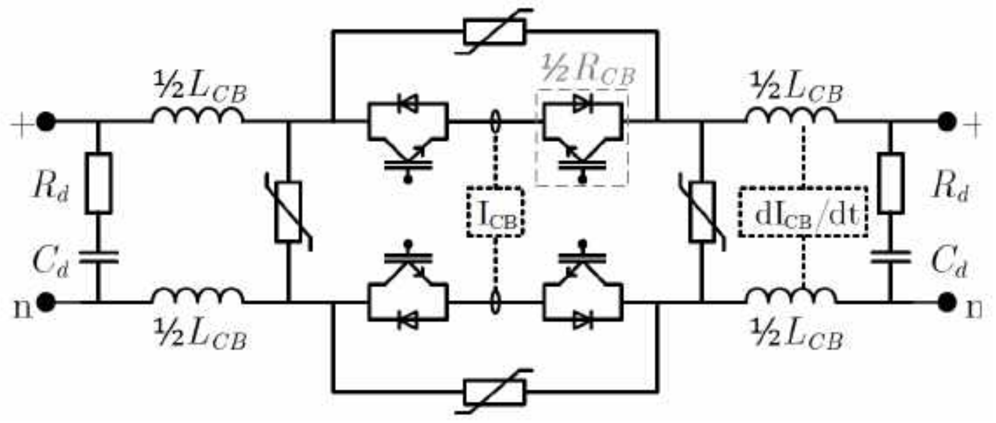
In such a system the inductive (pre-fault) current from the faulted section will flow in the non-faulted sections of the grid after fault clearing. This can cause the unnecessary tripping of non-faulted groups.

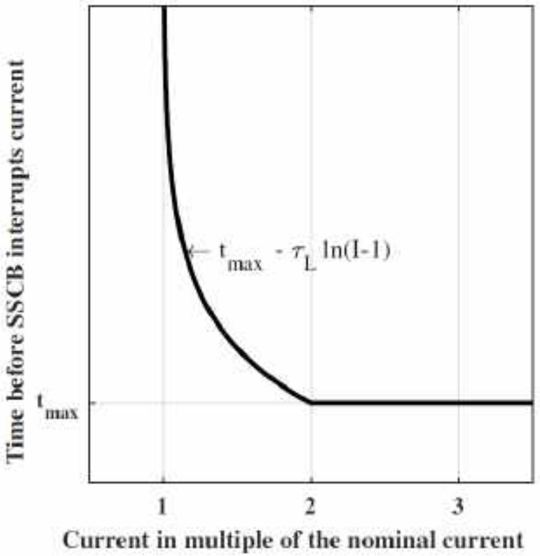
TUDelft

Plug and Play Protection Scheme

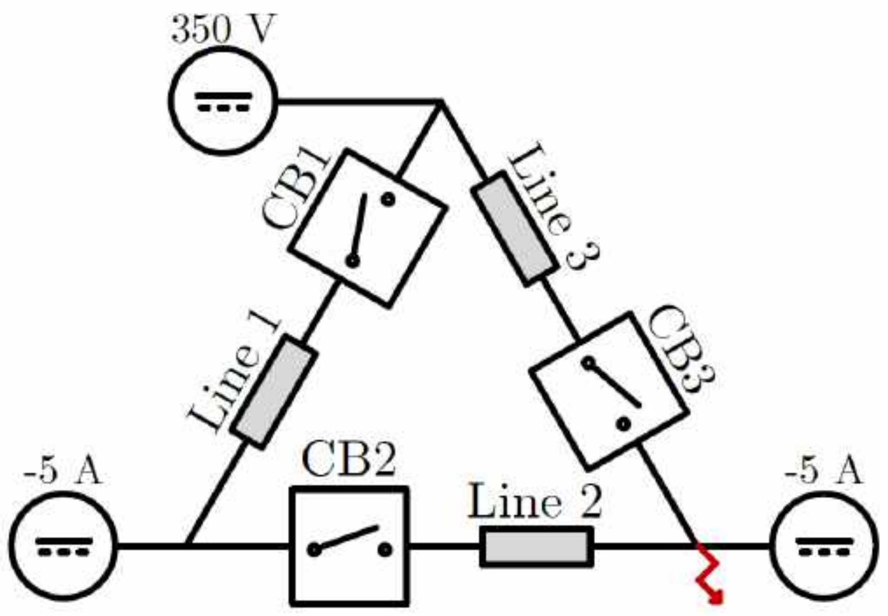
Fast fault propagation is solved by modifying the topology of the SSCB, such that it forms an LCR filter that delays propagation.

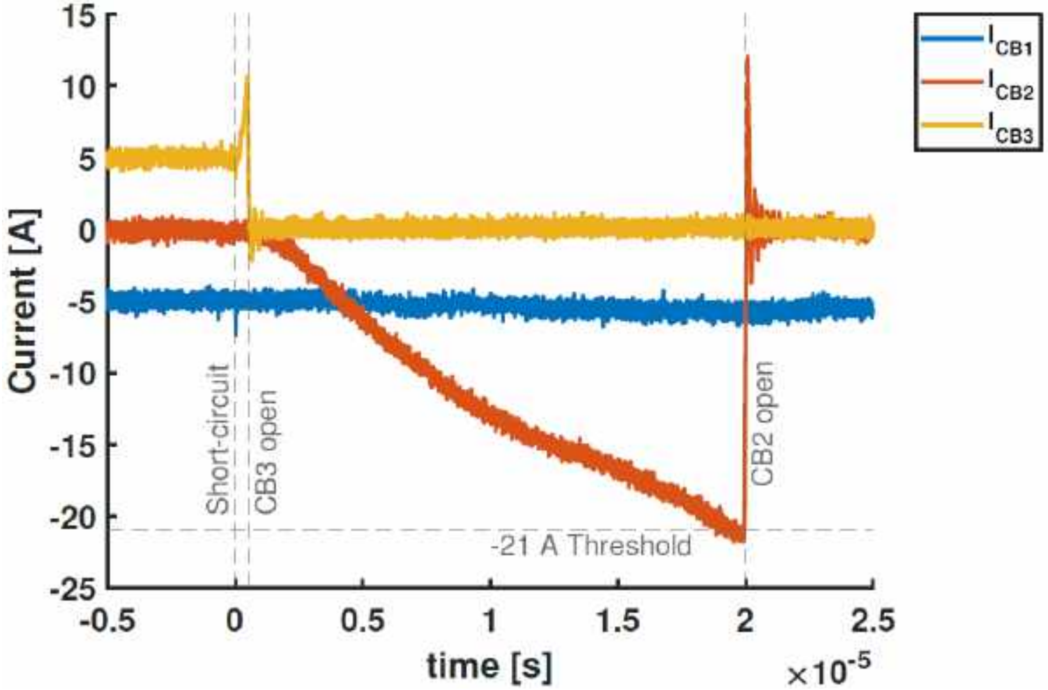
Commutation of inductive currents is ignored by employing a well-designed time-current characteristic.





Plug and Play Experimental Results





Roadmap for DC Systems

DC Nanogrids

- Radial DC feeders (lighting)
- Devices, protection, stability

DC Nanogrids V2.0

- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

DC microgrids / DC links

- Towards local generation local use (storage, EVs)
- Cellular concept
- Sizing (optimization)
- Protection, grounding
- Stability of DC grids
- Optimal power flow
- Power flow controller
- Demand side management
- Data over power line
- Power management
- Markets
- Harmonics

TUDelft

Roadmap for DC Systems

DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

DC microgrids / DC links
- Towards local generation local use (storage, EVs)
- Cellular concept
- Sizing (optimization)
- Protection, grounding
- **Stability of DC grids**
- Optimal power flow
- Power flow controller
- Demand side management
- Data over power line
- Power management
- Markets
- Harmonics

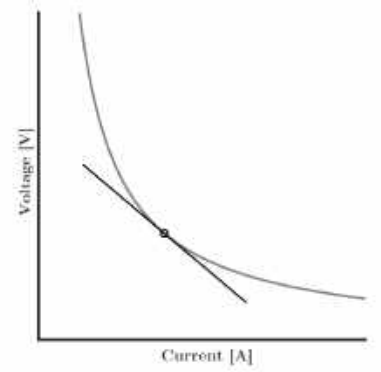
TUDelft

Stability of DC Grids

PhD topic of Nils H. van der Blij

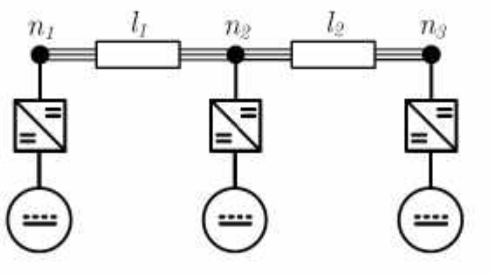
Challenges for the stability of DC grids:

- Low inertia
- Constant power loads
- Changing topology

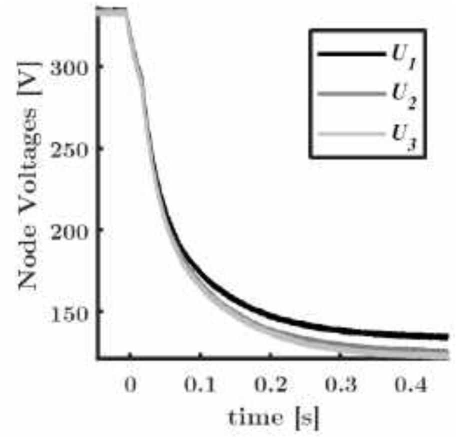


Two modes of instability in DC grids:

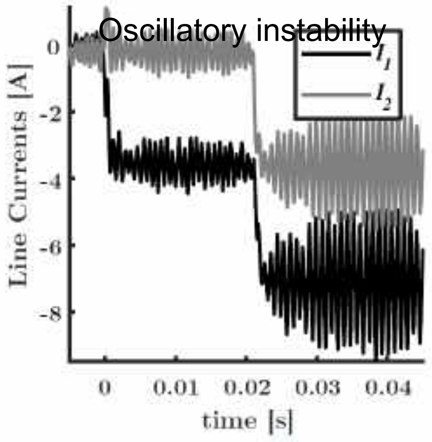
- Voltage instability (blackout)
- Oscillatory stability



Voltage instability (blackout)



Oscillatory instability



N. H. van der Blij, L. M. Ramirez-Elizondo, M. T. J. Spaan and P. Bauer, Stability and Decentralized Control of Plug-and-Play DC Distribution Grids", IEEE Access, vol. 6, 2018

Plug-and-Play Stability Criteria

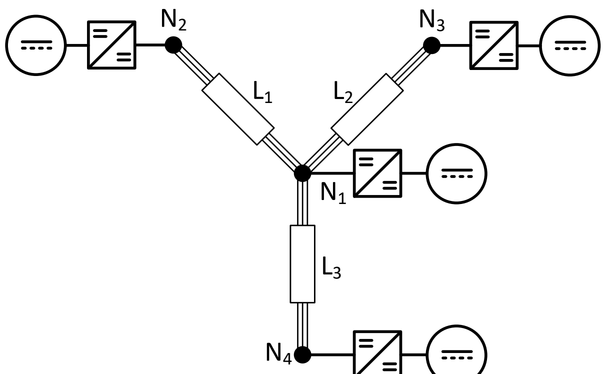
Lyapunov stability guidelines from a Brayton-Moser representation of the system:

$$P_\Sigma \leq \frac{U_0^2}{4(Z_s + R_\Sigma)}$$

$$P_\Sigma \leq \frac{U_{\min}(U_0 - U_{\min})}{Z_s + R_\Sigma}$$

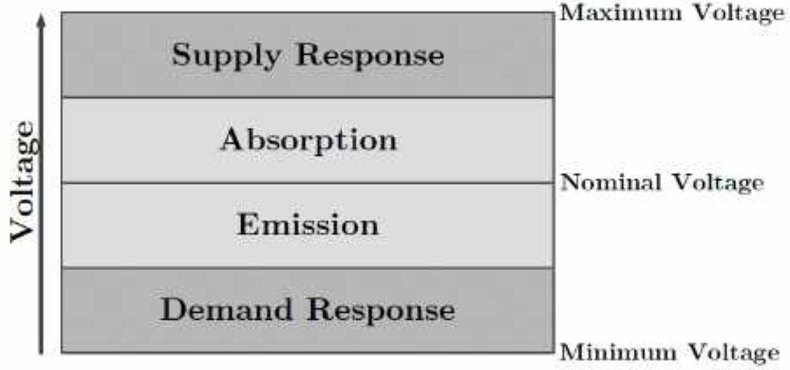
$$P_\Sigma \leq \frac{U_{\min}^2}{Z_s + R_\Sigma}$$

$$P_l \leq C_l U_{\min}^2 \min\left(\frac{R_j}{L_j}, \frac{1}{C_s Z_s}\right)$$



Plug-and-play stability can be achieved by:

- The output capacitance of constant power loads needs to be designed appropriately
- Control needs to ensure that demand and supply response



Roadmap for DC Systems

DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

DC microgrids / DC links
- Towards local generation local use (storage, EVs)
- Cellular concept
- Sizing (optimization)
- Protection, grounding
- Stability of DC grids
- Optimal power flow
- Power flow controller
- Demand side management
- Data over power line
- Power management
- Markets
- Harmonics

Roadmap for DC Systems

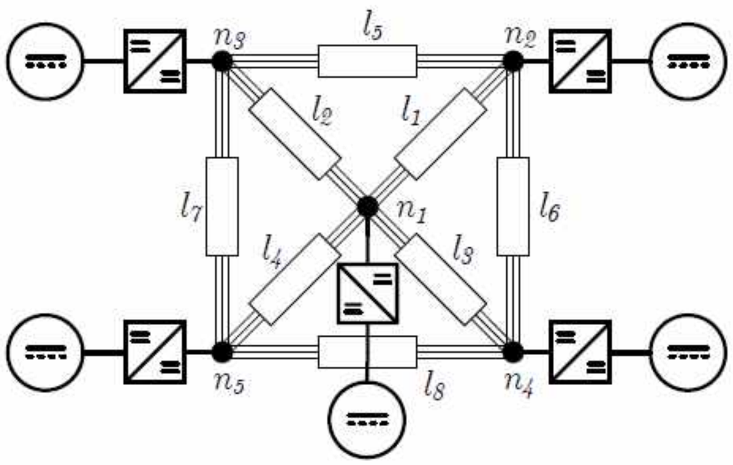
DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

DC microgrids / DC links
- Towards local generation local use (storage, EVs)
- Cellular concept
- Sizing (optimization)
- Protection, grounding
- Stability of DC grids
- **Optimal power flow**
- Power flow controller
- Demand side management
- Data over power line
- Power management
- Markets
- Harmonics

TUDelft

Power Flow



Current in each line, and each node:

$$I_L = R^{-1}\Gamma U_N$$
$$I_N = \Gamma^T I_L = \Gamma^T R^{-1}\Gamma U_N = Y U_N$$

Consequently, the system is quadratic:

$$P_N = \langle U_N, Y U_N \rangle$$

Direct Matrix Approximation:

- One node is either a slack node, or referenced to a specified voltage
- Iterations are made between determining the converter currents and calculating the node voltages

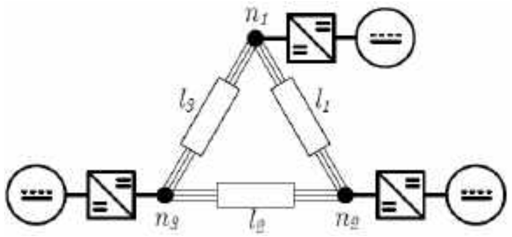
$$\check{U}_N^{k+1} = \check{Y}^{-1}\left(\begin{bmatrix} \frac{P_1}{U_1^k} \\ \vdots \\ \frac{P_n}{U_n^k} \end{bmatrix} - I_0\right)$$

N. H. van der Blij, L. M. Ramirez-Elizondo, M. T. J. Spaan and P. Bauer, A State-Space Approach to Modelling DC Distribution Systems", IEEE Transactions on Power Systems, vol. 33, no. 1, Jan. 2018.

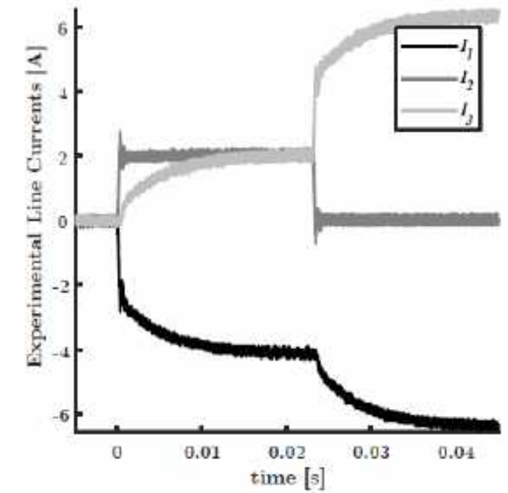
Dynamic Modelling

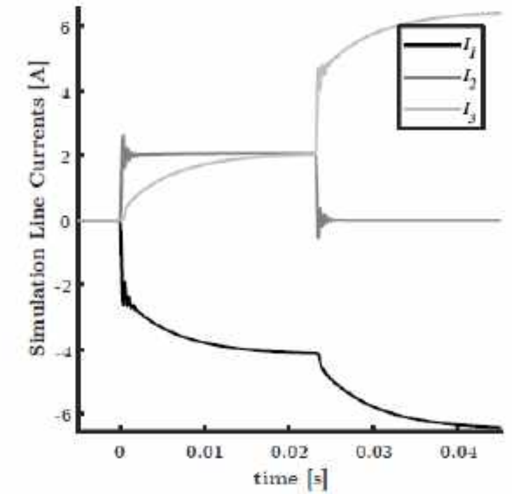
State-space model:

$$C\dot{U}_N = I_{\text{net}} \qquad \longrightarrow \qquad C\dot{U}_N = I_N - \Gamma^T I_L - GU_N$$
$$L\dot{I}_L = U_L, \qquad \qquad \qquad L\dot{I}_L = \Gamma U_N - RI_L$$



t [ms]	U_d [V]	Z_d [Ω]	P_2^* [W]	P_3^* [W]
-5	350	1	0	0
0	350	1	2100	0
23	350	1	2100	2100





Roadmap for DC Systems

DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

DC microgrids / DC links
- Towards local generation local use (storage, EVs)
- Cellular concept
- Sizing (optimization)
- Protection, grounding
- Stability of DC grids
- Optimal power flow
- Power flow controller
- Demand side management
- Data over power line
- Power management
- Markets
- Harmonics

TU Delft

Roadmap for DC Systems

DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

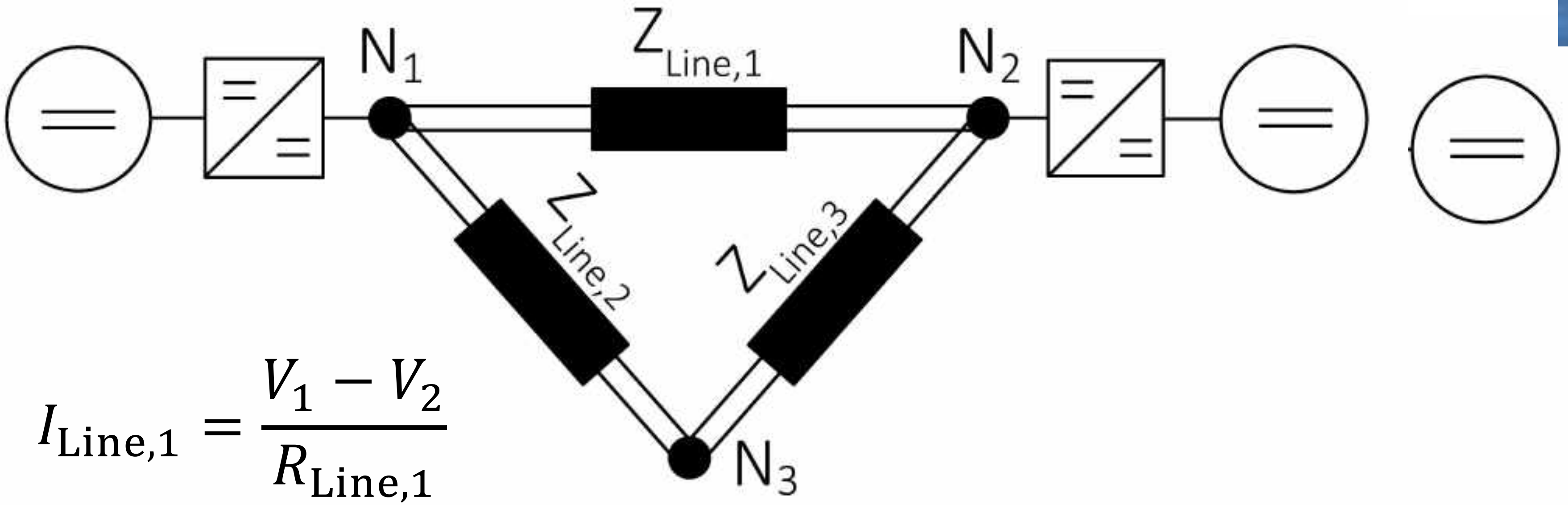
DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

DC microgrids / DC links
- Towards local generation local use (storage, EVs)
- Cellular concept
- Sizing (optimization)
- Protection, grounding
- Stability of DC grids
- Optimal power flow
- **Power flow controller**
- Demand side management
- Data over power line
- Power management
- Markets
- Harmonics

TU Delft

Power Flow in Meshed LVDC

Pavel Purgat

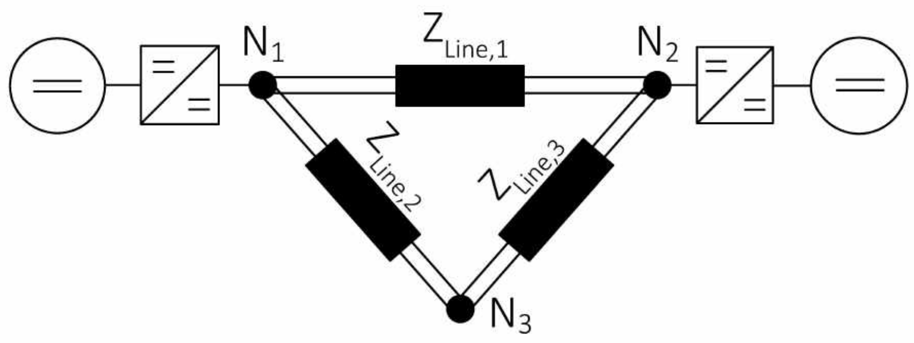


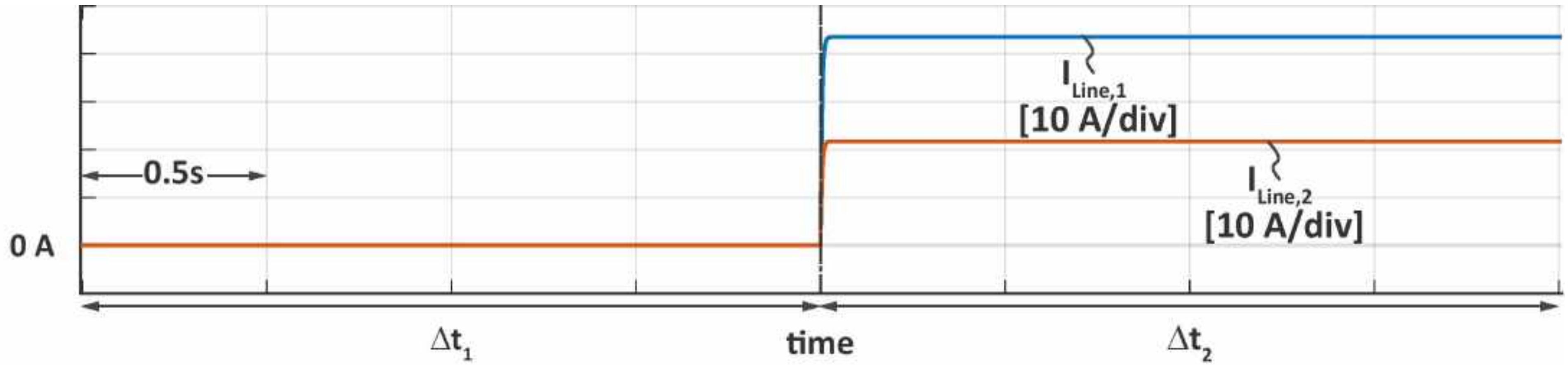
$$I_{\text{Line},1} = \frac{V_1 - V_2}{R_{\text{Line},1}}$$

$$I_{\text{Line},2} = I_{\text{Line},3} = \frac{V_1 - V_2}{R_{\text{Line},2} + R_{\text{Line},3}}$$

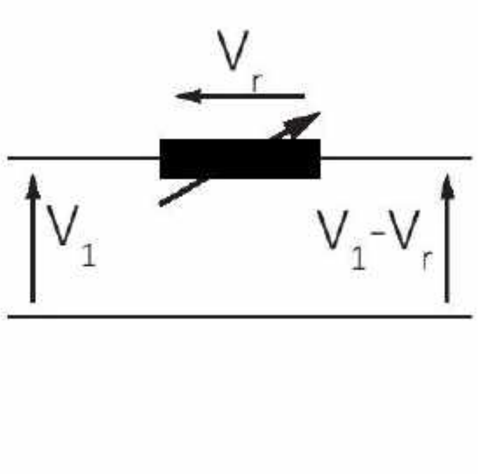
P. Purgat, N. H. van der Blij, Z. Qin and P. Bauer, "Partially Rated Power Flow Control Converter Modeling for Low Voltage DC Grids", IEEE Journal of Emerging and Selected Topics in Power Electronics, 2019

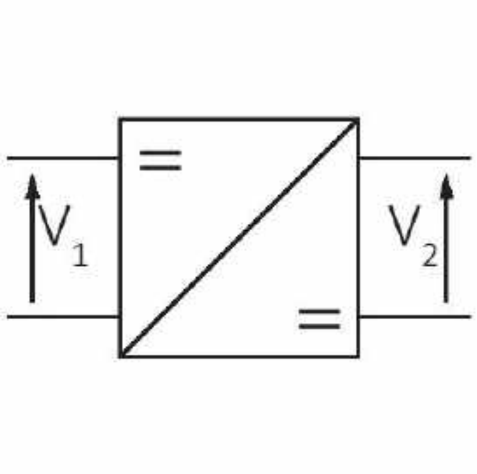
Power Flow in Meshed LVDC

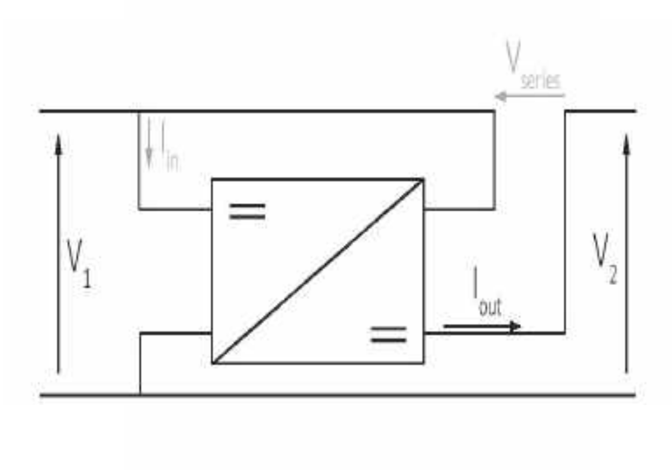




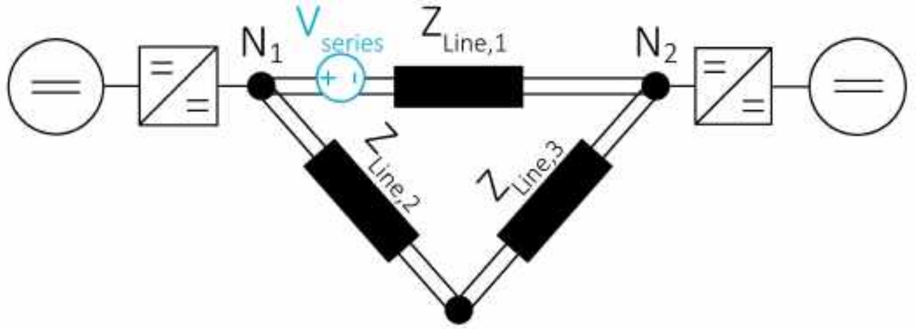
Power Flow in Meshed LVDC

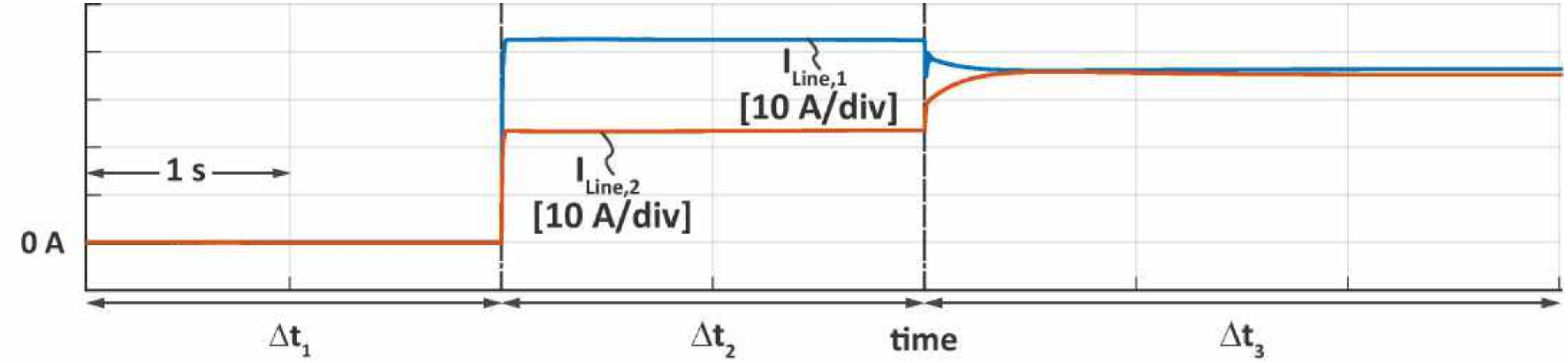






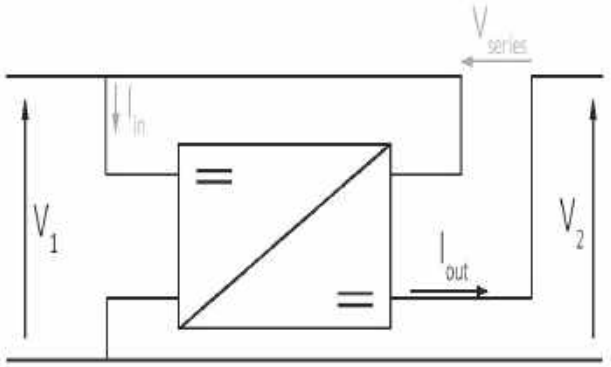
Power Flow Control Converter

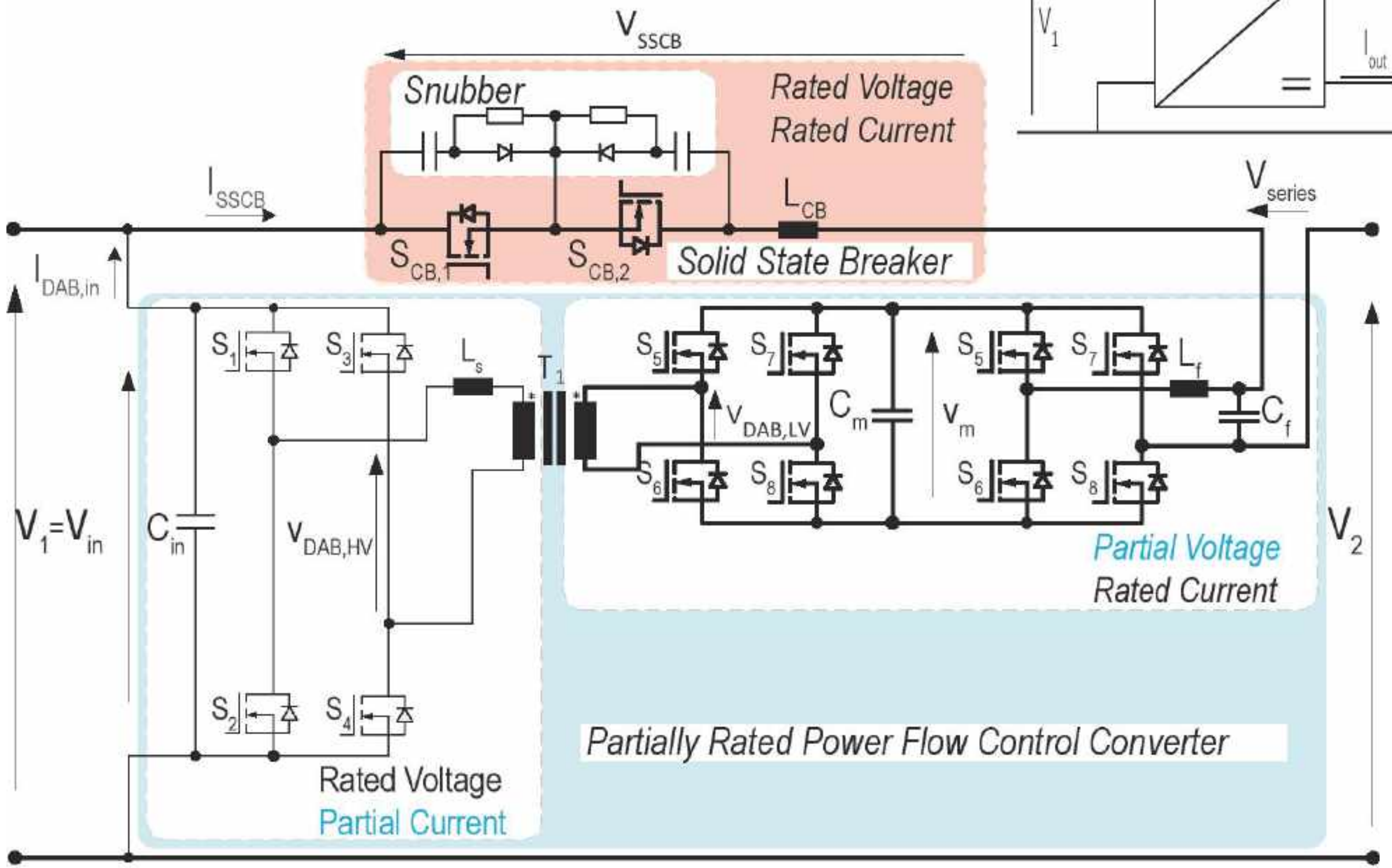




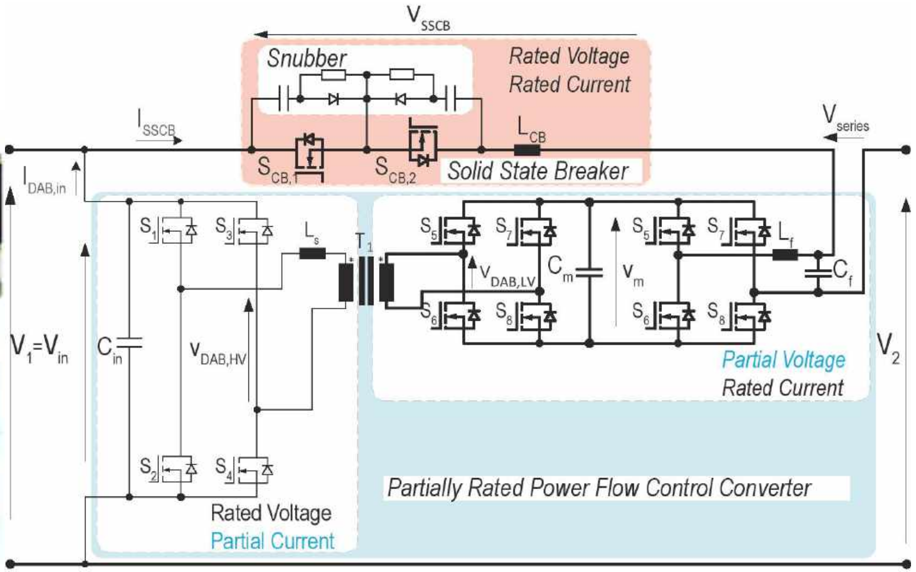
TUDelft

Power Flow Control Converter





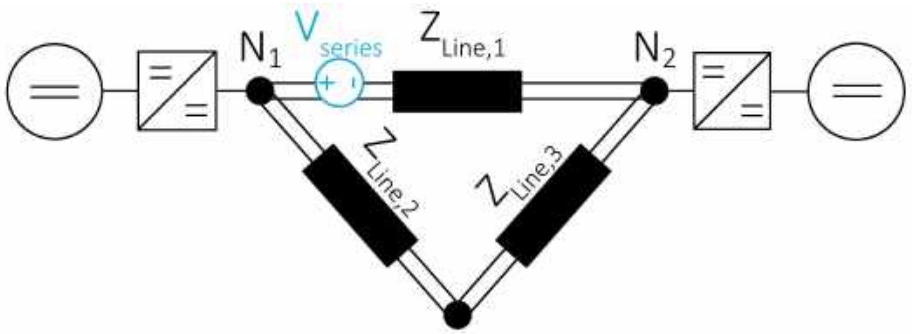
Power Flow Control Converter

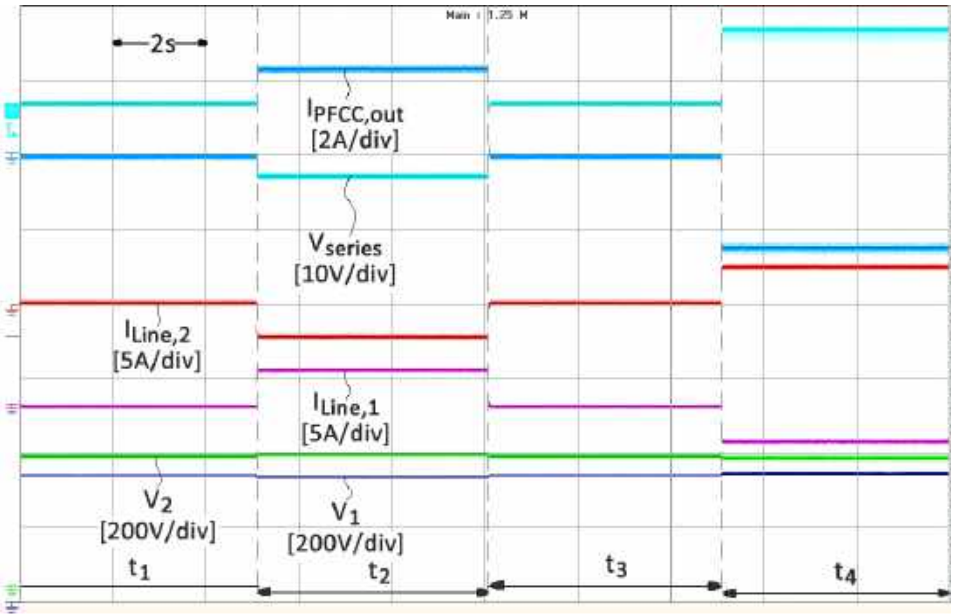


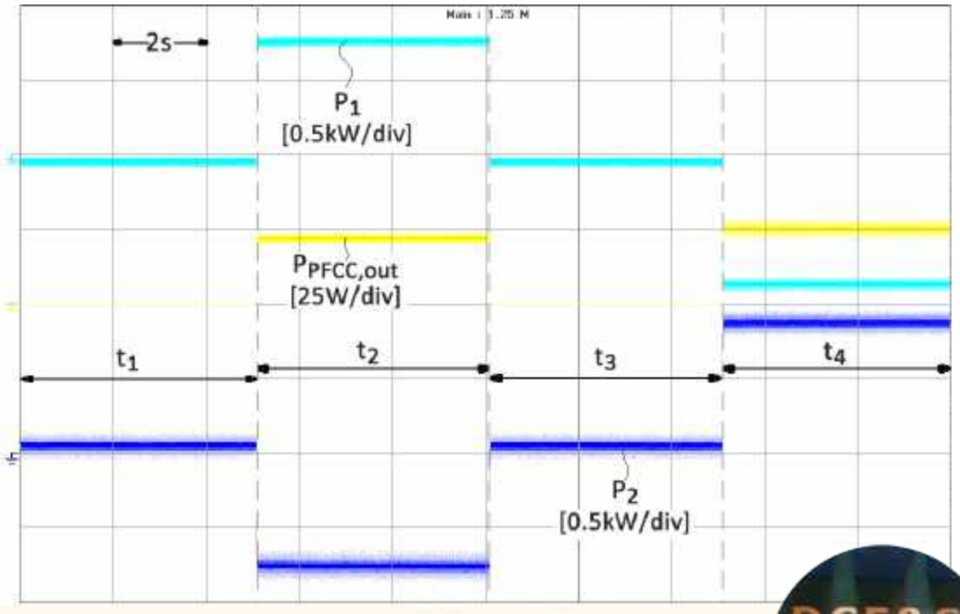
Switching Frequency	< 100 kHz
HV Voltage Rating	< 800 V

Si & SiC MOSFETs

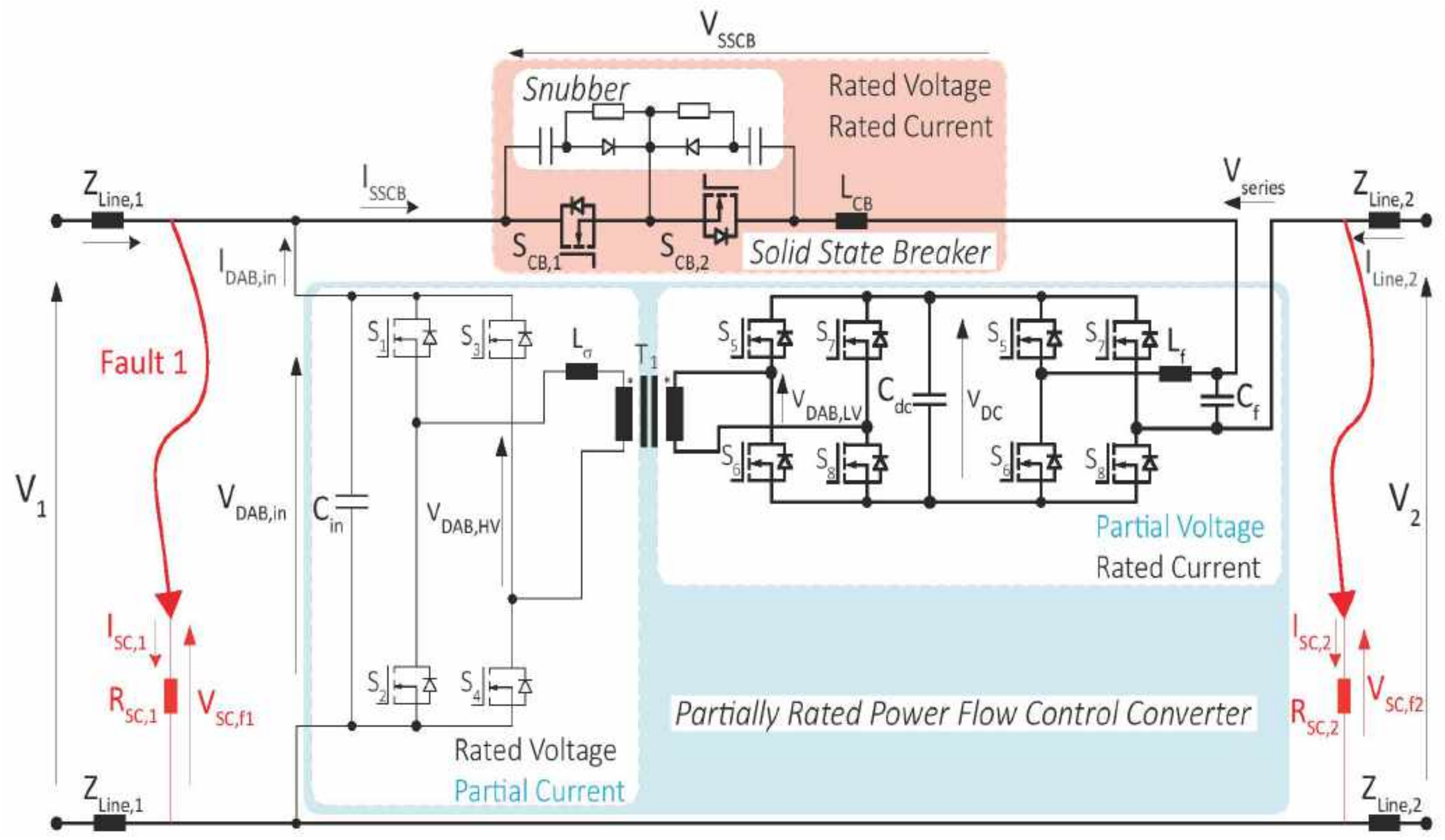
Testing


N1
Vseries
ZLine,1
N2
ZLine,2
ZLine,3

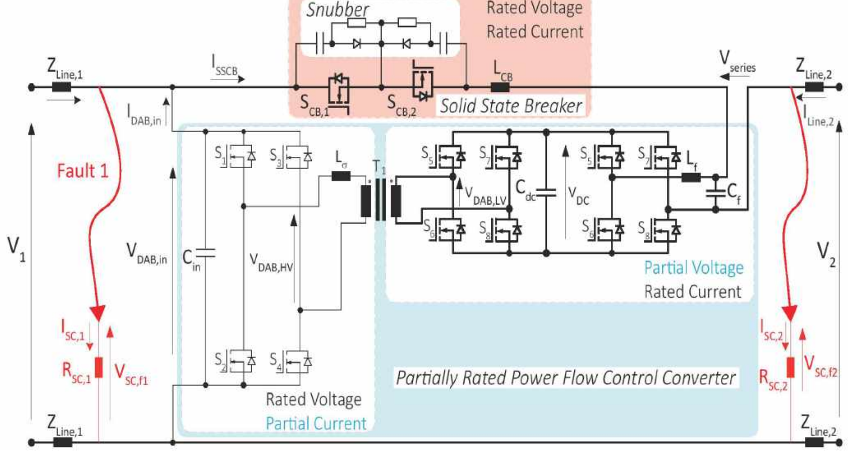

2s
IPFCC,out
[2A/div]
Vseries
[10V/div]
ILine,2
[5A/div]
ILine,1
[5A/div]
V2
[200V/div]
V1
[200V/div]
t1
t2
t3
t4

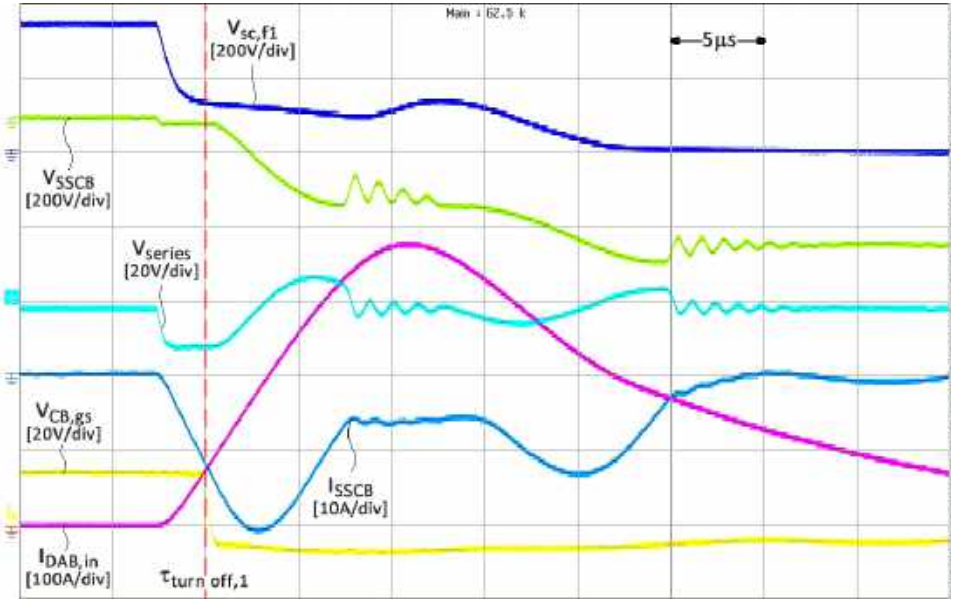

2s
P1
[0.5kW/div]
PPFCC,out
[25W/div]
t1
t2
t3
t4
P2
[0.5kW/div]

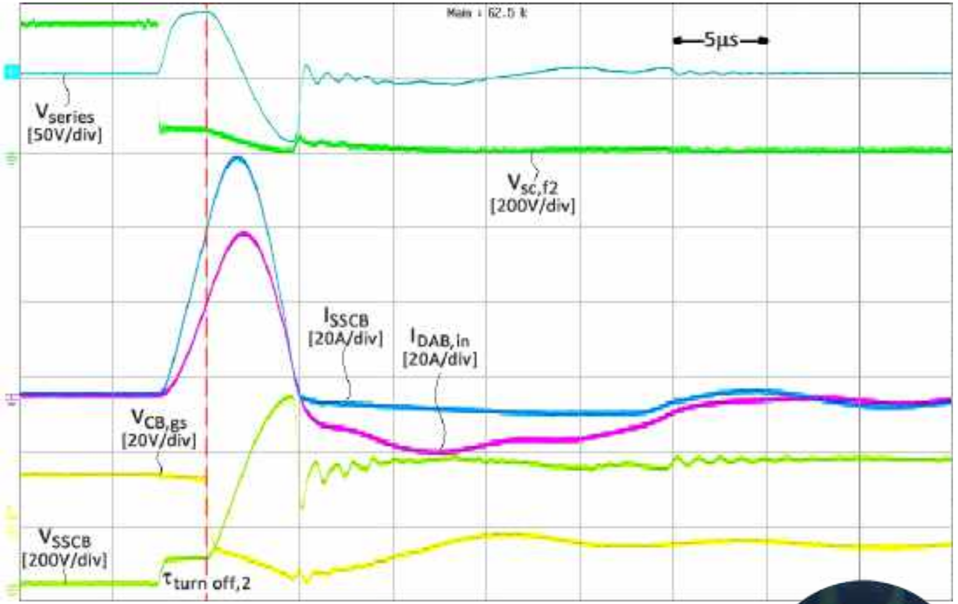
Power Flow Control Converter



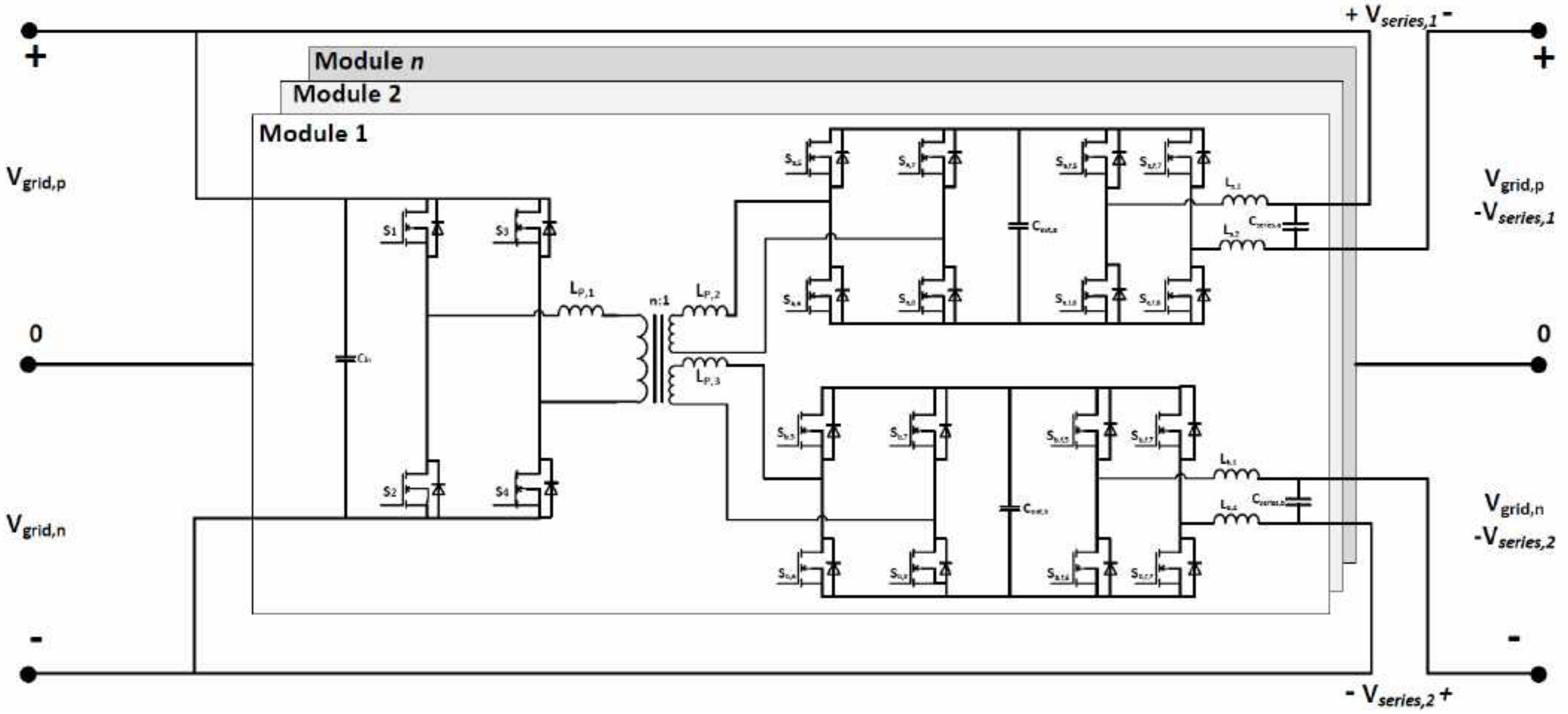
Testing – Short Circuit



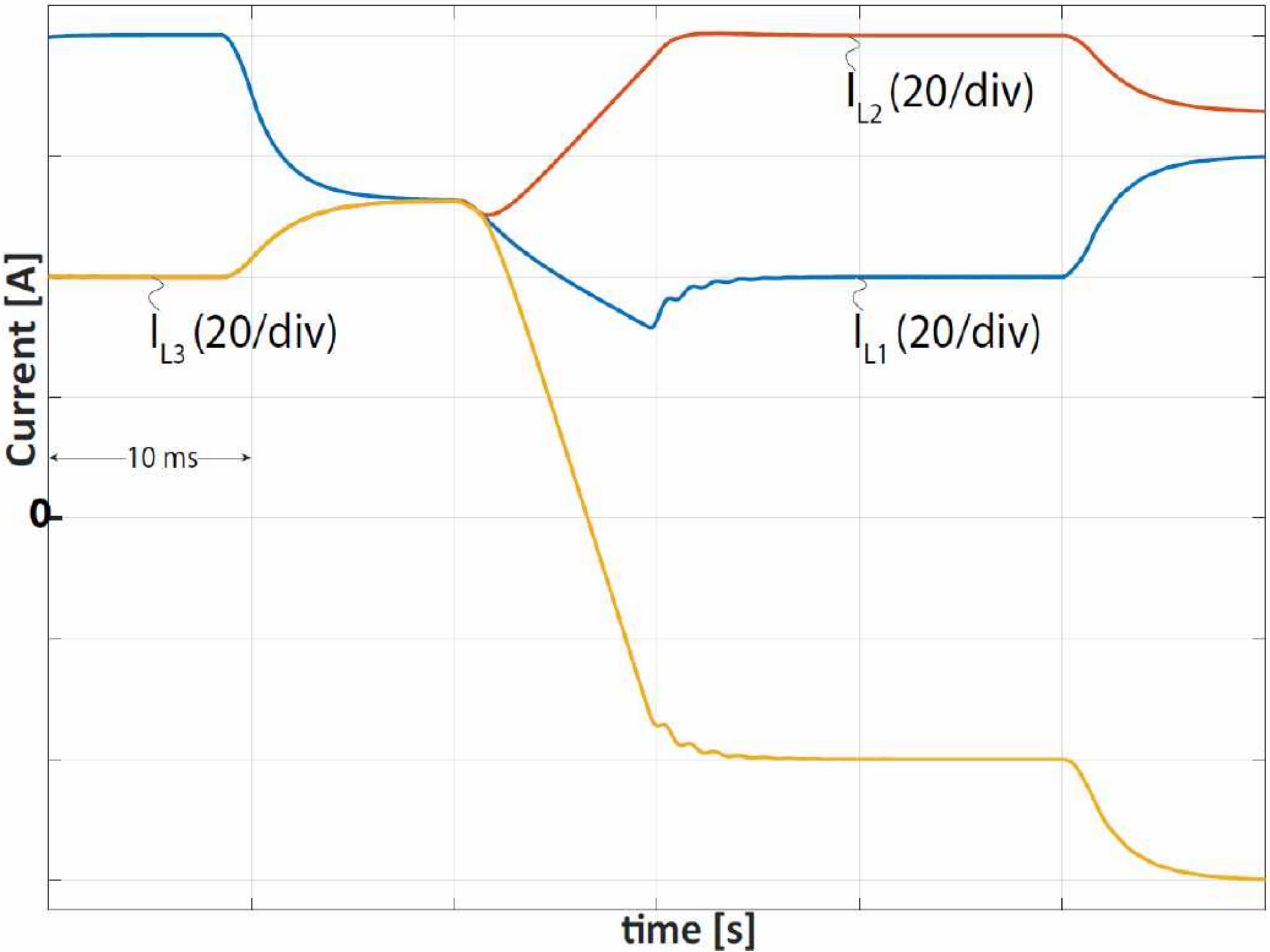




THE PFCC FOR BIPOLAR LVDC DISTRIBUTION



+
control board



I_{L2} (20/div)
I_{L3} (20/div)
I_{L1} (20/div)
Current [A]
10 ms
0
time [s]

Roadmap for DC Systems

DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

DC microgrids / DC links
- Towards local generation local use (storage, EVs)
- Cellular concept
- Sizing (optimization)
- Protection, grounding
- Stability of DC grids
- Optimal power flow
- Power flow controller
- Demand side management
- Data over power line
- Power management
- Markets
- Harmonics

Roadmap for DC Systems

DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

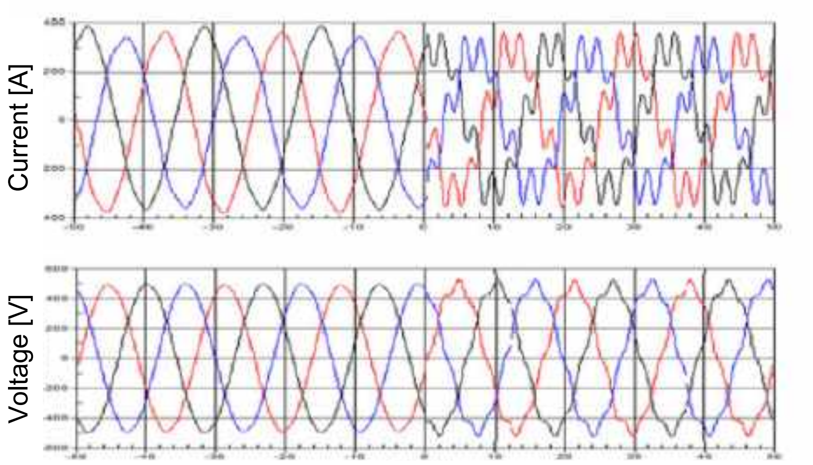
DC microgrids / DC links
- Towards local generation local use (storage, EVs)
- Cellular concept
- Sizing (optimization)
- Protection, grounding
- Stability of DC grids
- Optimal power flow
- Power flow controller
- Demand side management
- Data over power line
- Power management
- Markets
- **Harmonics**

Integration of Power Electronics

- Studying integration problems in systems with high population of power electronics
- Ensuring the stable joint operation of multiple power electronic converters
- Developing and testing control measures for smartly compensating distortions in AC and DC grids

Lucia Beloqui Larumbe

PV farms[1]



Designing and testing remedial measures

Roadmap for DC Systems

DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

DC microgrids / DC links
- Towards local generation local use (storage, EVs)
- Cellular concept
- Sizing (optimization)
- Protection, grounding
- Stability of DC grids
- Optimal power flow
- Demand side management
- Data over power line
- Power management
- Markets
- Harmonics

Radial DC grids
- Connecting DC microgrids
- **Refurbishing the system for (partially) DC infra**
- Modular converters with integrated protection
- Integrated control market approach
- Integrating cells/microgrids
- Interface, interact, integrate

TUDelft

Roadmap for DC Systems

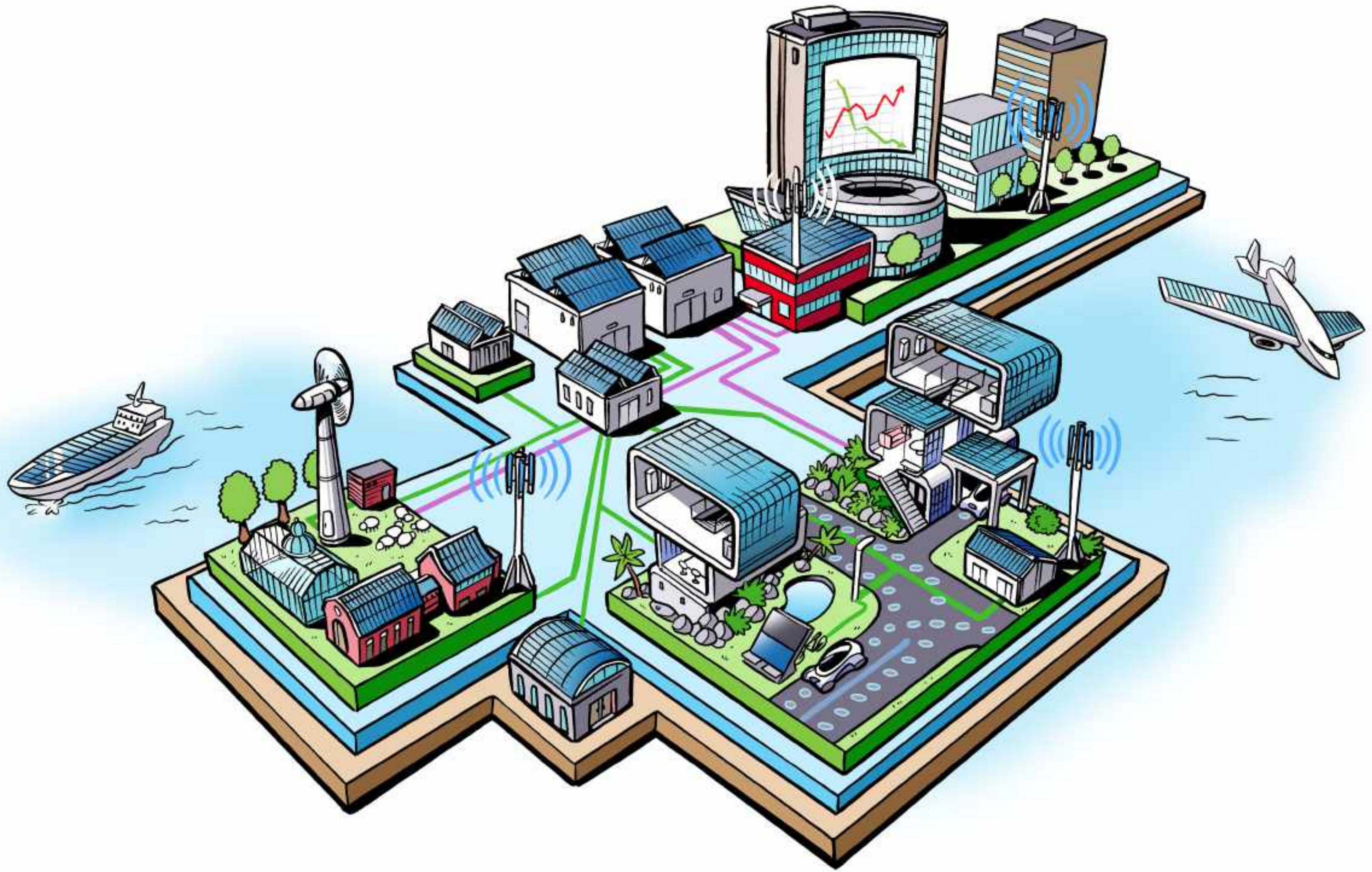
DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

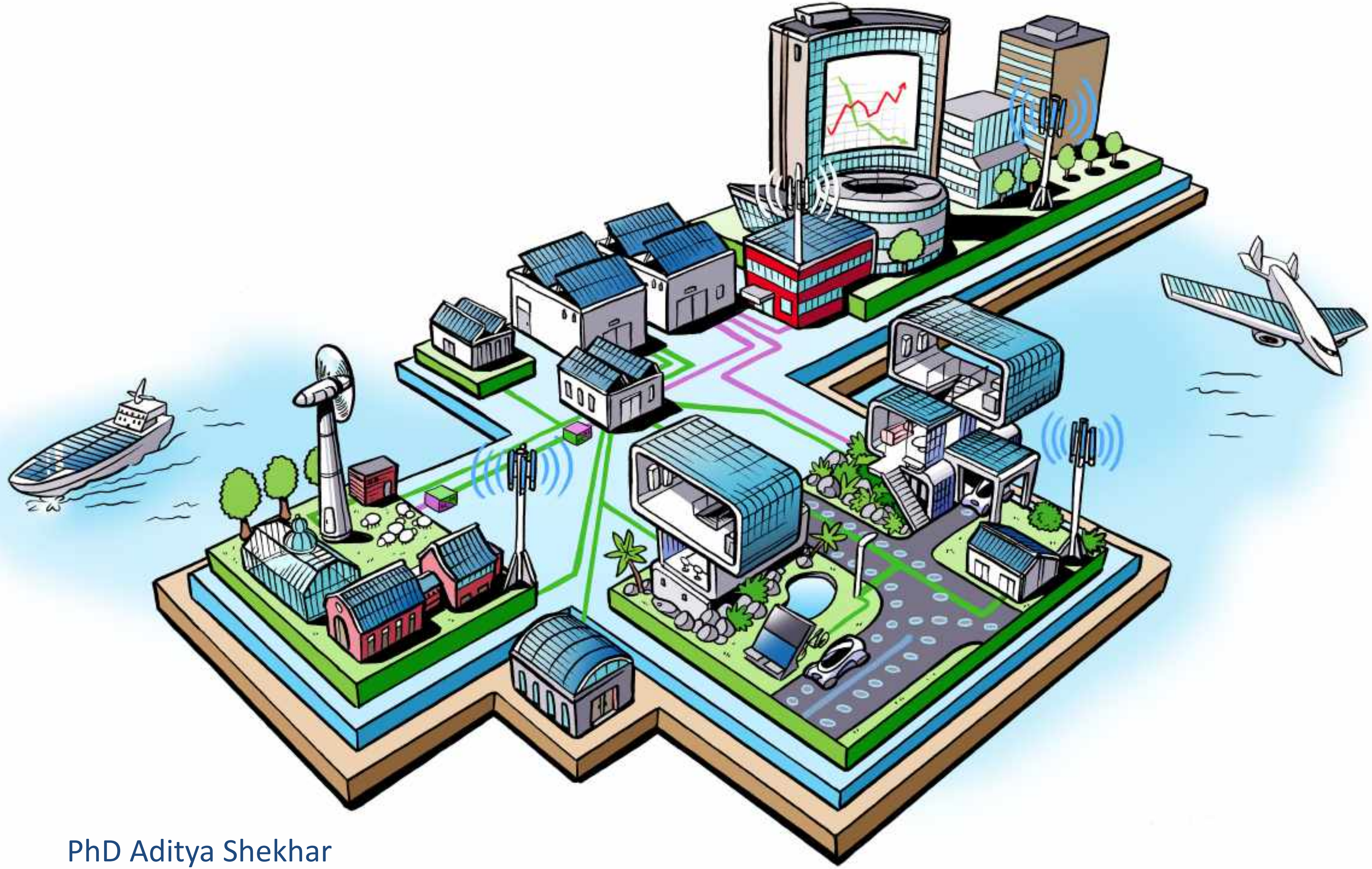
DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

DC microgrids / DC links
- Towards local generation local use (storage, EVs)
- Cellular concept
- Sizing (optimization)
- Protection, grounding
- Stability of DC grids
- Optimal power flow
- Demand side management
- Data over power line
- Power management
- Markets
- Harmonics

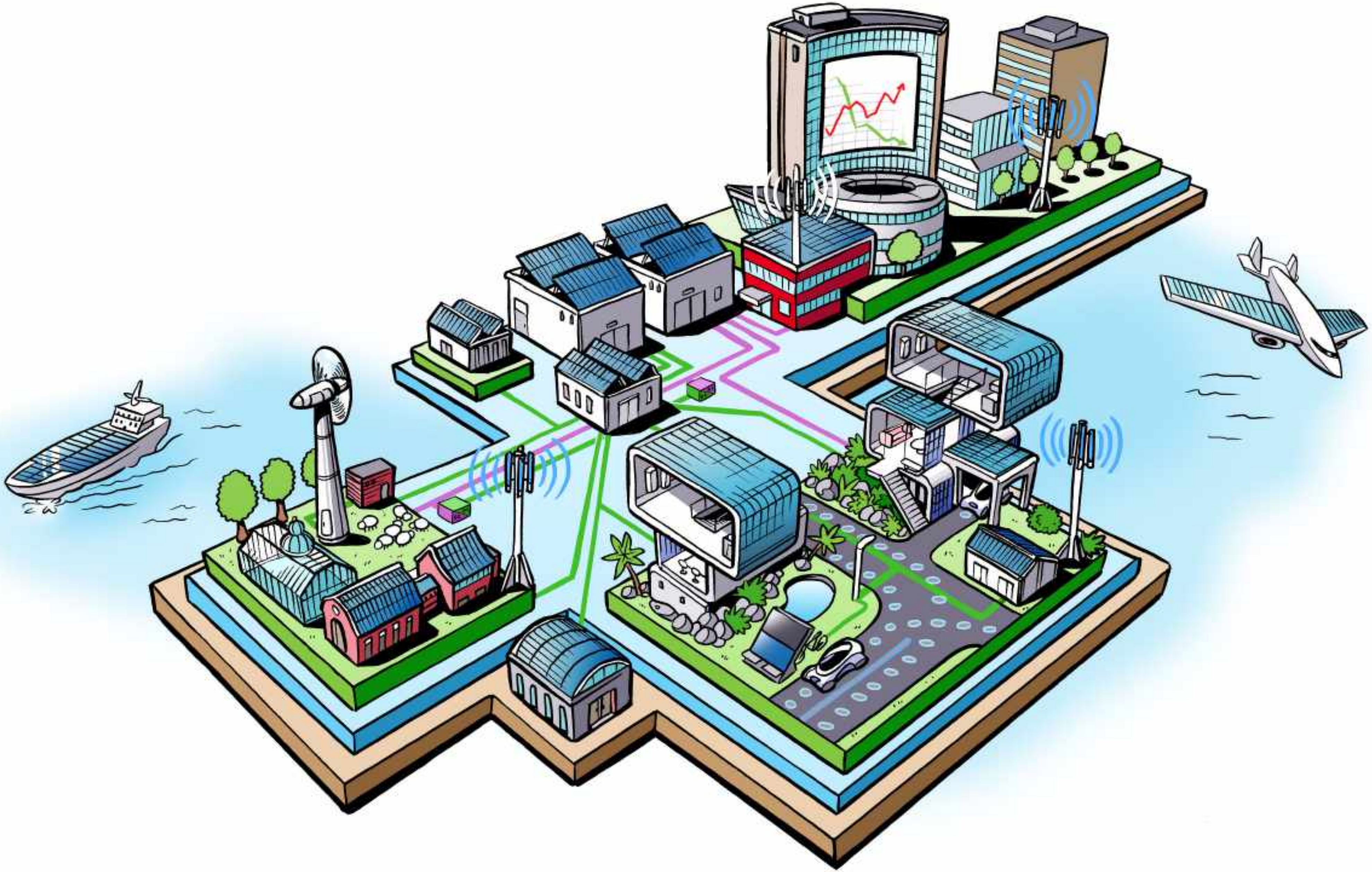
Radial DC grids
- Connecting DC microgrids
- Refurbishing the system for (partially) DC infra
- Modular converters with integrated protection
- Integrated control market approach
- Integrating cells/microgrids
- Interface, interact, integrate

TU Delft



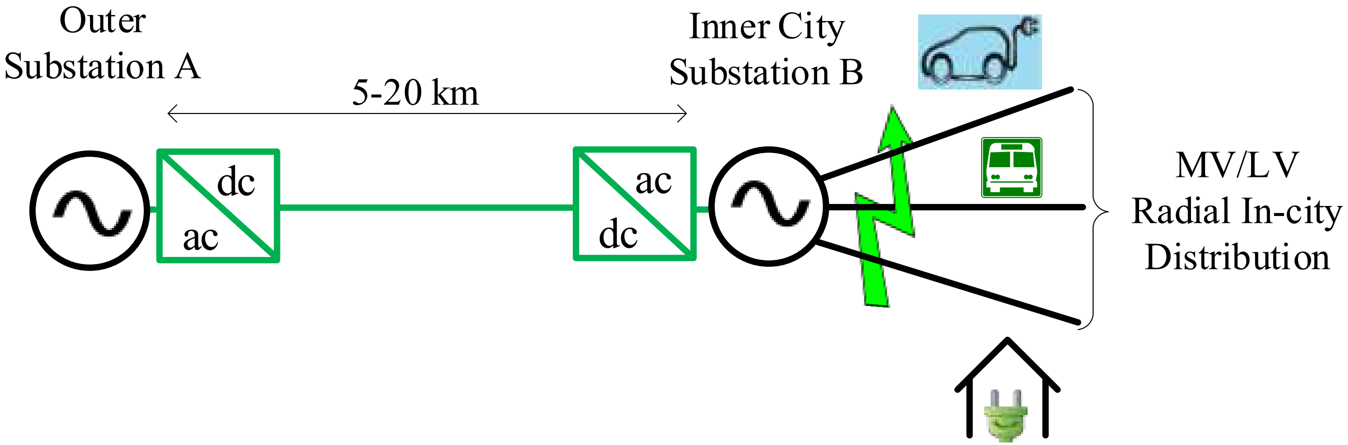


PhD Aditya Shekhar



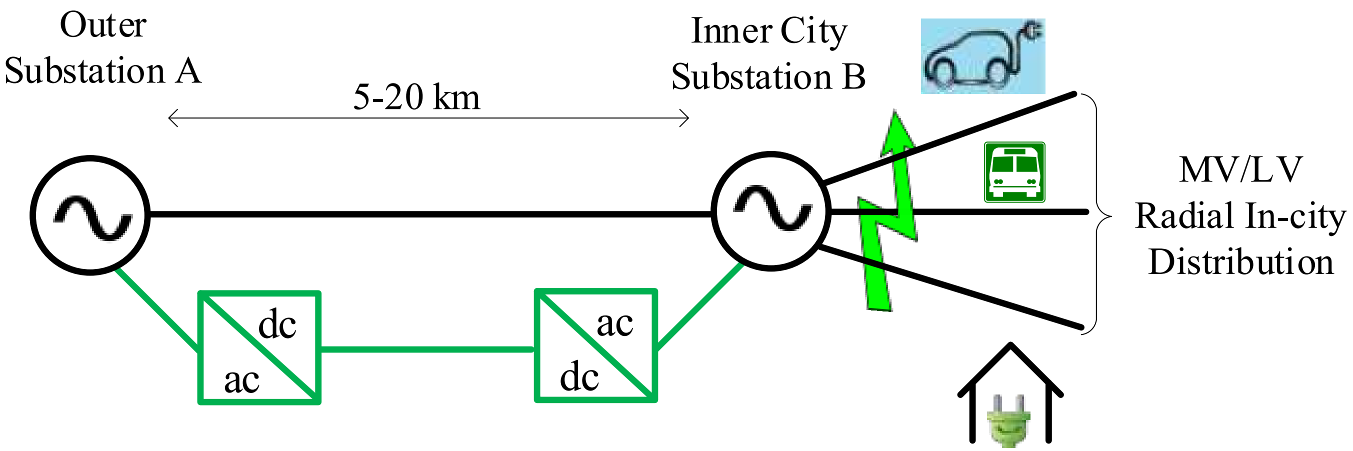
Refurbished AC to DC Links

PhD Topic of Aditya Shekhar



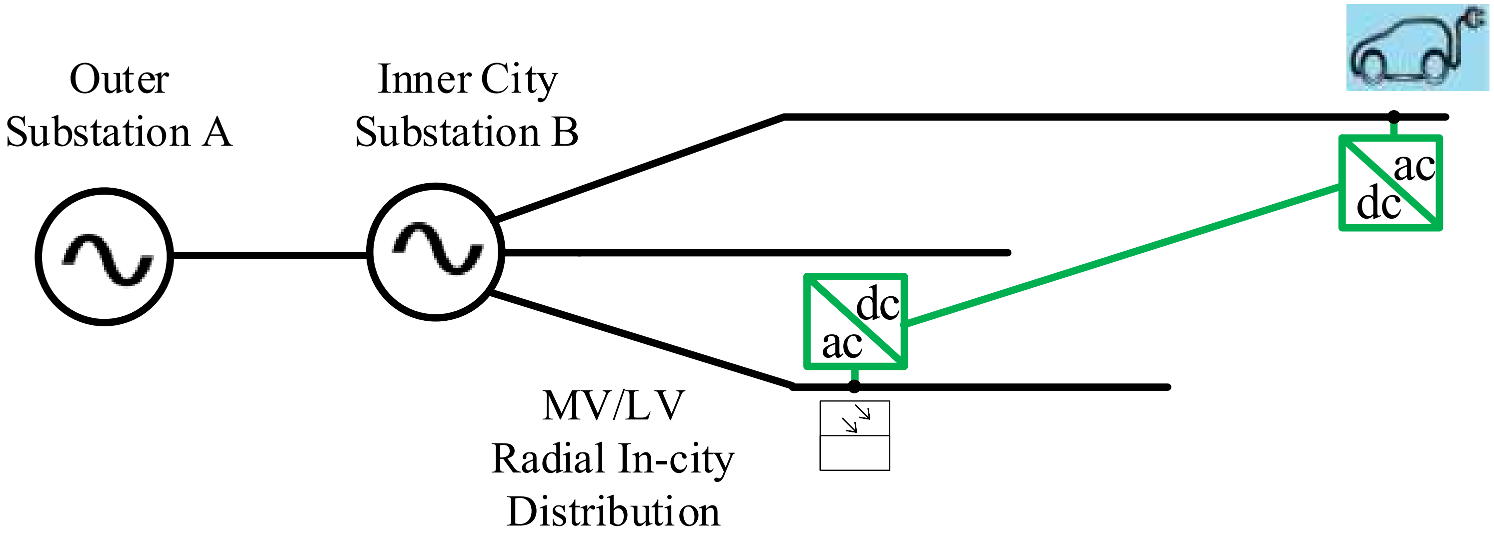
- existing ac link conductors can be refurbished to operate under dc by bringing two converters at each end

Parallel AC-DC Reconfigurable Links



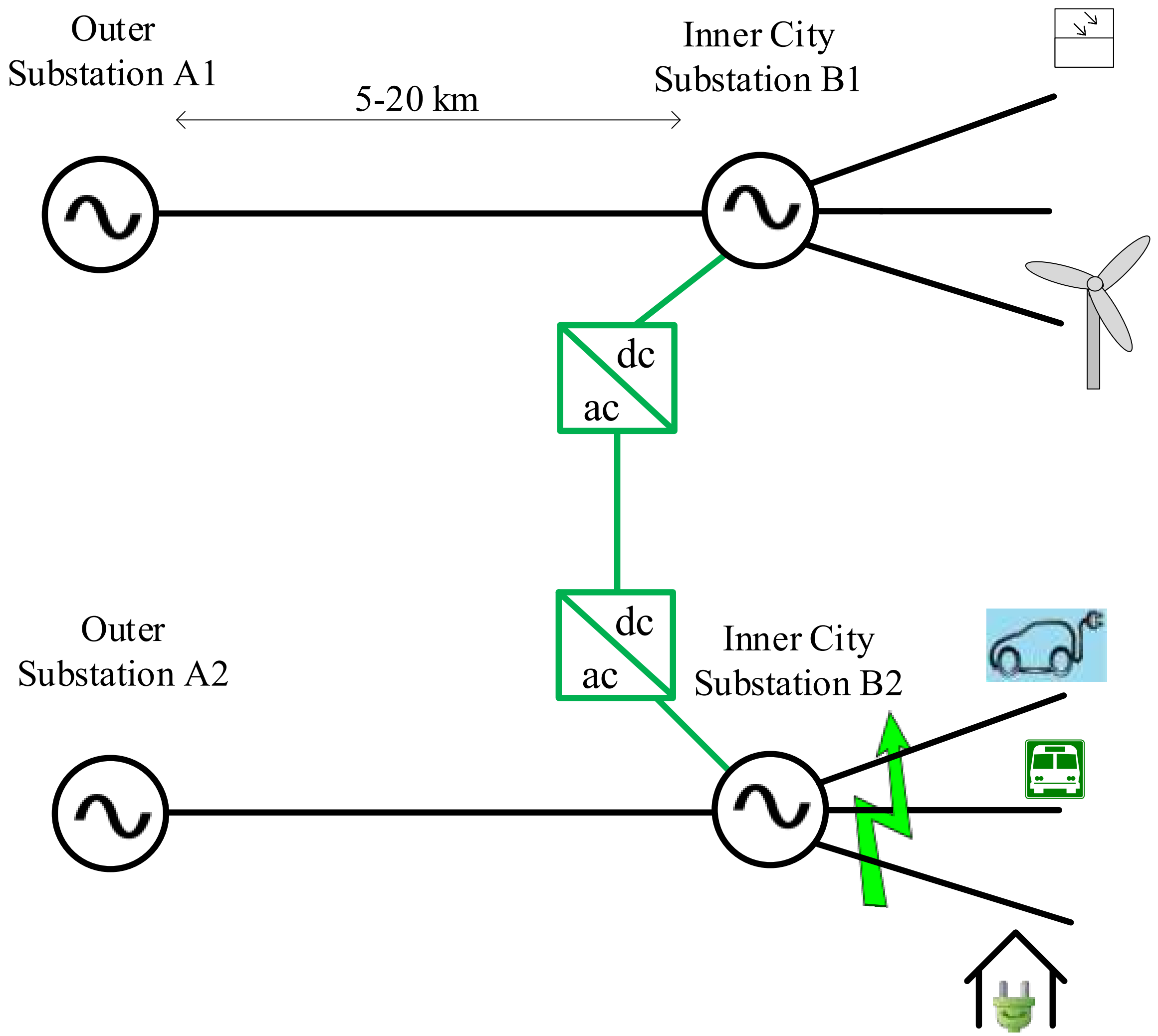
- In most cases, the bulk power transfer link depicted in figure consists of multiple conductors for double, triple or more three phase links.
- parallel ac-dc operation can offer the same power capacity using reconfiguration techniques. The active power can be steered using the dc link converters to run the system at maximal efficiency for any load demand.

In-City Compact Power Redirection



- power can be redirected compactly within the same geographical area from local areas of excess generation to those with higher demand.

Zonal Interconnection



- Zonal interconnection for efficient power transfer between different geographical locations can be advantageous in achieving lower distribution losses

Capacity Enhancement

Link length = 10 km, Load power factor = 0,9, XLPE Medium Voltage Cable

Current Enhancement

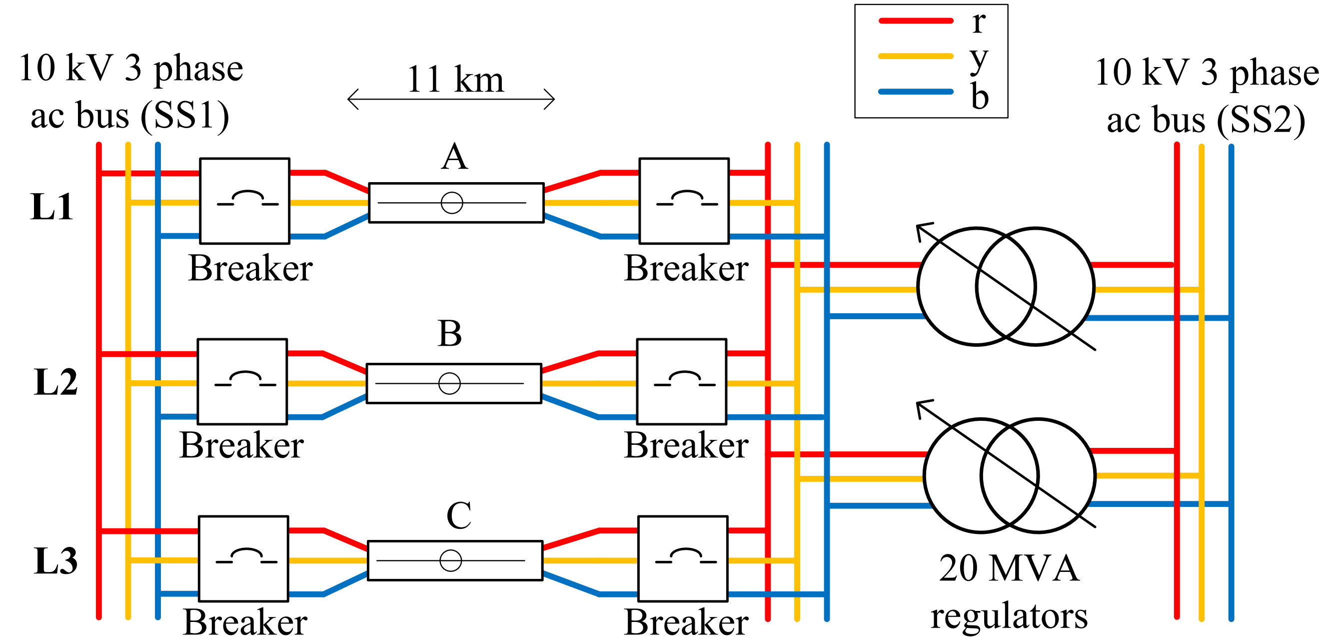
Dielectric Losses	Skin Effect	Thermal Proximity
$P_{\text{loss,ac}} = V_{\text{ac,rated}}^2 (C_{\text{ph}}\omega) tan(\delta)$ $P_{\text{loss,dc}} = \frac{\sqrt{2} V_{\text{ac,rated}}^2 (2\pi r)}{\rho_{\text{ins}}}$	$I_{\text{dc,rated}} = \sqrt{\frac{I_{\text{ac,rated}}^2 R_{\text{ac,90}}}{R_{\text{dc,90}}}}$	$I_{\text{dc,rated}} = k_{\text{tp}} \sqrt{\frac{I_{\text{ac,rated}}^2 R_{\text{ac,90}}}{R_{\text{dc,90}}}}$

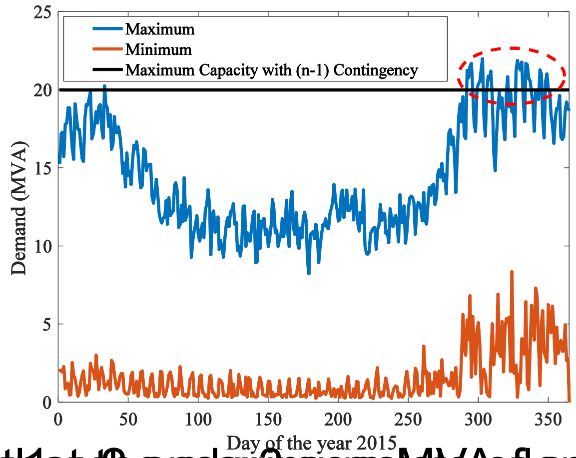
- **Correction factor relevant for special cases**

TU Delft

A. Shekhar, E. Kontos, L. Ramírez-Elizondo , A. R. Mor and P. Bauer, "Grid Capacity and Efficiency Enhancement by Operating Medium Voltage AC Cables as DC Links with Modular Multilevel Converters," International Journal of Electrical Power & Energy Systems, Volume 93, December 2017, Pages 479-493

CASE-STUDY: ALLIANDER'S MV DISTRIBUTION SYSTEM

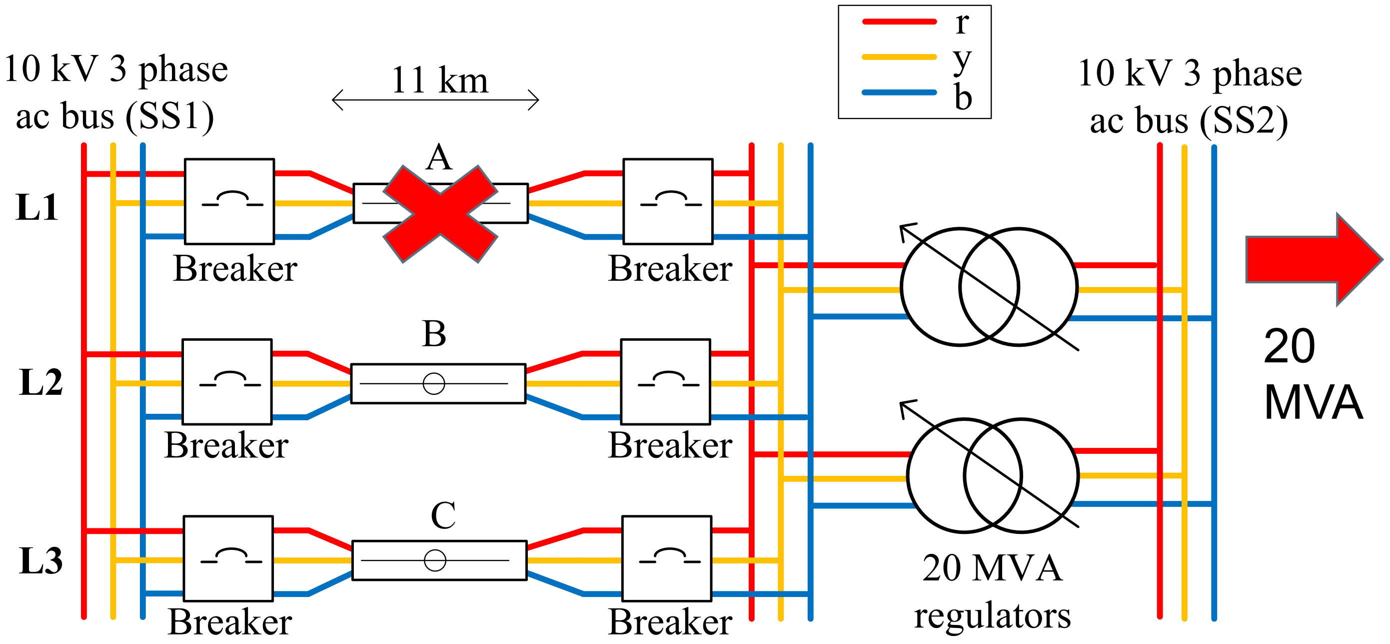


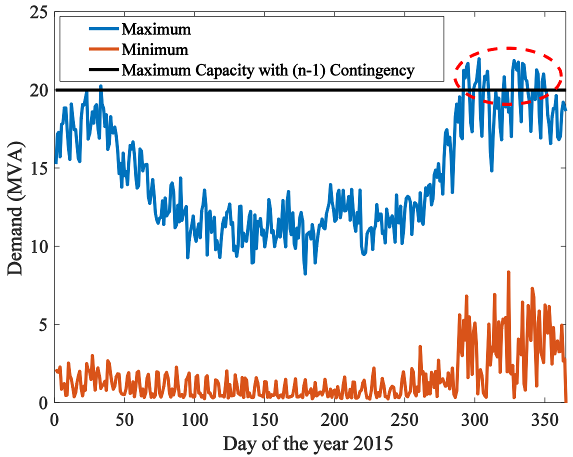


It can be observed that the maximum demand exceeds the limit of (n-1) contingency several times

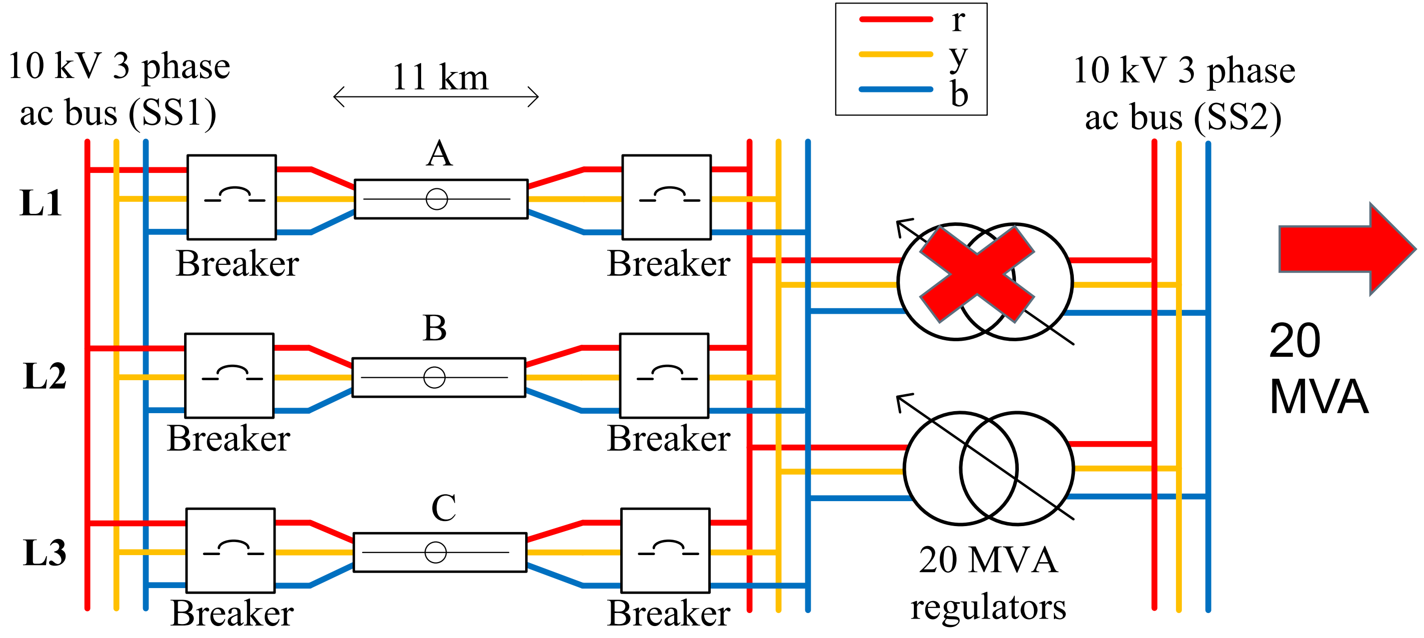
Each transmission link L1, L2 and L3 consists of a 3 phase, crosslinked polyethylene (XLPE) 3x1x630A aluminium cored cables A, B and C

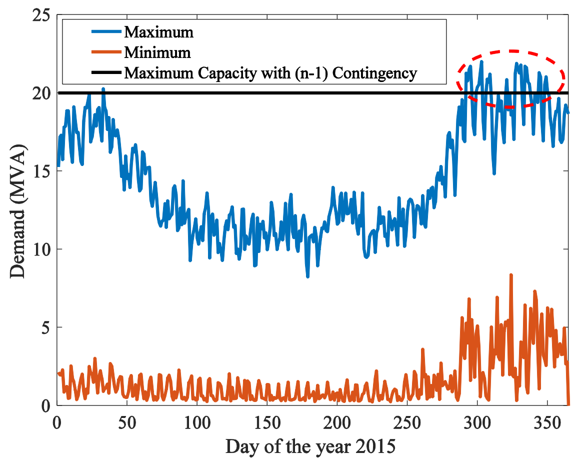
ALLIANDER'S SYSTEM



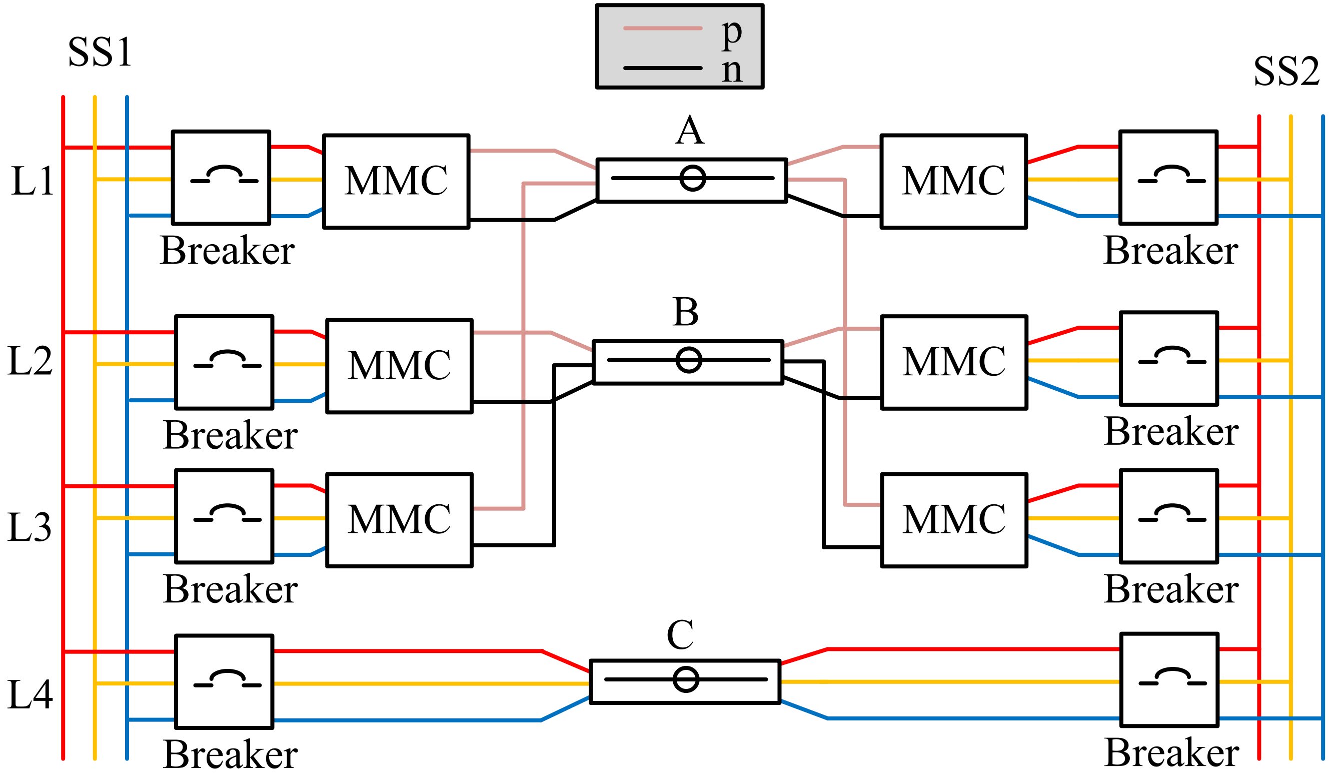


ALLIANDER'S SYSTEM





PROPOSED TOPOLOGY 1



- During normal operation proposed topology has a capacity of 40 MVA as against 30 MVA for the original system
- refurbished 6 conductors of 3-core cables A and B to operate as dc links .

Roadmap for DC Systems

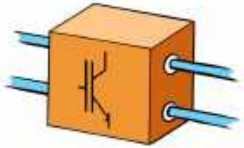
DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

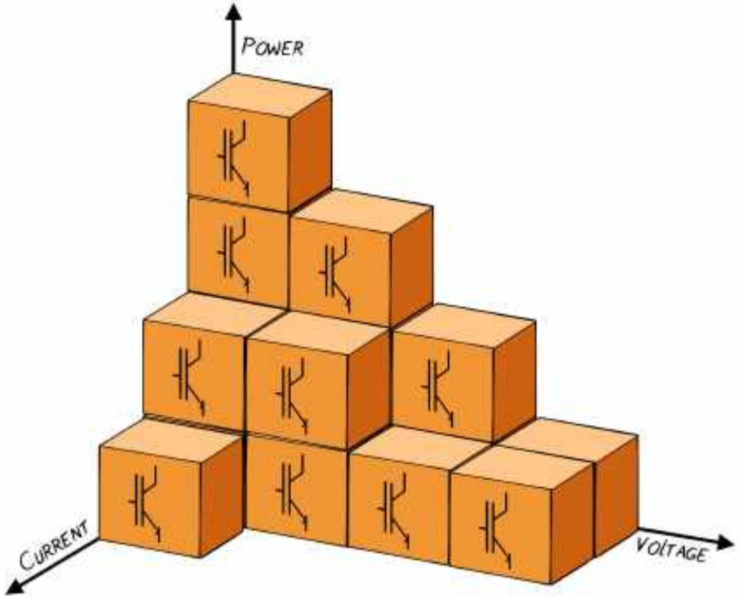
DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

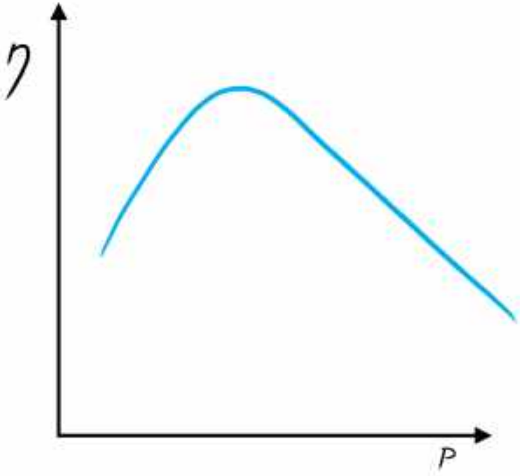
DC microgrids / DC links
- Towards local generation local use (storage, EVs)
- Cellular concept
- Sizing (optimization)
- Protection, grounding
- Stability of DC grids
- Optimal power flow
- Demand side management
- Data over power line
- Power management
- Markets
- Enabling Blockchain

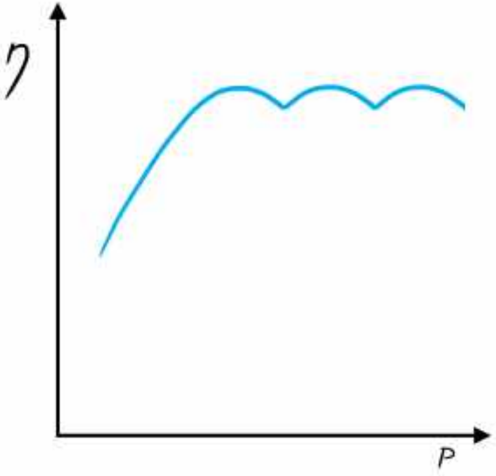
Radial DC grids
- Connecting DC microgrids
- Refurbishing the system for (partially) DC infra
- **Modular converters with integrated protection**
- Integrated control market approach
- Integrating cells/microgrids
- Interface, interact, integrate

Modularity





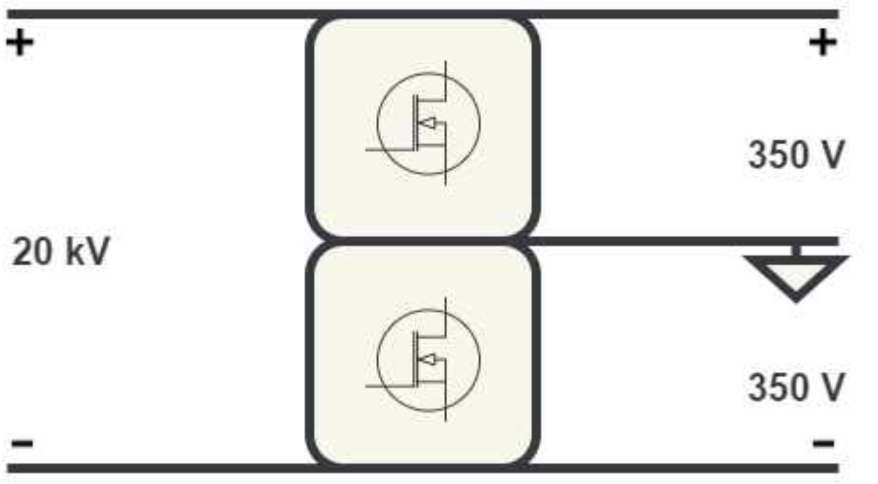




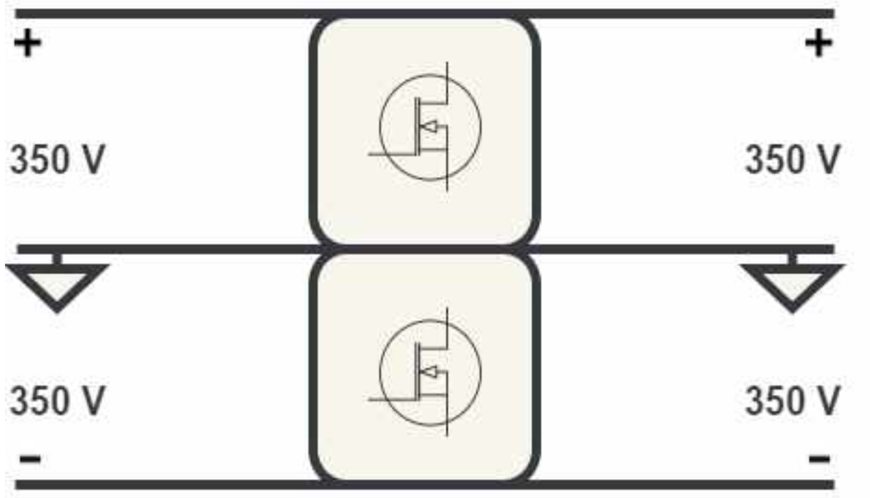
TU Delft

PhD Pavel Purgat

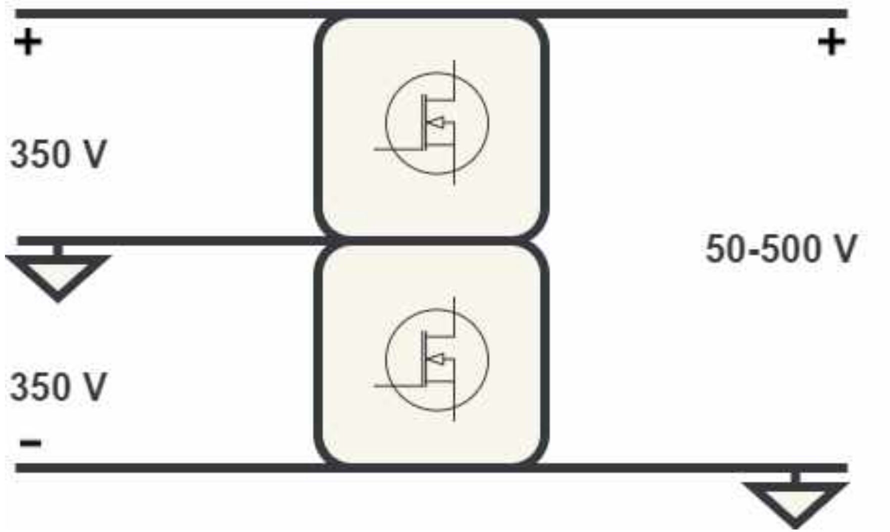
Low Voltage DC System Designer' View



MVDC/LVDC
Connection

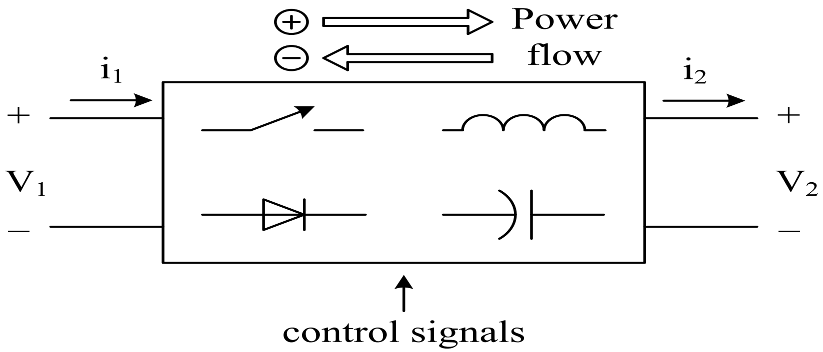


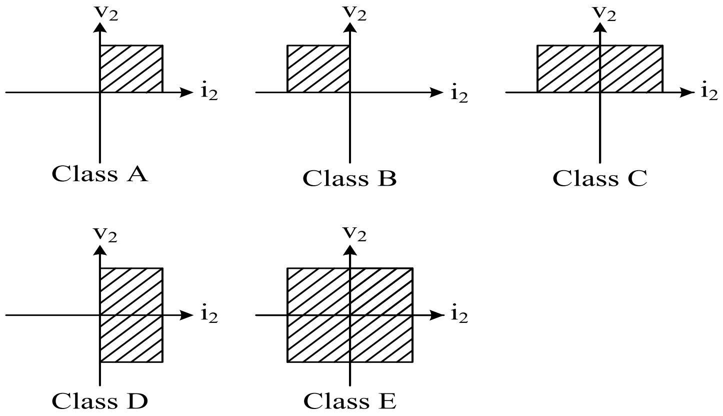
LVDC/LVDC
Connection



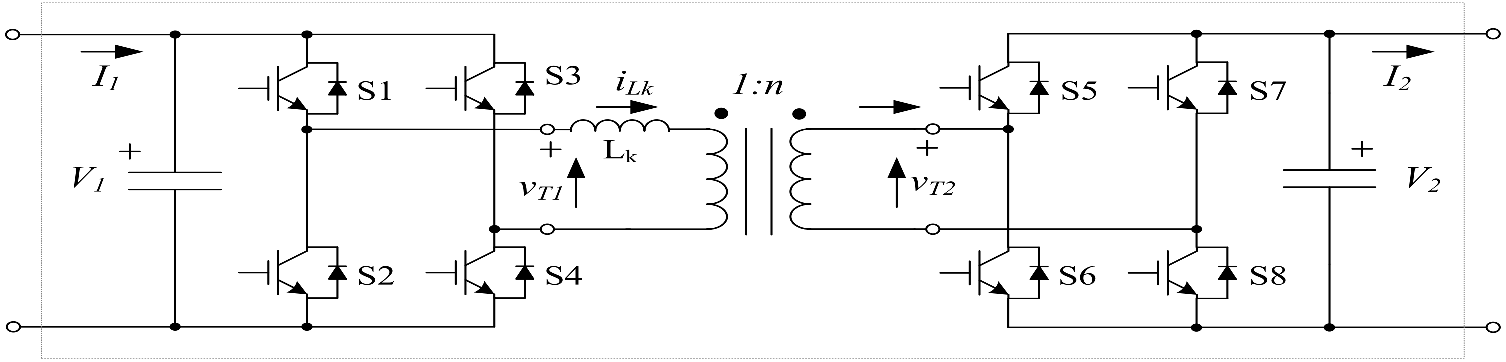
LVDC Electric Vehicle
Charging

DC- DC Converter – Electronic transformer Edison's missing link



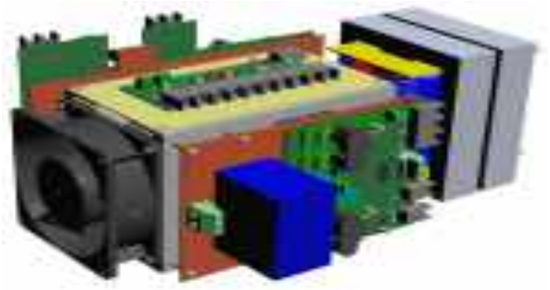


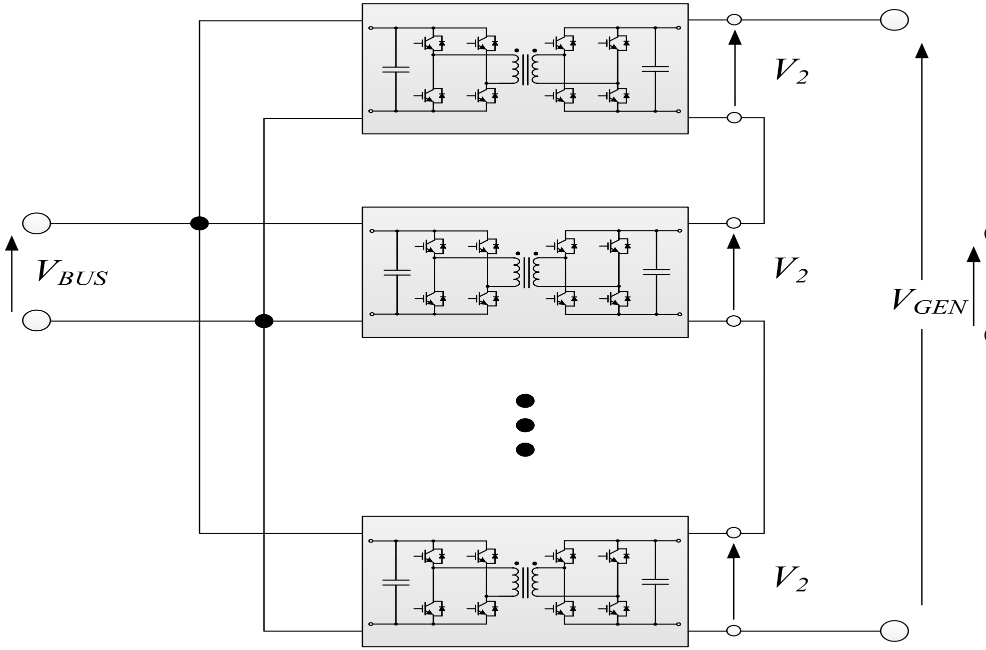
DAB module

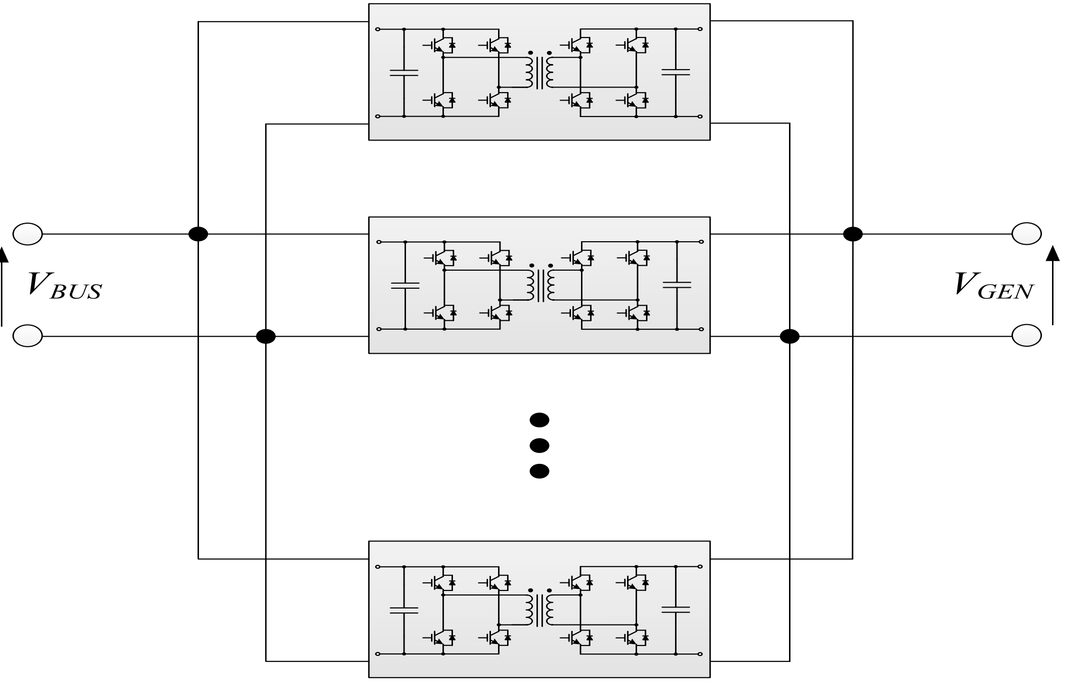


TU Delft

Series -parallel

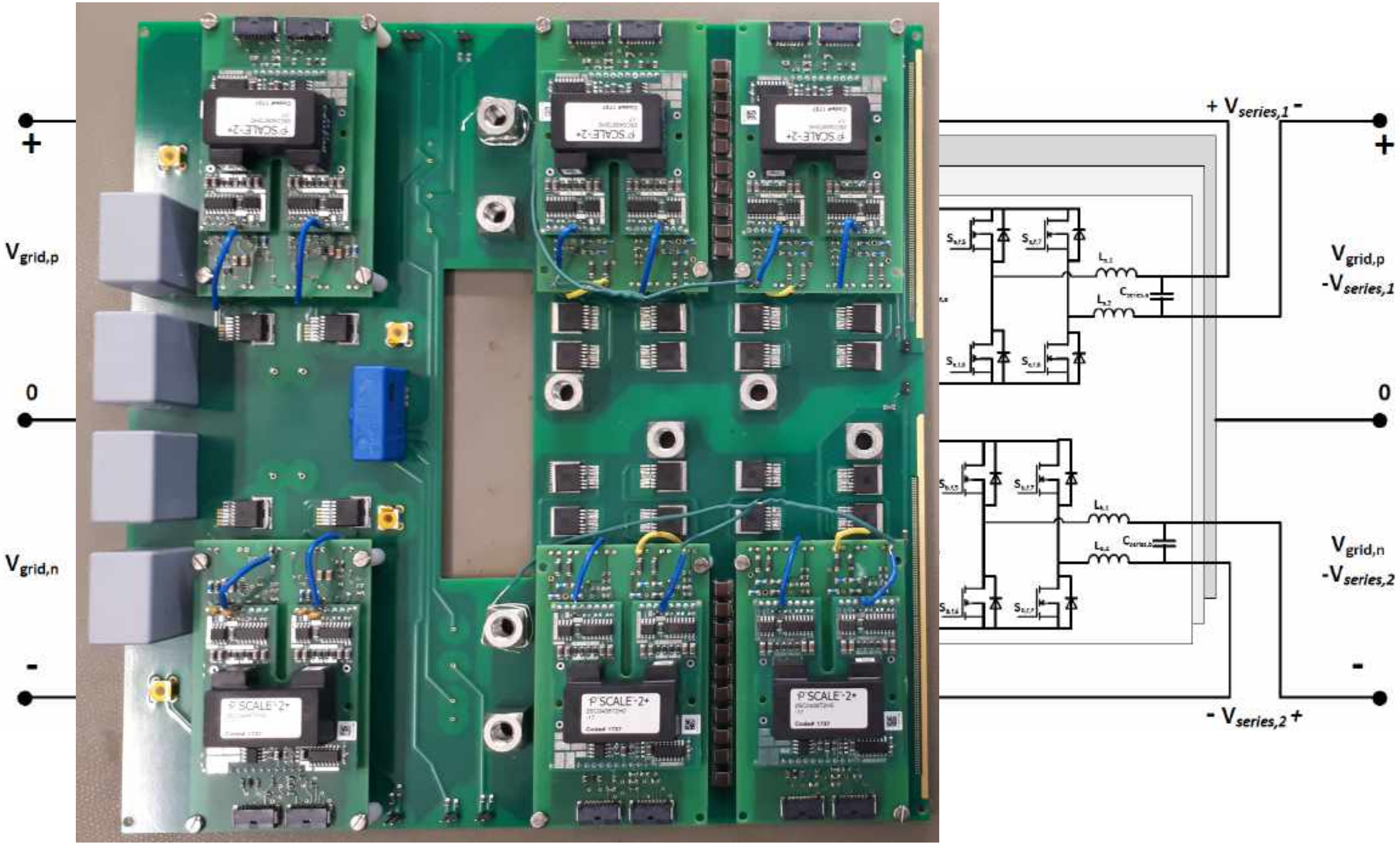






TUDelft

TRIPLE ACTIVE BRIDGE



Roadmap for DC Systems

DC Nanogrids
- Radial DC feeders (lighting)
- Devices, protection, stability

DC Nanogrids V2.0
- Bidirectional power flow
- PV and storage
- DC house nanogrid
- PV charging systems of EVs
- DC ready devices and USB power delivery
- Enable demand response

DC microgrids / DC links
- Towards local generation local use (storage, EVs)
- Cellular concept
- Sizing (optimization)
- Protection, grounding
- Stability of DC grids
- Optimal power flow
- Demand side management
- Data over power line
- Power management
- Market
- Harmonics

Radial DC grids
- Connecting DC microgrids
- Refurbishing the system for (partially) DC infra
- Modular converters with integrated protection
- Integrated control market approach
- Integrating cells/microgrids
- Interface, interact, integrate

Meshed DC distribution grids
- Sustainable, reliable, high efficient, low cost DC distribution grid with renewable energy, and electric vehicles
- Fexibility and modularity
- Decentralized control
- New distribution of costs, market and usage structures
- Integration of multiple energy carriers (gas&elec.)


thank you
danke
рахмат
謝謝
ngiyabonga
teşekkür ederim
spas
Баярлалаа
mersi
kia ora
barka
welalin
tack
mahalo
tapadh leat
спасибо
faafetai lava
vinaka
спасибі
blagodaram
dank je
misaotra
matondo
paldies
grazzi
gracias
хвала
asante
manana
obrigada
tenki
murakoze
chokrane
nanni
nandri
kiitos
dankie
dhanyavad
mauruuru
köszönöm
bedankt
bayarlalaa
gràcie
hvala
enkosi
akun
dankon
aciū
djiere dieuf
tau
mochchakkeram
дякую
mamnun
dziękuję
chnorakaloutioun
grafias ago
gràcies
sulpáy
taiku
go raibh maith agat
sobodi
děkuji
obrigado
mèsi
didi madloba
sagolun
sukriya
kop khun krap
ありがとう
najis tuke
tanemirt
grazie
arigatô
takk
dakujem
trugarez
kam sah hamnida
rahmat
terima kasih
rahmet
ευχαριστώ
diolch
dhanyavadagalu
shukriya
merce
мерси
তোমাকে ধন্যবাদ
감사합니다
xiexie
merci

TU Delft

TU Delft