Efficient Integration of Renewable Energy Resources:

From DC nanogrids to DC macrogrids

Nils H. van der Blij

N.H.vanderBlij@TUDelft.nl

Contents

- Introduction
- DC Distribution Grids
- Modelling of DC Systems
- Plug-and-Play Stability
- Selective Protection

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Nils H. van der Blij

2013

Researcher
Delft University of Technology
FE modeling of BDFIMs

2014

Researcher
University of Cambridge, United Kingdom
Iron loss, thermal and magnetic modelling

2015

Business & Operations Analyst
Accenture, Amsterdam
IT project management

Researcher
Delft University of Technology
Wind energy MOOC

2016

2017

PhD Exchange (3 months)
Zhejiang University, China
Experimental work on DC microgrids

2018

PhD Candidate
Delft University of Technology
Modelling, stability, control and protection of DC grids

2019

PhD Exchange (2 months)
Waterloo University, Canada
Power flow methods for DC grids

2020

Assistant Professor
Delft University of Technology
e-Refinery and electrification of industrial processes

Today

Introduction

DC Grids

Modelling

Stability

Protection

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DC Systems, Energy Conversion and Storage

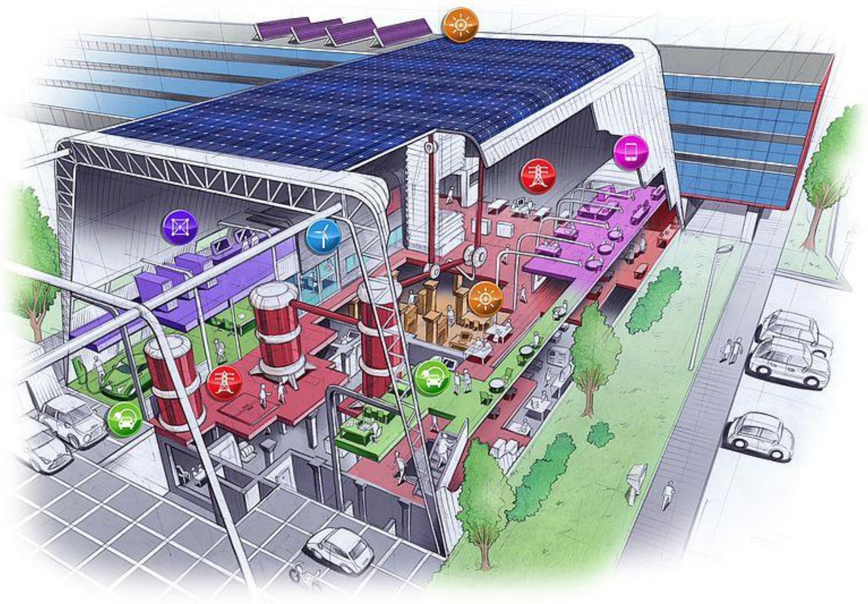
Research Team:

- Professors: 1+2
- Assist. Professors: 9
- Support Staff: 12
- PhD & Postdocs: 31

Research Pillars:

- Power Electronics
- DC Systems
- Electric Mobility
- High Voltage Technology
- Energy Storage

New Electrical Sustainable Power Lab



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DC Systems, Energy Conversion and Storage

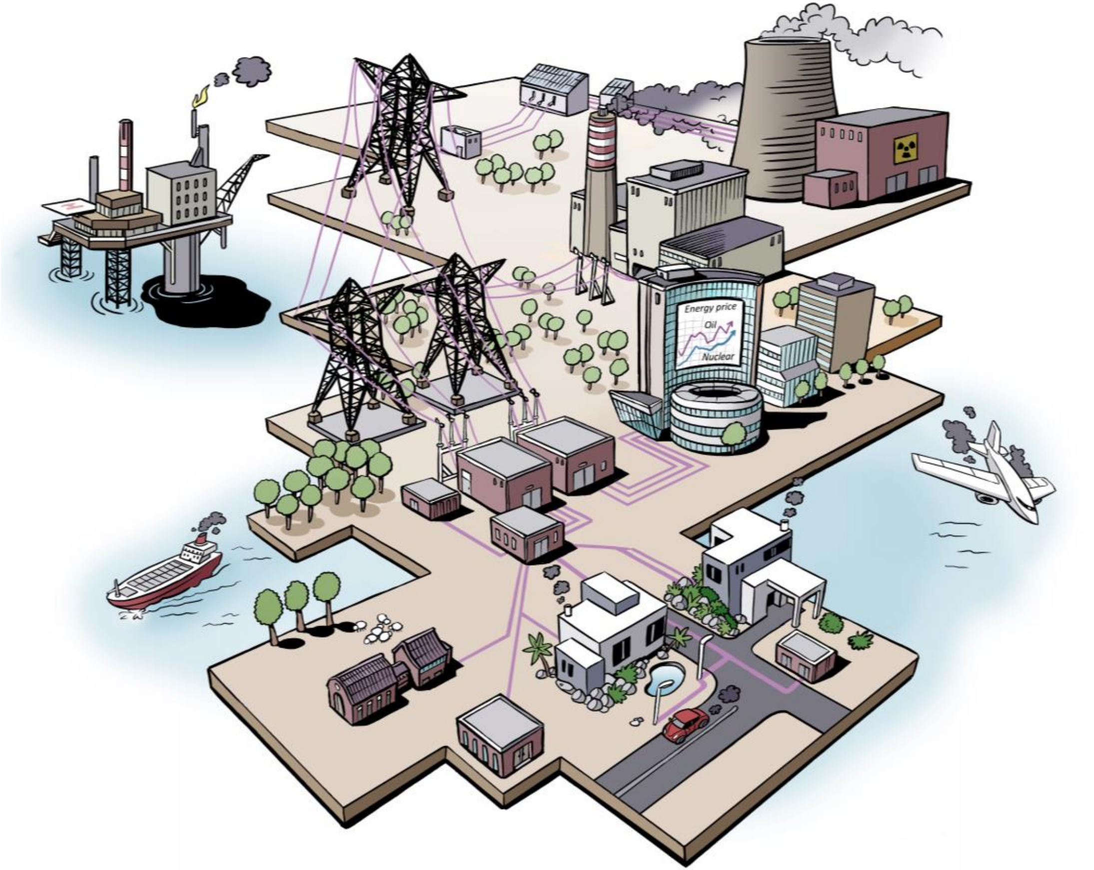
High Voltage Lab

Energy Storage Lab

Power Electronics Lab

Power Conversion Lab

Status Quo



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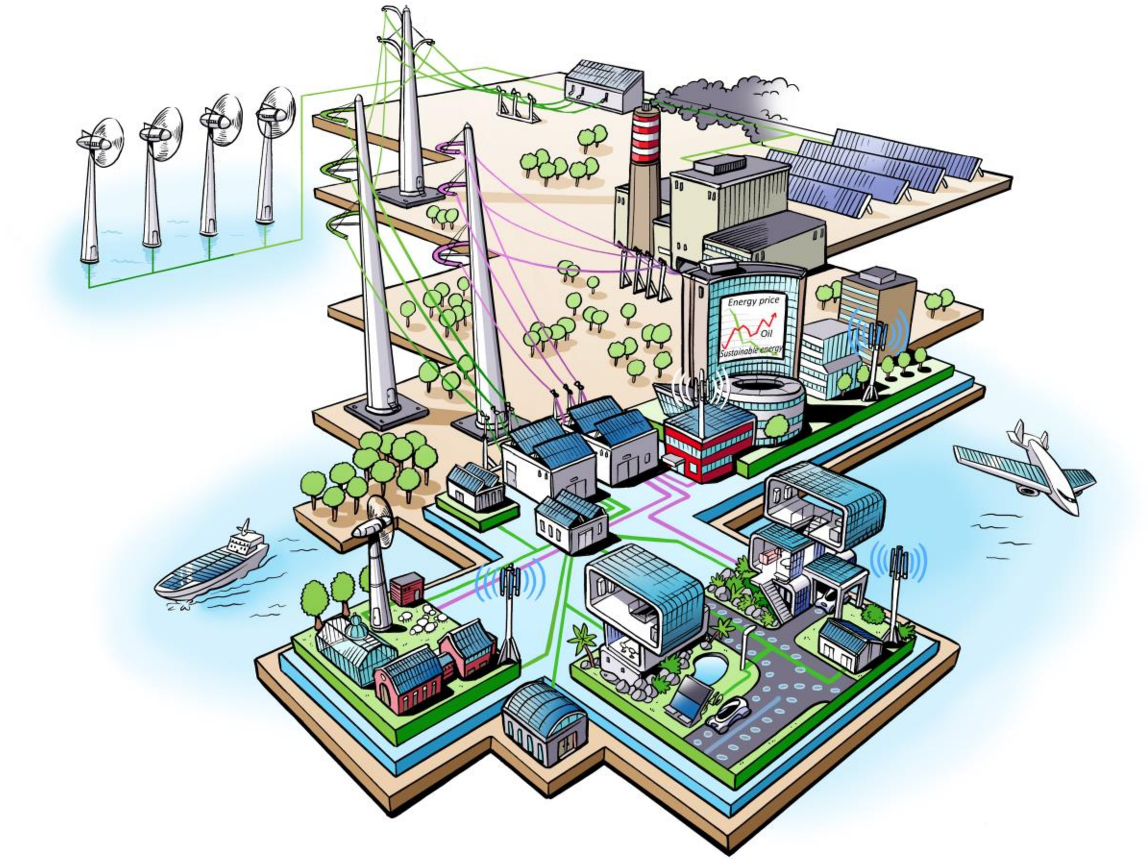
Vision for the Future



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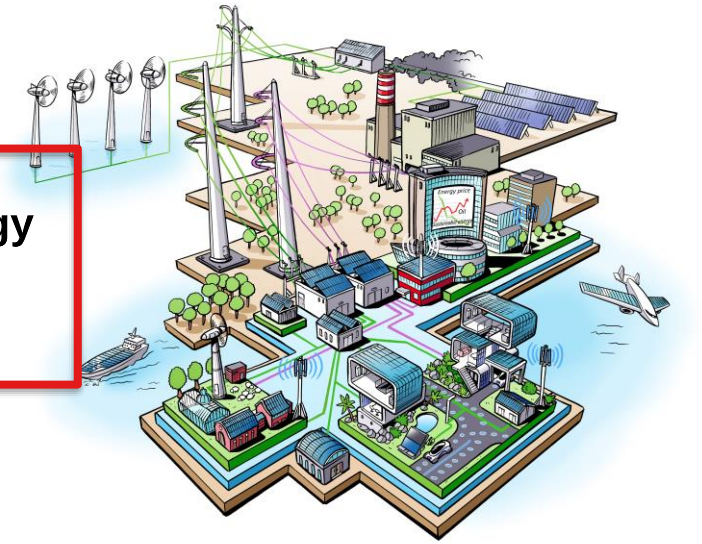
Requirements for the Energy Transition

- **Renewable Energy Generation**
  - Photovoltaic panels
  - Wind generation
  - Geothermal utilization

- **Transportation of Renewable Energy**
  - High voltage transportation
  - Direct current grids

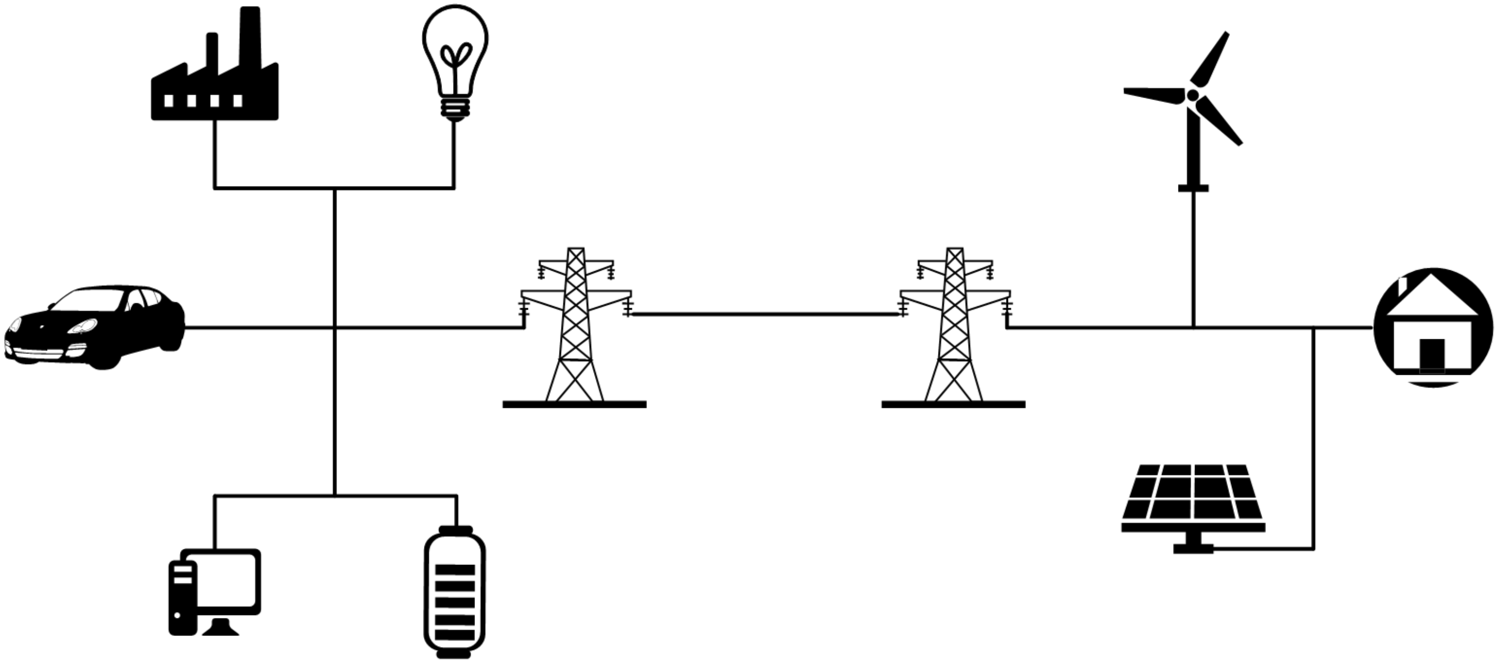
- **Electrification of Processes**
  - Electric mobility
  - Electric cooking and heating
  - Sustainable fuel production



Challenges for Electrical Grids

- Reduced inertia
- Changing architectures
- Bi-directional power flow
- Increased throughput due to electrification
- Increasing uncertainty of demand and supply

Direct Current Grids



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Why DC Distribution Grids?

- **Improved system efficiency**
  - Renewable Energy Technologies are DC
  - Most modern loads are also DC
  - Less losses for distribution/transmission
- **Improved system capacity**
- **Reduced utilisation of raw materials**
- **Improved controllability with power electronics**

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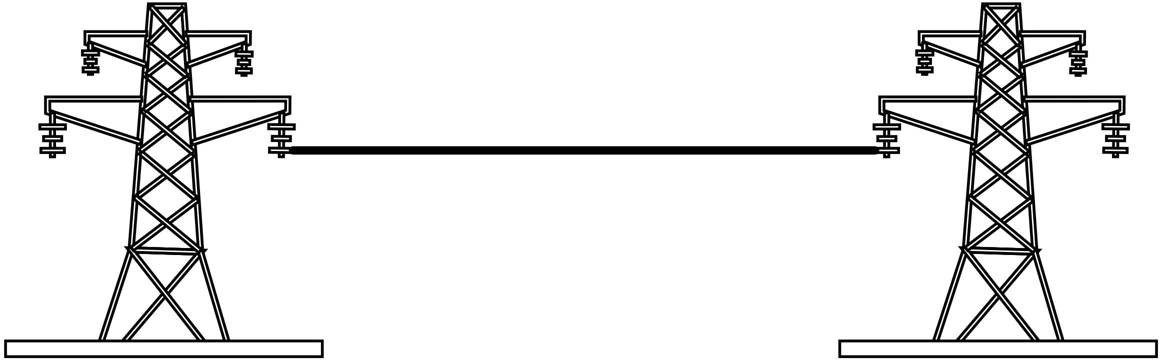
Why did we choose AC?

Efficient transportation of electrical energy requires high voltage



Total power: $P_{total} = UI$

Power dissipated: $P_{losses} = RI^2$

What Changed?

In short: Semiconductor devices and power electronics

4.5 MVA 50 Hz

5.0 MVA 1 kHz

Figures from: https://electricenergyonline.com/energy/magazine/1276/article/the-war-of-currents.htm

Consumer electronics

- Higher efficiency
- Lower cost
- Smaller size

Figure from: https://charbycharge.com/how-gallium-nitride-transforms-chargers/

Pulse - TU Delft

- **Energy Neutral**
- **PV Generation: 150 MWh/year**
- **PV, Lighting and USB-C on DC**

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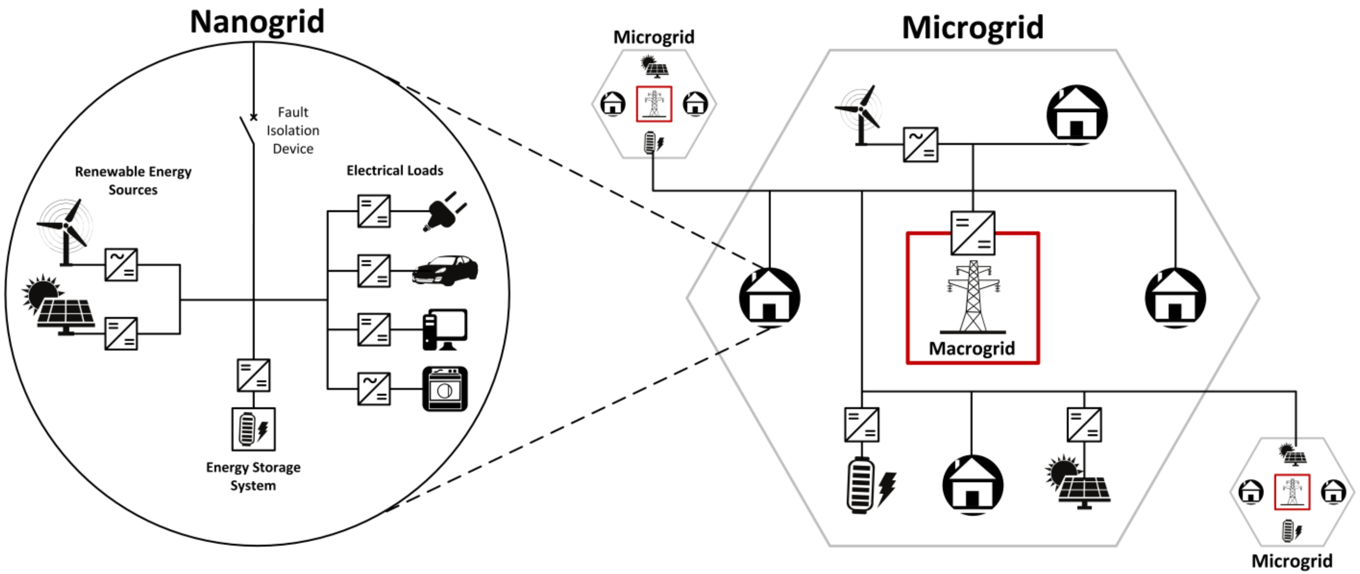
Public Lighting

- Fewer components
- Long lifetime DC drivers
- Integrated communication

From DC Nanogrids to DC Macrogrids

- **Nanogrid**: Small user or application based
- **Microgrid**: Interconnected nanogrids (neighborhood for example)
- **Macrogrid**: Medium and high voltage distribution/transmission grid



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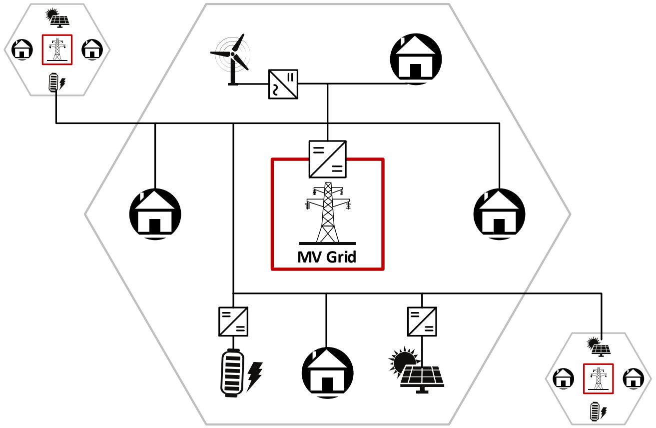
From DC Nanogrids to DC Macrogrids

Technical Challenges:

- Uncertainty of supply and demand
- Changing system topology
- Low inertia of the grids
- Limitations of power electronics

Non-technical Challenges:

- (Market) inertia of AC systems
- Standardization



Decentralization is key!

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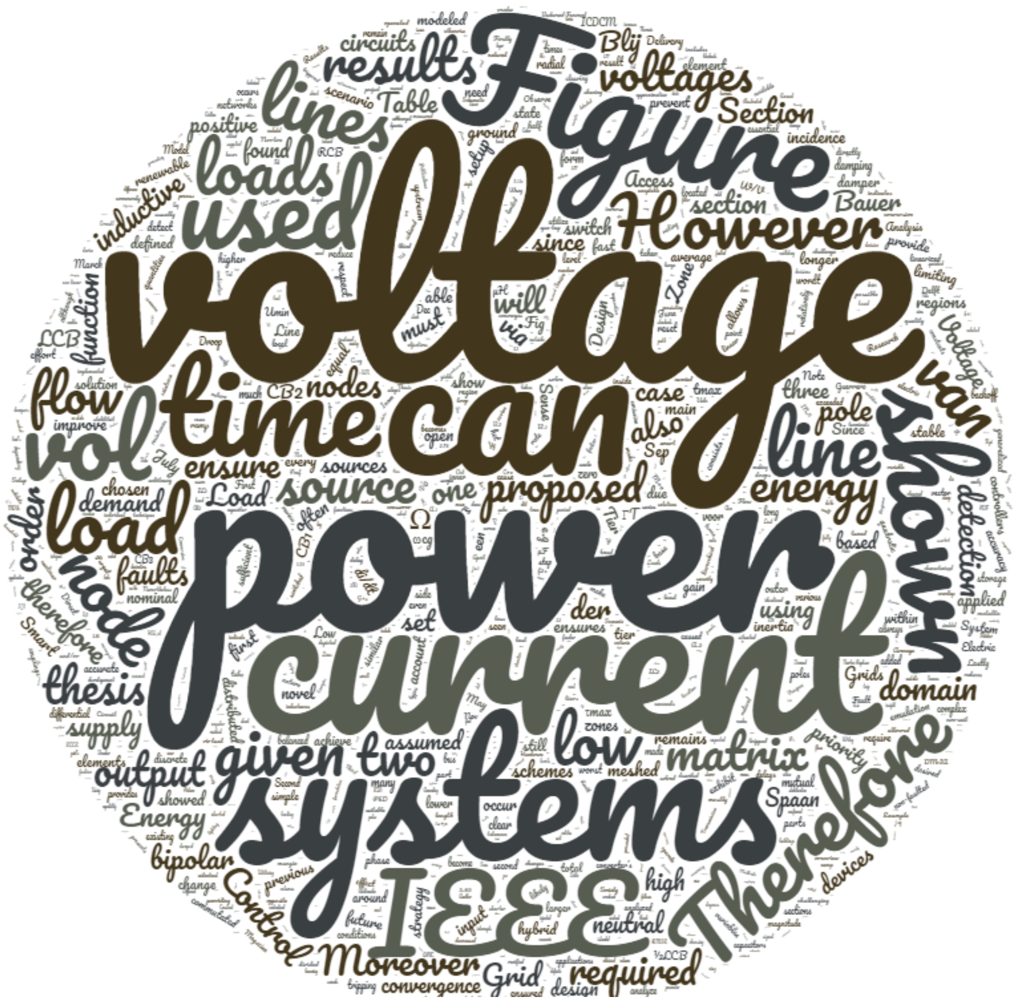

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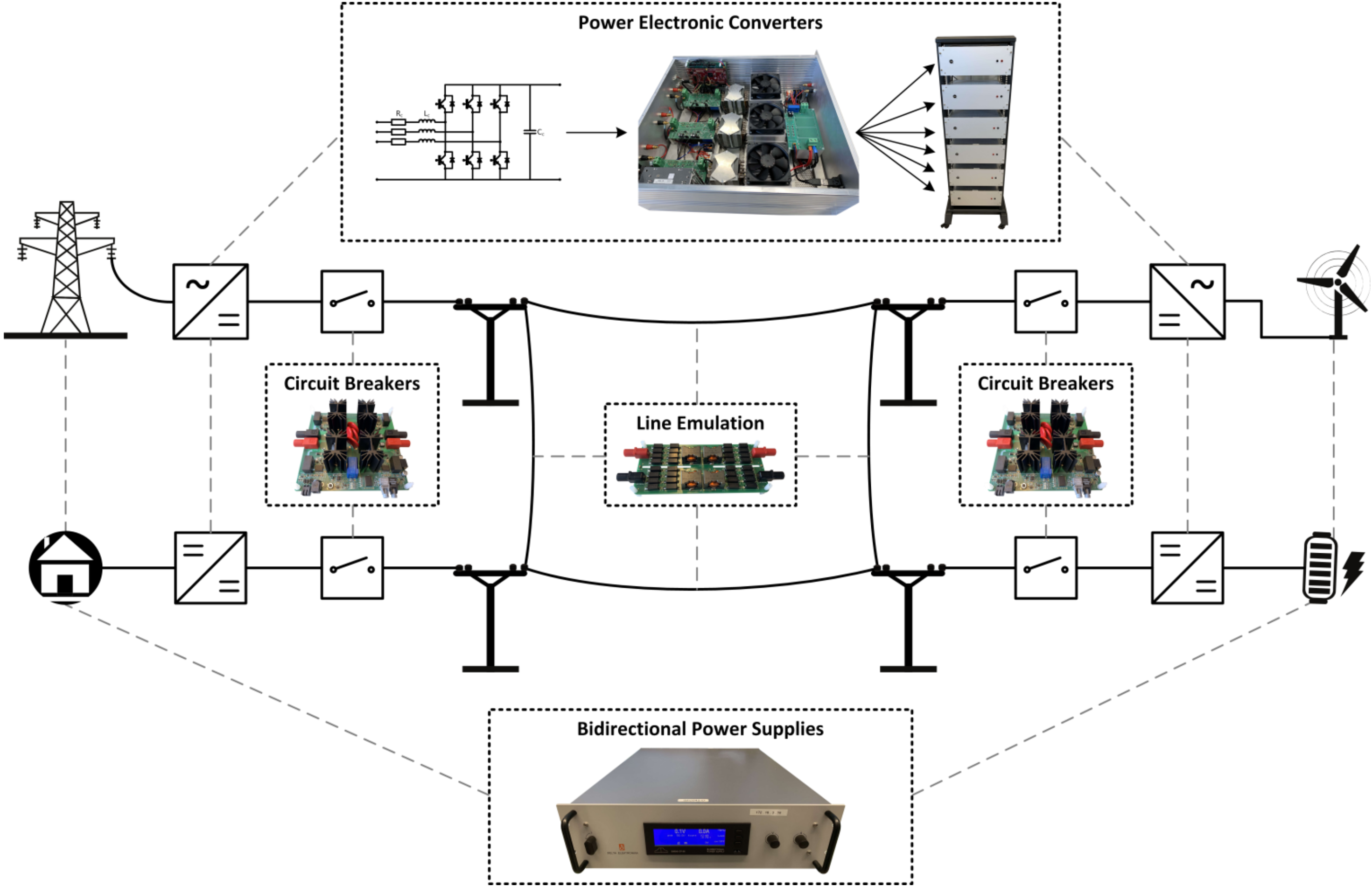
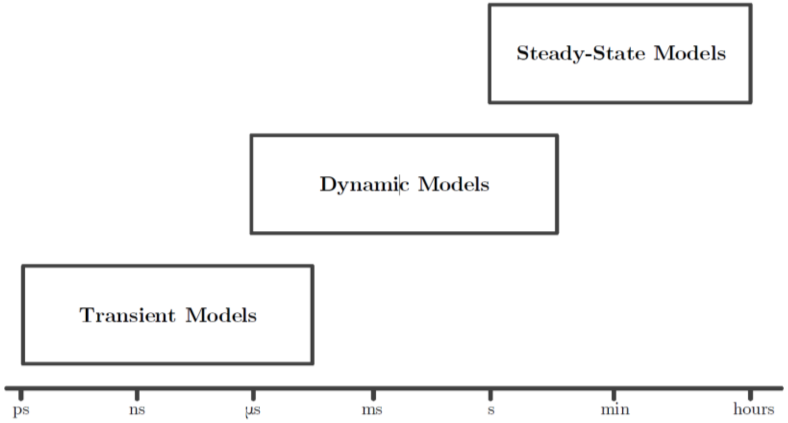
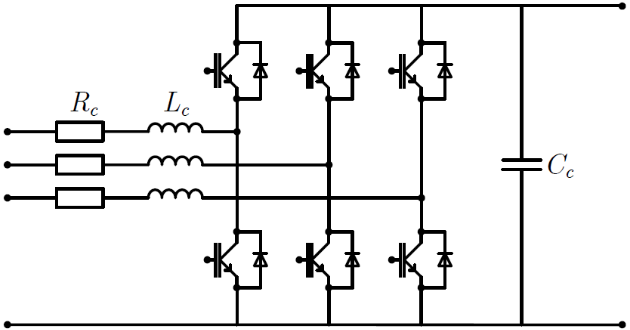


Modelling DC Grids

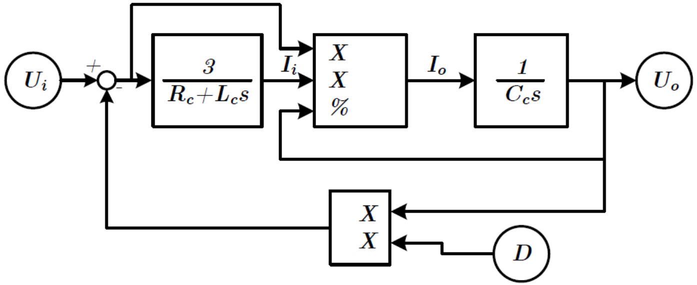
Models are crucial to predict, analyze, design and optimize the behavior of DC systems.



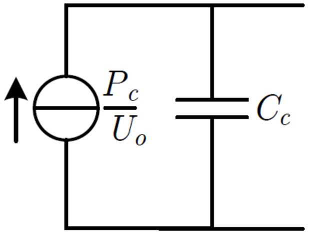
Converter Modelling



(a) Switching model



(b) Average model



(c) Idealized model

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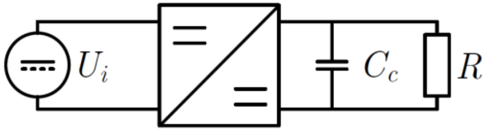
Converter Modelling



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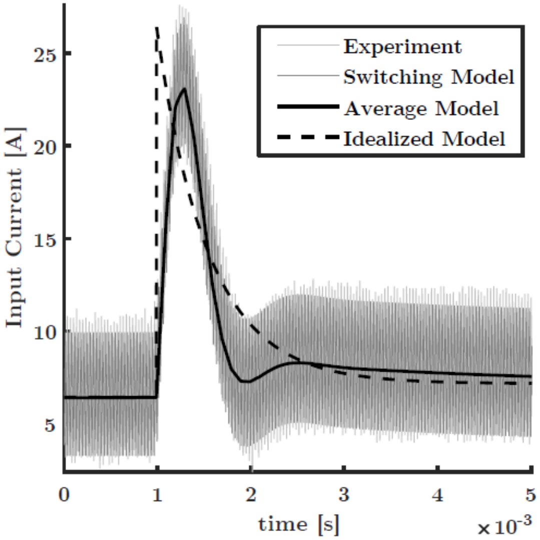

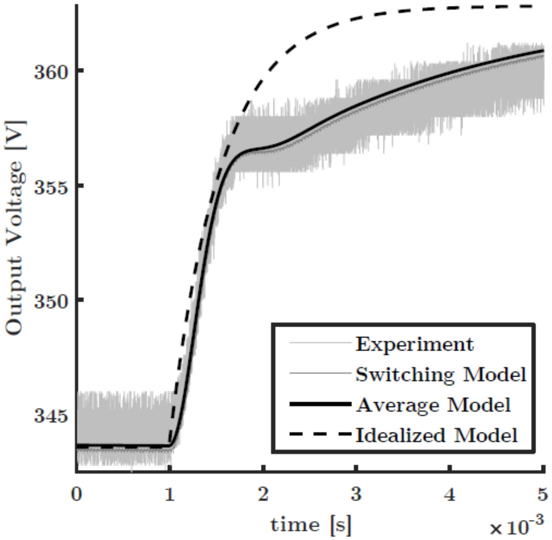

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Modelling of DC Microgrids

Introduction

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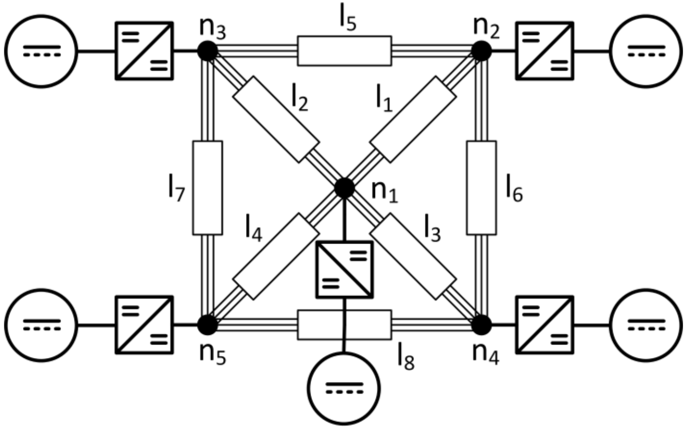
- **Changing configurations**
  - Nodes
  - Lines
  - Conductors
- **Mutual couplings**
  - Conductance
  - Capacitance
  - Mutual inductance



State-Space Model

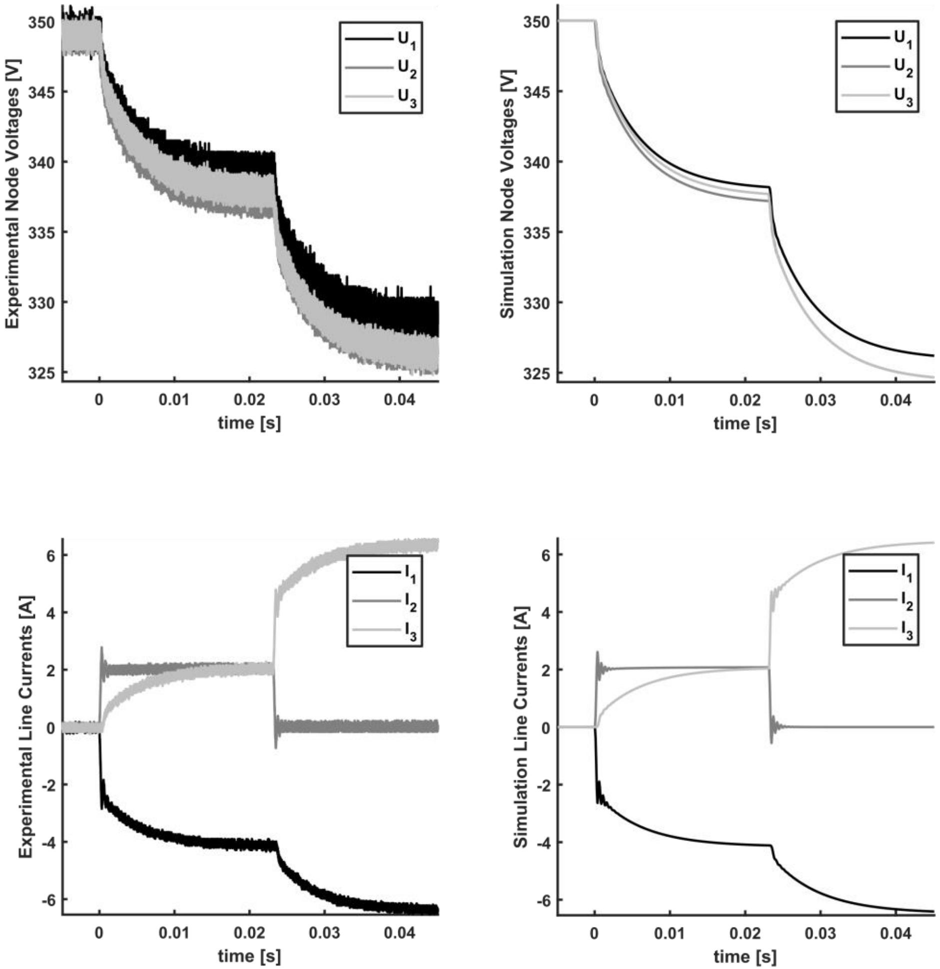
Incidence matrix to describe the system:

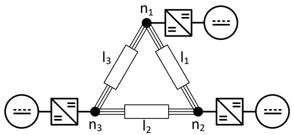
$$\mathbf{\Gamma}(j,i) = \begin{cases} 1 & \text{if } I_j \text{ is flowing from node } i \\ -1 & \text{if } I_j \text{ is flowing to node } i \end{cases}$$

Each node voltage is defined by its capacitance and the currents flowing into it over time, and each line current is defined by the voltage over its inductance over time.

Dynamically, the system can be described as:

$$\boldsymbol{C\dot{U}_N = I_N - \Gamma^T I_L - G U_N}$$
$$\boldsymbol{L\dot{I}_L = \mathit{\Gamma} U_N - R I_L}$$


Experimental Node Voltages [V]
time [s]
U1
U2
U3
Simulation Node Voltages [V]
time [s]
Experimental Line Currents [A]
I1
I2
I3
Simulation Line Currents [A]


n1
n2
n3
l1
l2
l3

Stability of DC Macrogrids

Introduction

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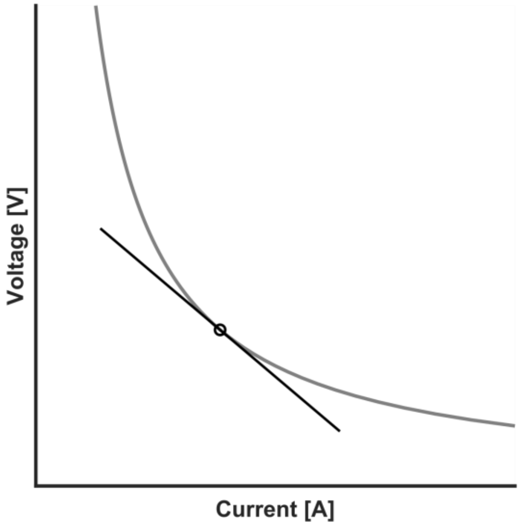
- **Low inertia**
  - Power electronics
  - Renewable energy
  - Not just a DC problem
- **Constant power loads**
- **Changing topology**



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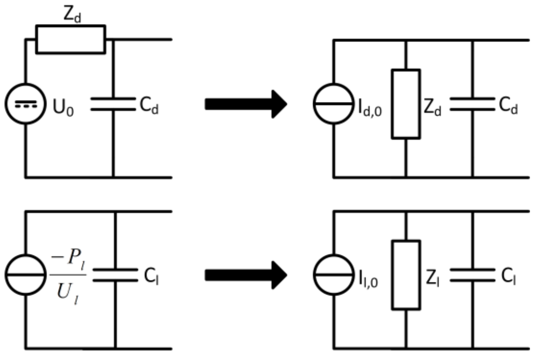
Determining Stability

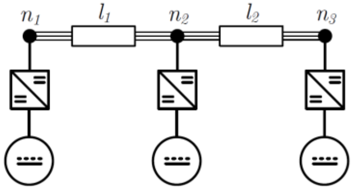
- **Small-signal converter model**
- **Integrate it into the state-space model**
- **Derive the eigen-values**

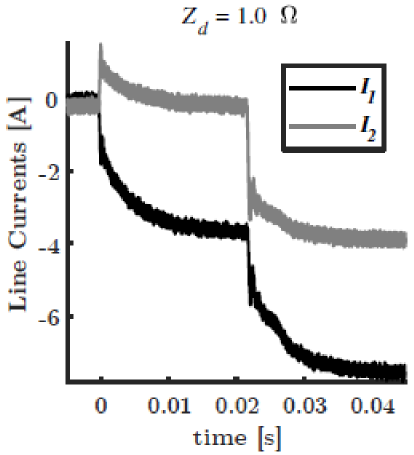
Sensitivity:

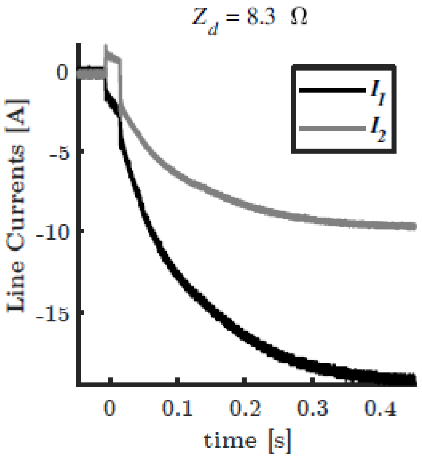
- (Line) inductance
- Load capacitance
- Source capacitance

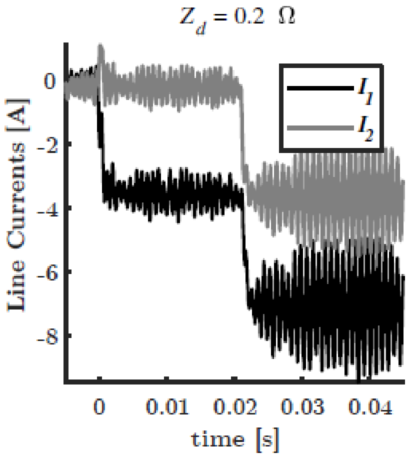


Two Forms of Instability









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Plug-and-Play Stability

Introduction

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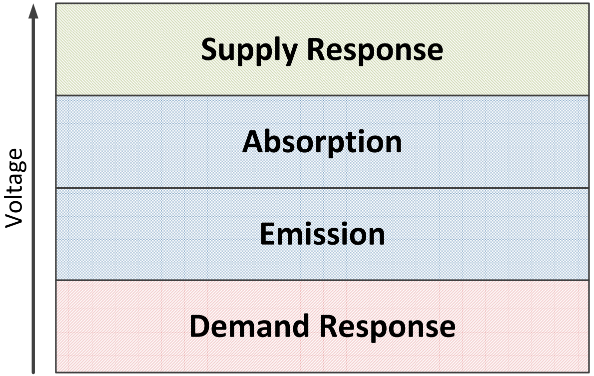
- **Equilibrium Instability:**
  - Decentralized control
  - Voltage dependent demand/supply response



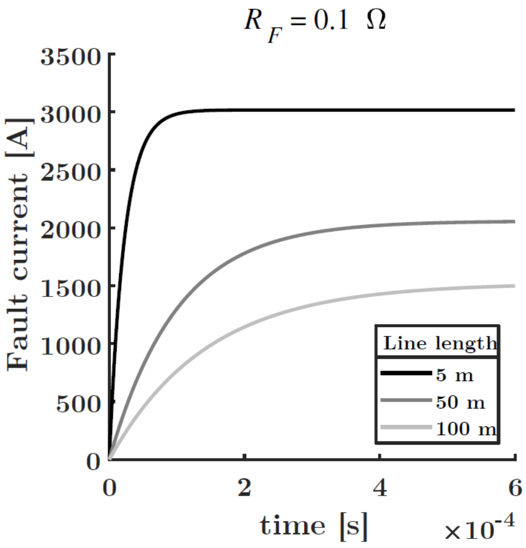
- **Oscillatory Instability:**

$$C_o = \frac{\tau_{max} P_L}{U_{min}^2}$$

$$\tau = \frac{L}{R}$$

Challenges for DC Protection

- **High steady-state fault currents**
- **No natural zero-crossing**
- **Fast interruption required**
  - Black-out
  - Component overloading
- **Selectivity**
  - Bi-directionality
  - Meshed topologies
  - Fast interruption



Solid-State Circuit Breaker

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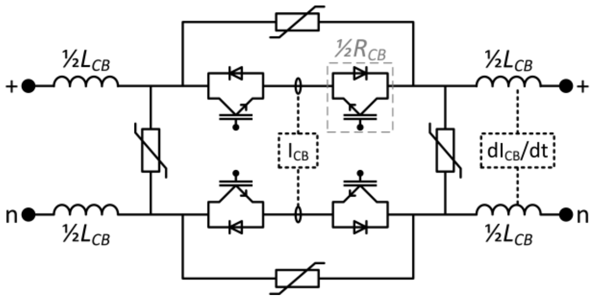
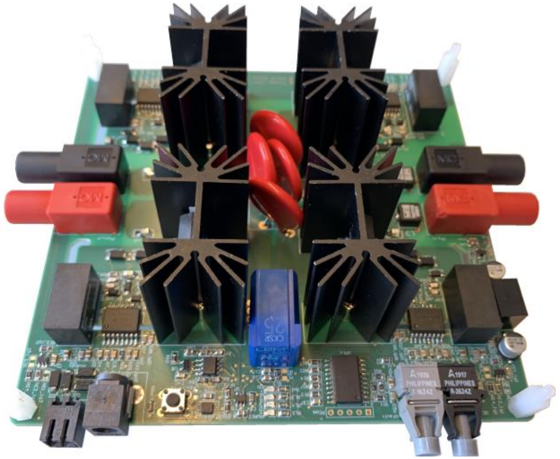


Parameter	Acronym	Value
Nominal voltage	U_{nom}	350 [V]
Nominal current	I_{nom}	16 [A]
On-state resistance per pole	R_{CB}	130 [mΩ]
Current limiting inductance	L_{CB}	1.0 [μH]
Fault clearing time	t_{CB}	1.0 [μs]



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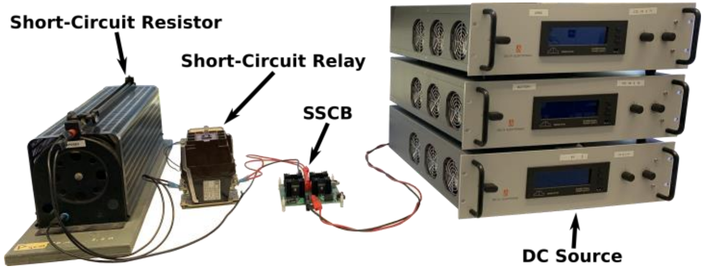
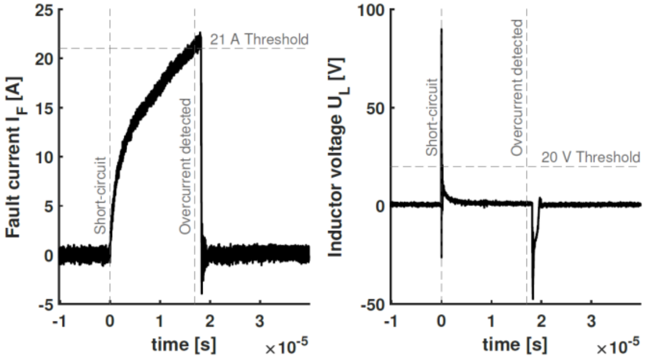
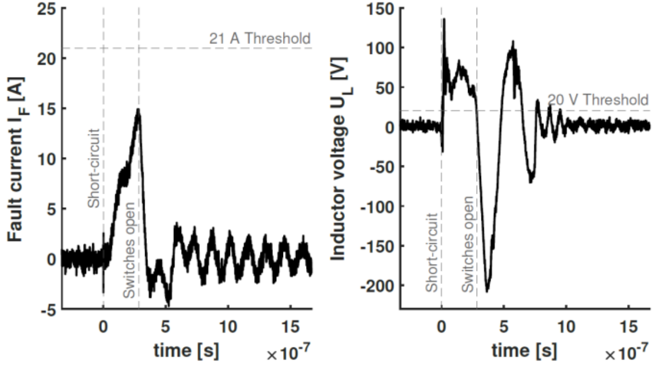
Experimental Validation

- Introduction
- DC Grids
- Modelling
- Stability
- **Protection**





Overcurrent detection



di/dt detection

Selectivity: Fast Fault Propagation

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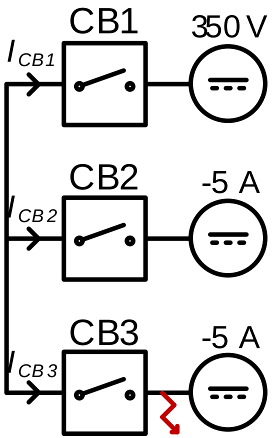

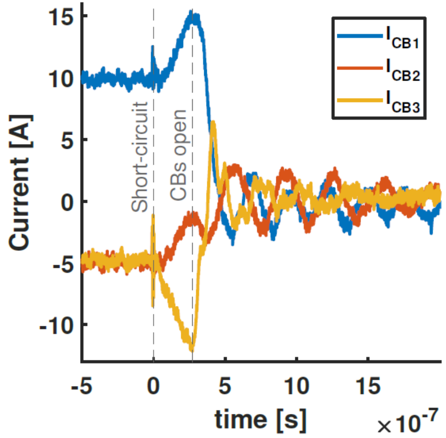

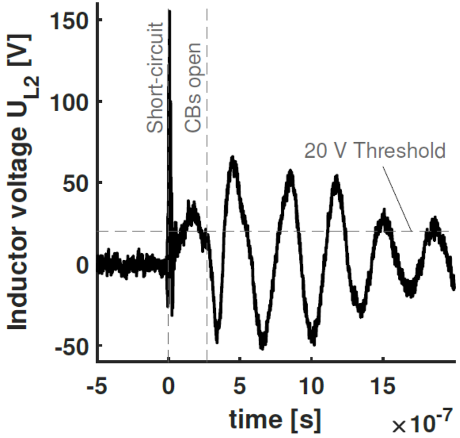

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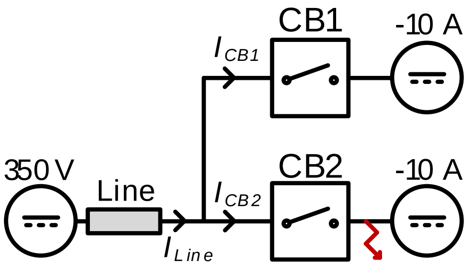
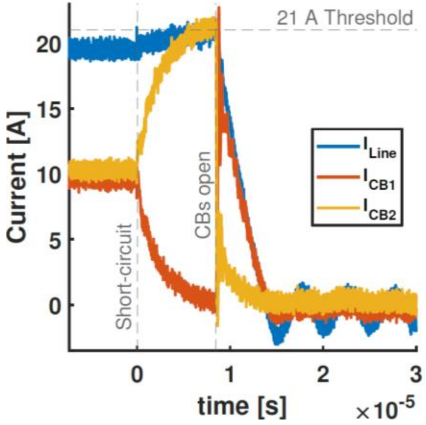
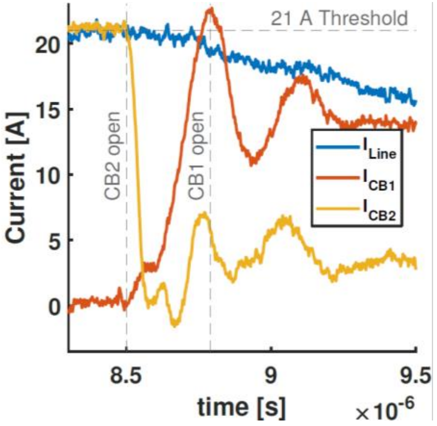
Selectivity: Current Commutation







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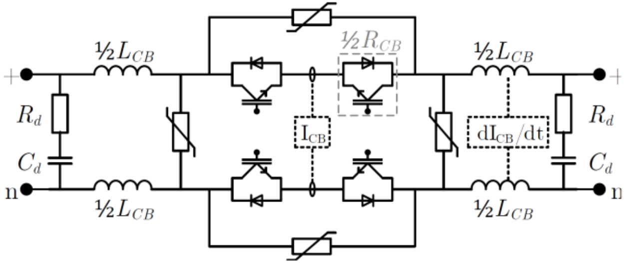
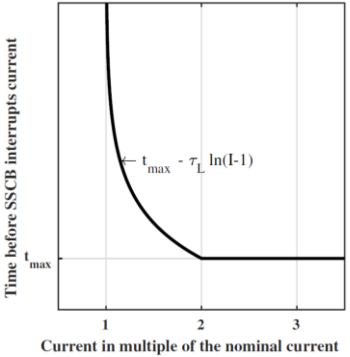
Selectivity: A Simple Solution

- Addition of the RC dampers to SSCB topology



- Time-current characteristic



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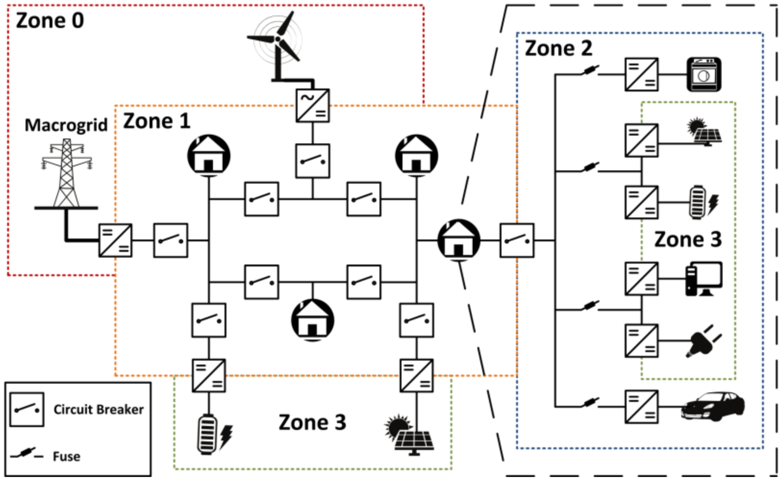
Protection of DC Microgrids

- **Zone 1:** Medium/High Voltage
- **Zone 2:** 350 – 1500 V
- **Zone 3:** < 42 V

- **Tier A:** No protection
- **Tier B:** Device protection
- **Tier C:** Overcurrent protection
- **Tier D:** Current prevention



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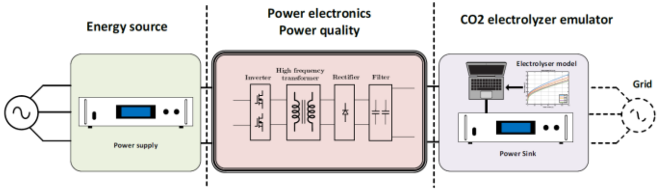
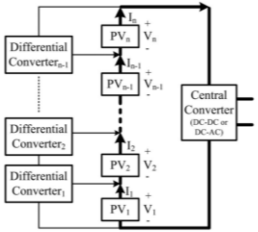
My Future is DC

Cristian Pașcalău
Graduation: 01/10/2023
- Model of CO_2 electrolyzers
- Power electronic topology selection
- Design of a 10 kW converter for electrolysis
- Design of modular 100 kW conversion



Sachin Yadav
Graduation: 1/9/2024
- LV/MV direct current systems
- High power electronic converters
- Fuel cell shipboard systems

Pierpaolo Granello
Graduation: 15/9/2024
- Partial power processing
- Modular power electronics
- Low voltage gain power conversion



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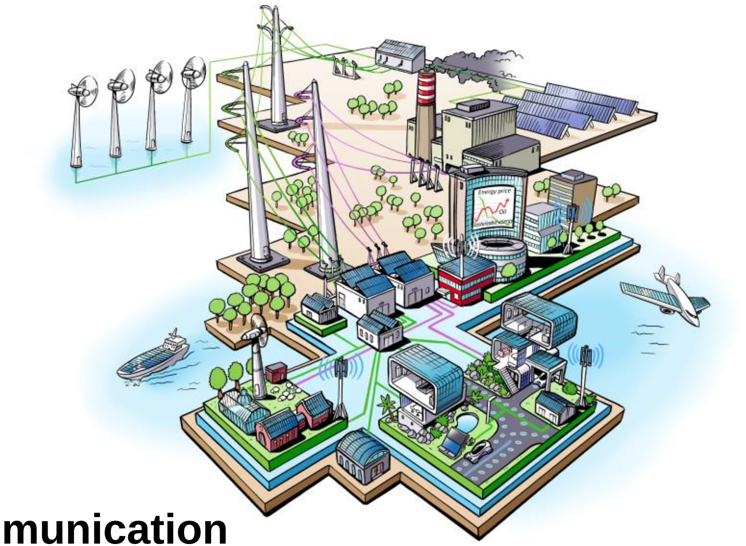
Recap

- Challenges for future grids
- Several DC applications
- Models for DC distribution grids
- Plug-and-play stability
- Selective protection without communication



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