Modern power electronics dominated systems

Clustering & Global challenges

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Outline

- Power system transition
- How converters should respond?
- Converter control modes and key differences
- Challenges - Relevant examples
- A UPC research example
- Conclusions

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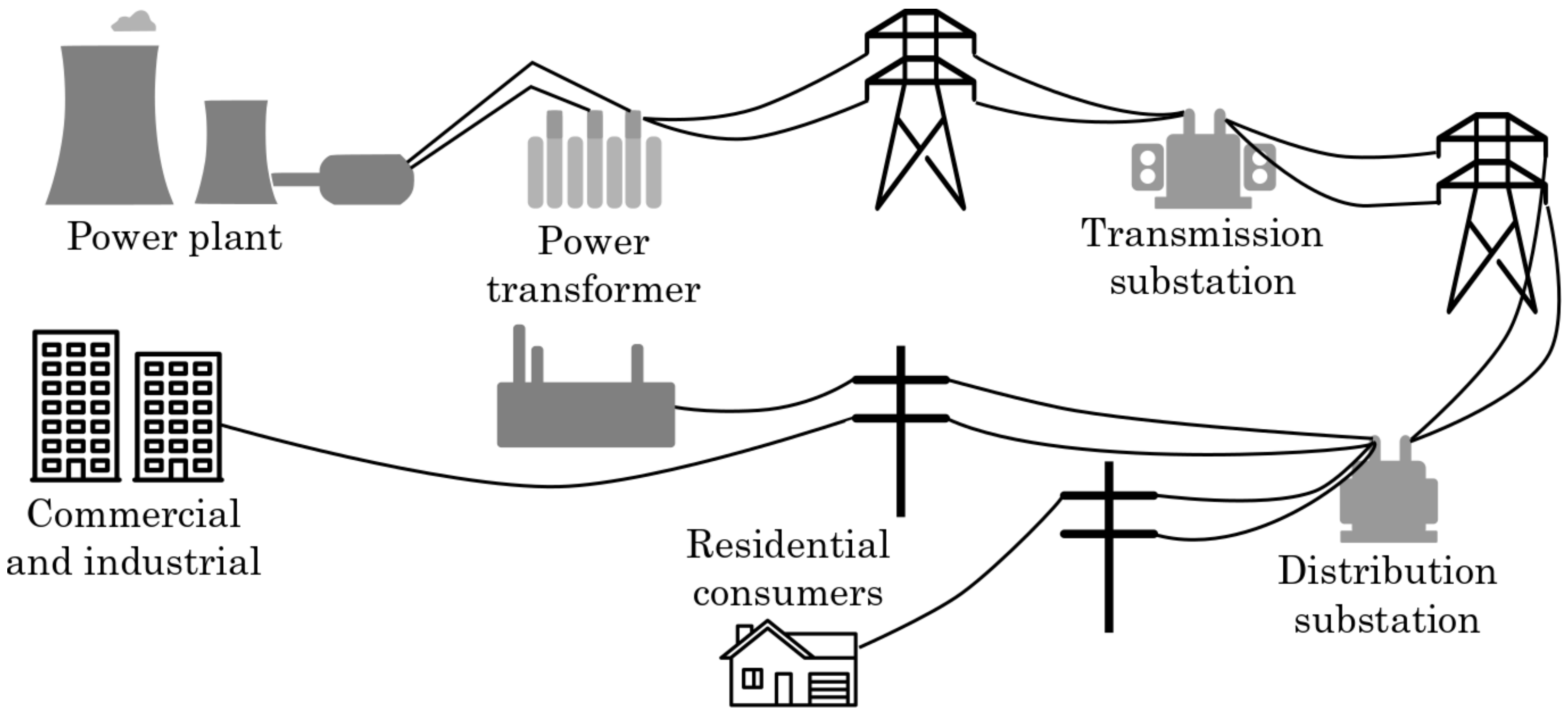
Conventional power system

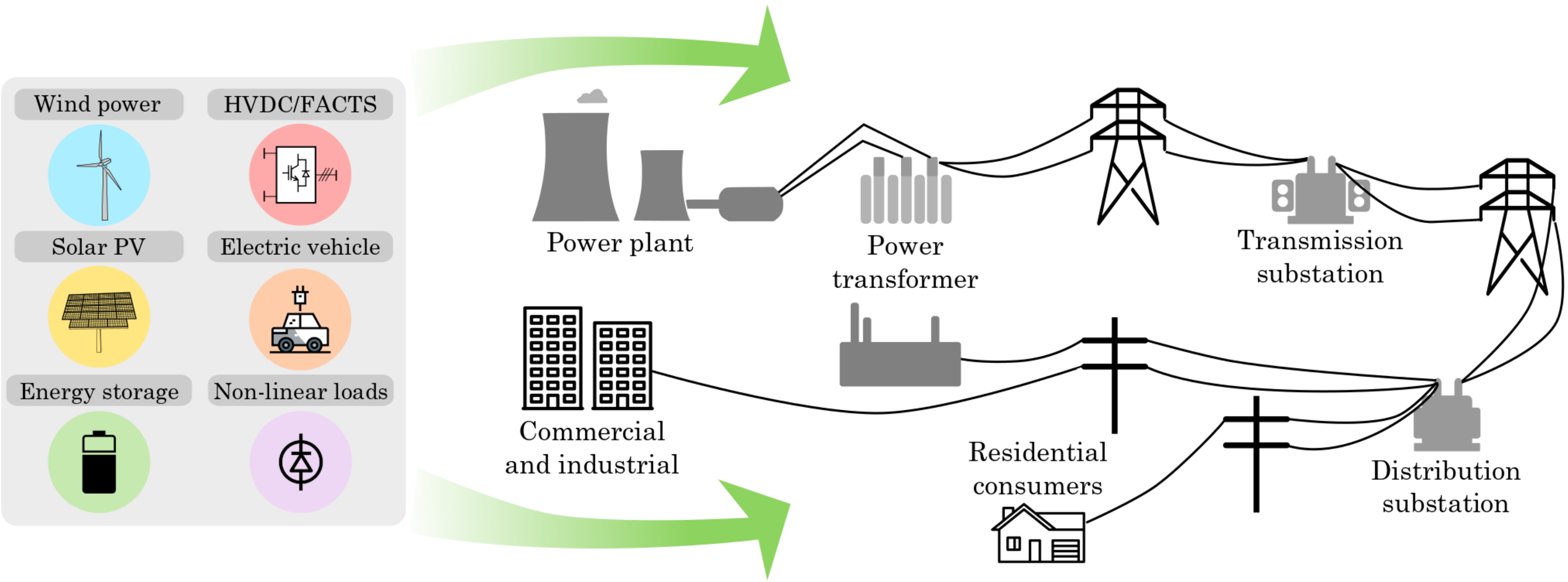
Renovating the synchronous generation-dominated power system



Towards the future power system

New elements

- **New elements** are being connected to the power system
- All these elements are **power-electronics-interfaced systems**
- This is changing the way that power system should be planned, designed, engineered, operated and controlled.



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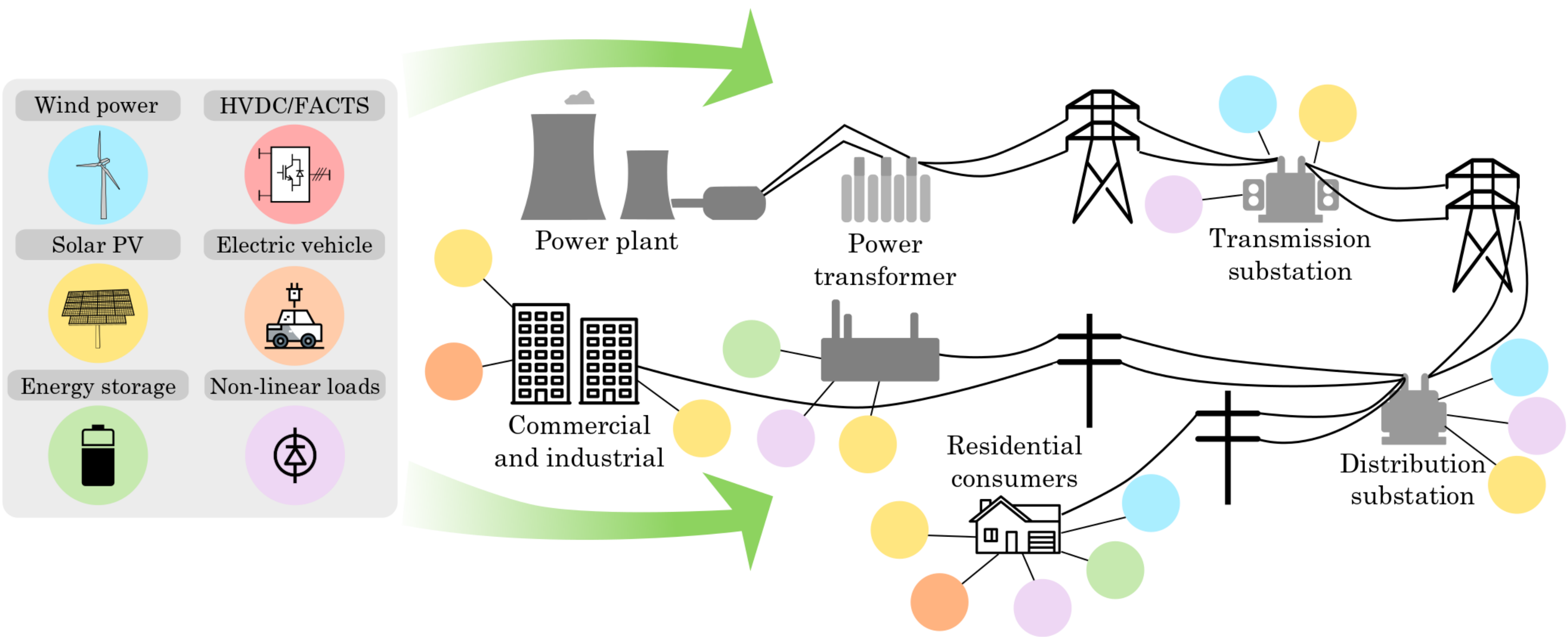
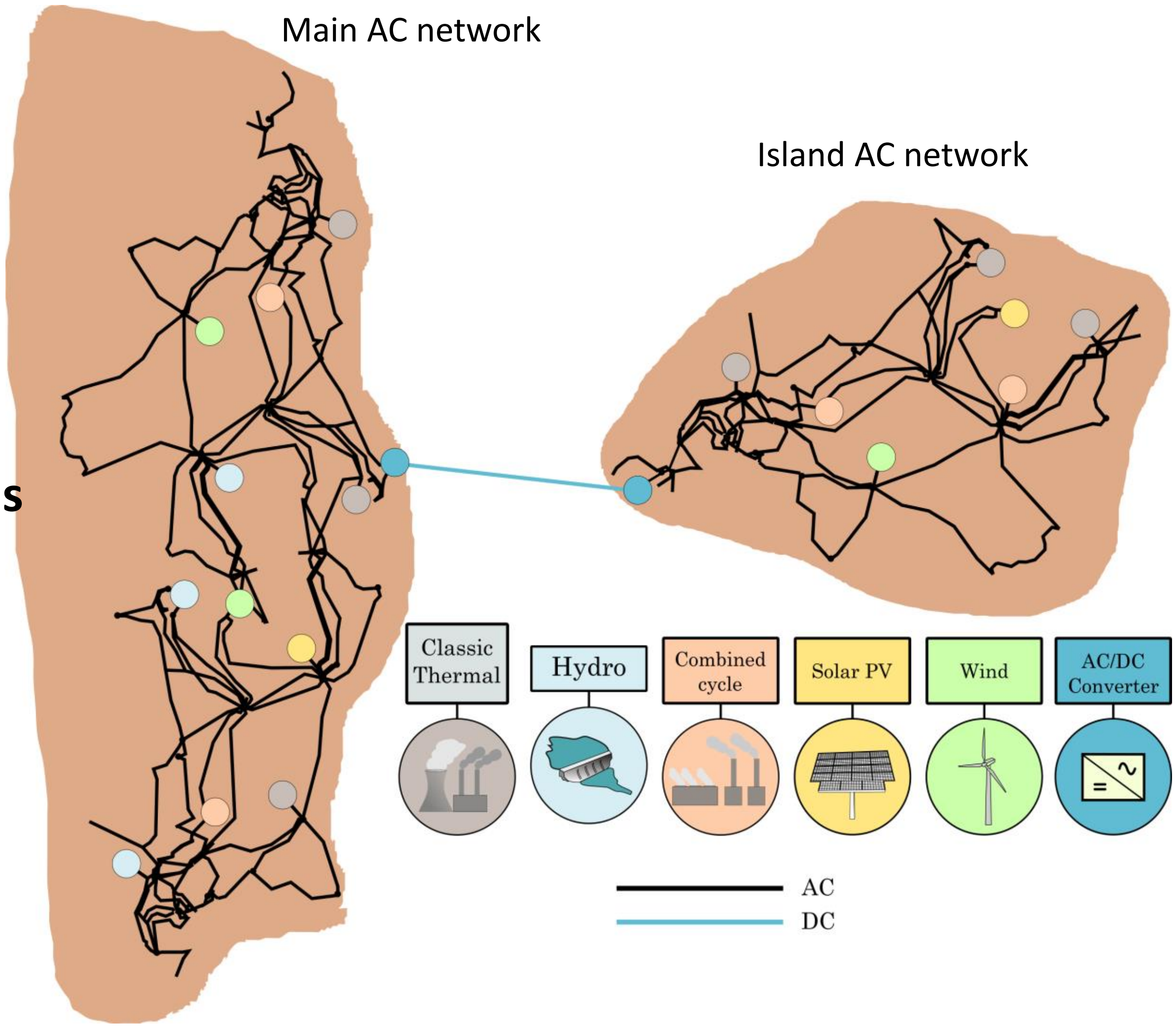


Power system with large penetration of power electronics

Large penetration of power electronics – A closer view of the transition

- **Increasing presence of power-electronics-** interfaced systems
- **PEs** are very different **different from synchronous generators**
- New types of **interactions** will appear
- Network **inertia** can be **reduced**
- **PEs** have **limited short-circuit current**
- **New challenges!**



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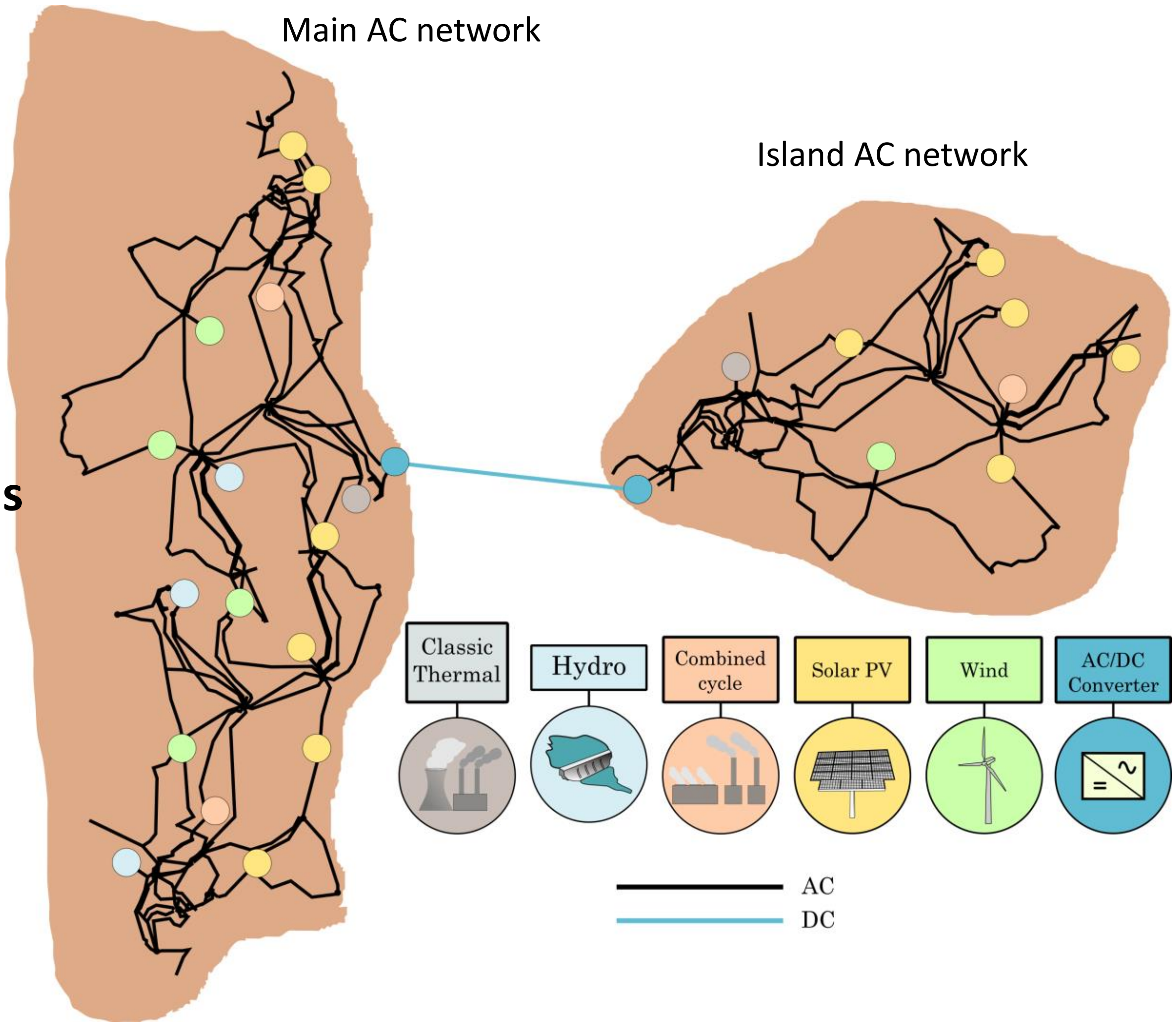

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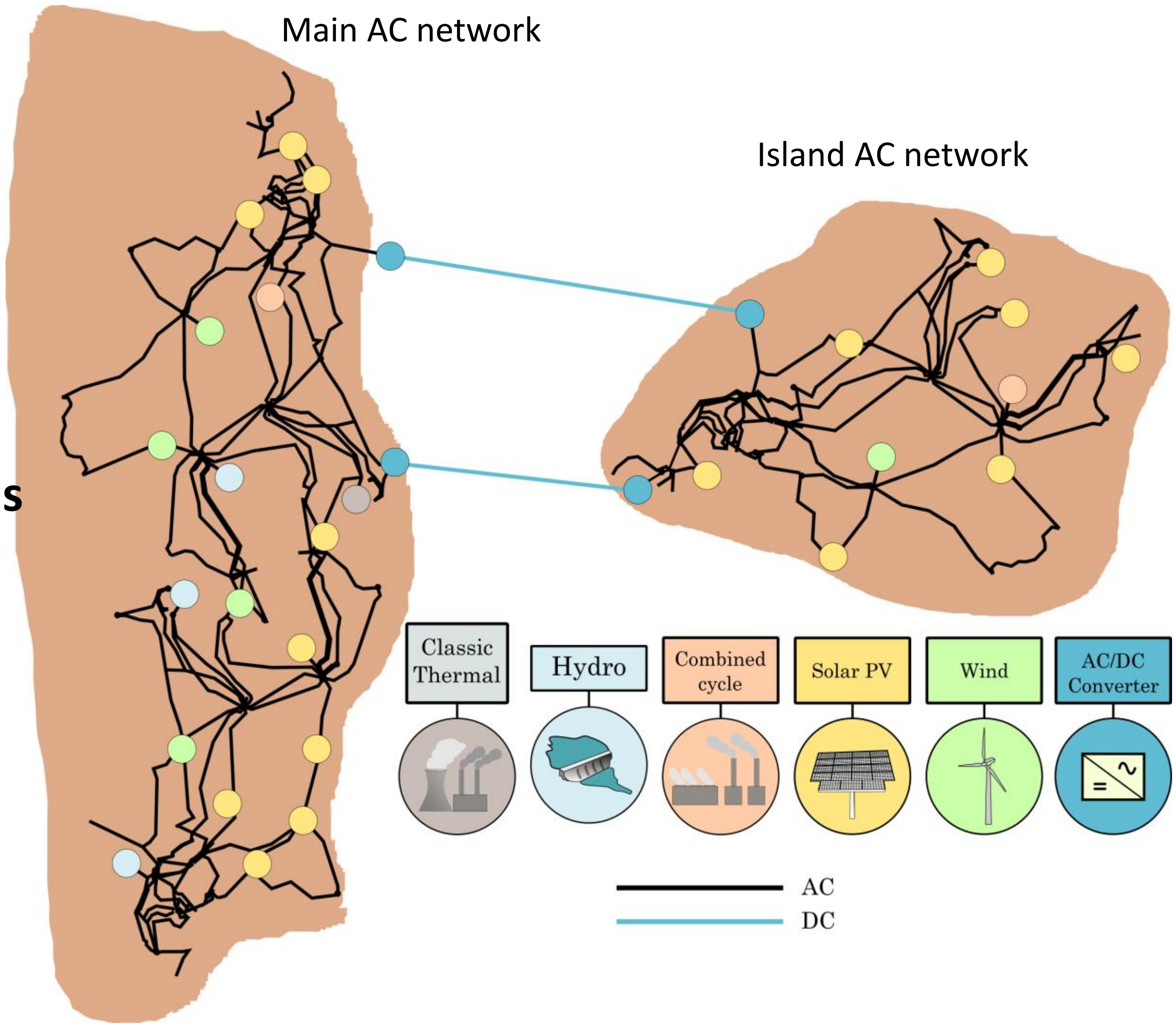
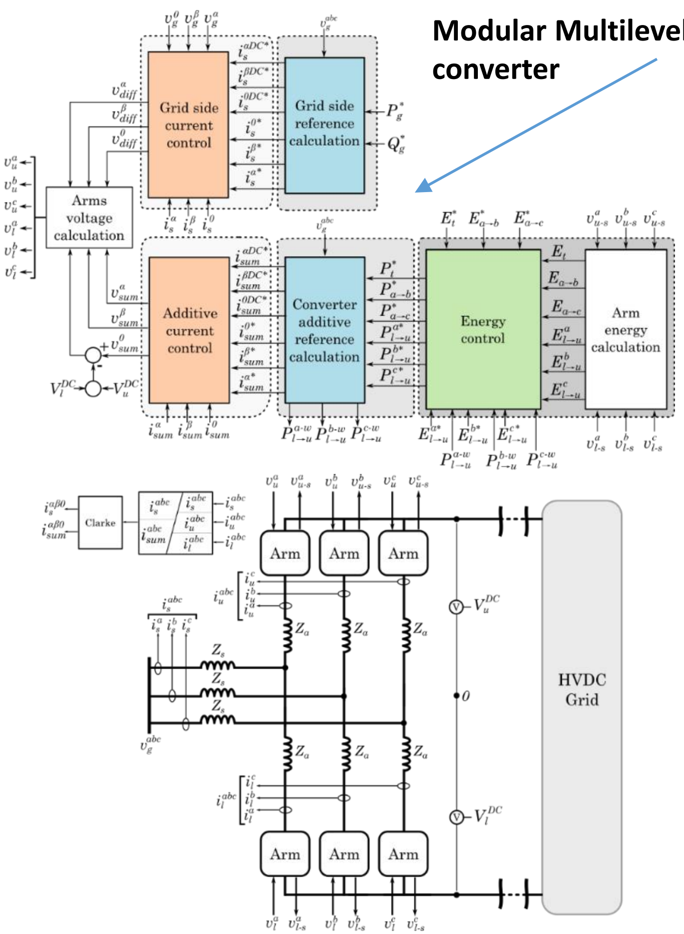


Power electronics vs Synchronous generators

Main differences

- **PEs** are different importantly **different from SGs**

Modular Multilevel HVDC converter



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Synchronous generator+turbine

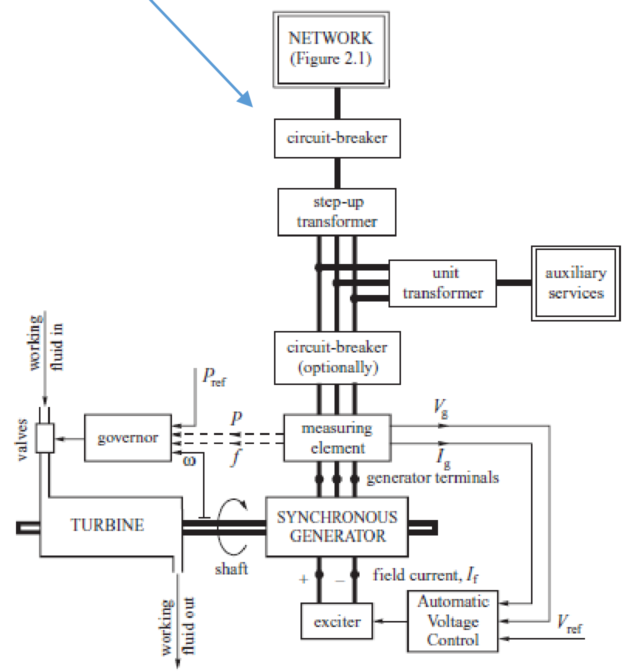

Figure 2.2 Block diagram of a power generation unit.

Source: Machowski2008

Power electronics vs Synchronous generators

Main differences

- **PEs** are different importantly **different from SGs**

Modular Multilevel HVDC converter

Source: Siemens

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Multi-stage steam turbine + generator

Source: Siemens (Wikipedia)

Outline

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- How converters should respond?
- Converter control modes and key differences
- Challenges - Relevant examples
- A UPC research example
- Conclusions

How PEs should respond?

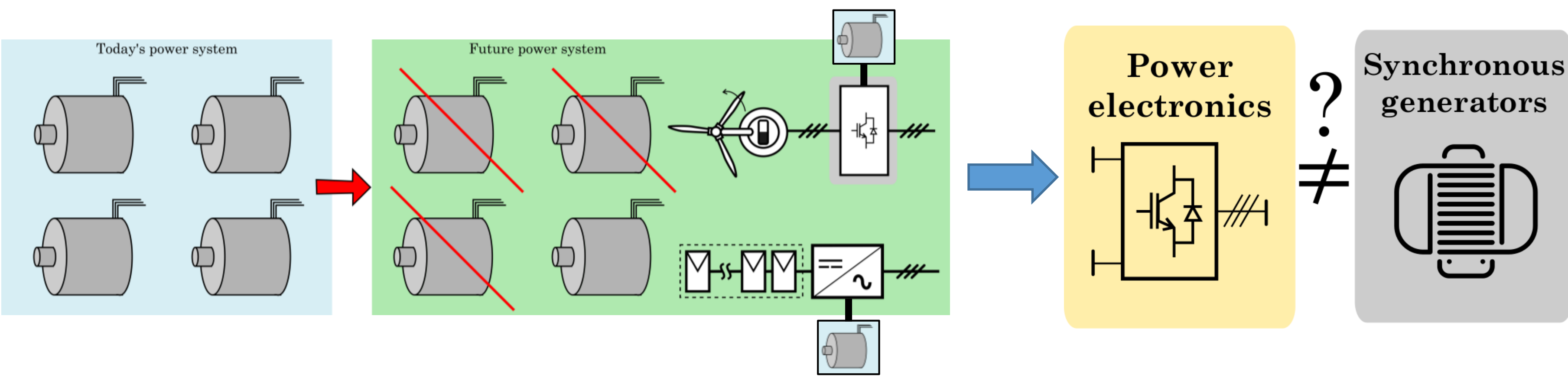
Possible solution – Design PEs to operate as SGs

- **Increasing PE penetration** raises the question of **whether the PE interfaces can**:
  - Be made to **emulate** the same behavior as **synchronous machines**

This approach, from an AC power system designer's perspective, will **reduce/eliminate the impact** of **having less synchronous generation**

- A possible option would be:
  - **Define new grid codes requiring converters** connecting generation/storage **to behave as** if they were **synchronous generators**

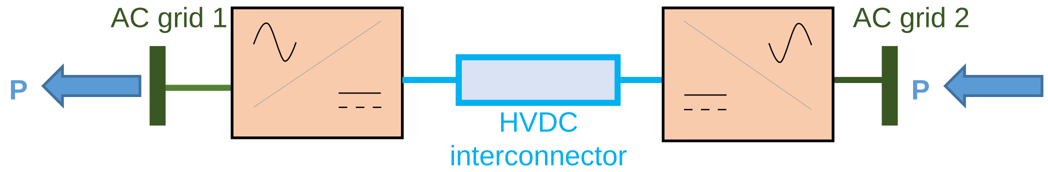
However, **PE manufacturers** have raised concerns, **highlighting the cost impact of these requirements**



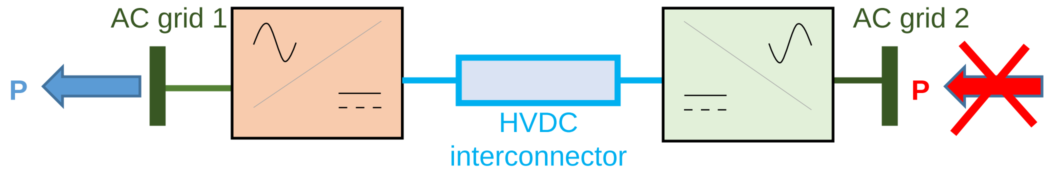
Power electronics vs Synchronous generators

Ilustrative example – Clear differences!

- A response to a **sudden demand in power flow** at one end of a **DC link will be rapidly transferred** to the other terminal and on to the other AC system.



- If the **other AC system** is **not able to accommodate the change in power demand**, the DC link cannot respond.



- The amount of **inherent storage in a DC transmission link** (valves or transmission cable) is **very small compared to** both the **requirements/capabilities of the connected AC grids**.
- The **main decision** to be made is, therefore, the **economically feasible level of over-capacity** that can be justified in DC transmission links.
- **Also, it can lead to a substantial change** in **converter design include additional energy storage elements** such as batteries or super-capacitors (depending on the services to provide)

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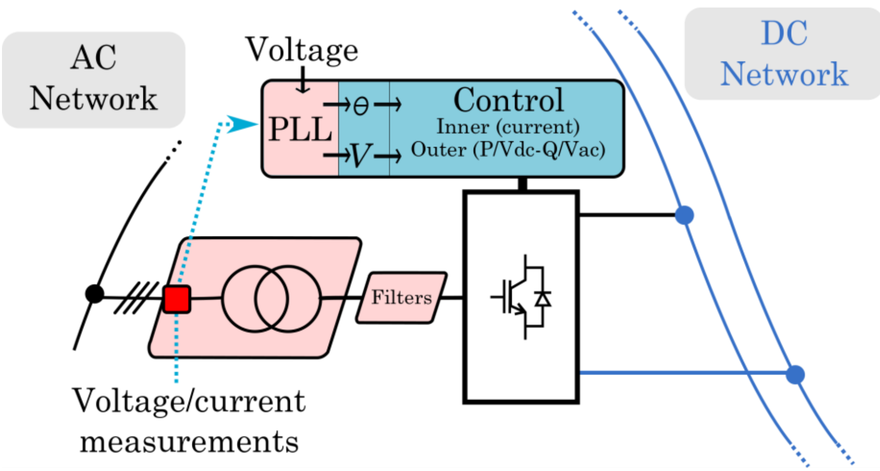
Power electronics vs Synchronous generators

VSC control modes – Programmable modes

The terminologies for **VSC operation modes** are widely used but lack any strict definition*:

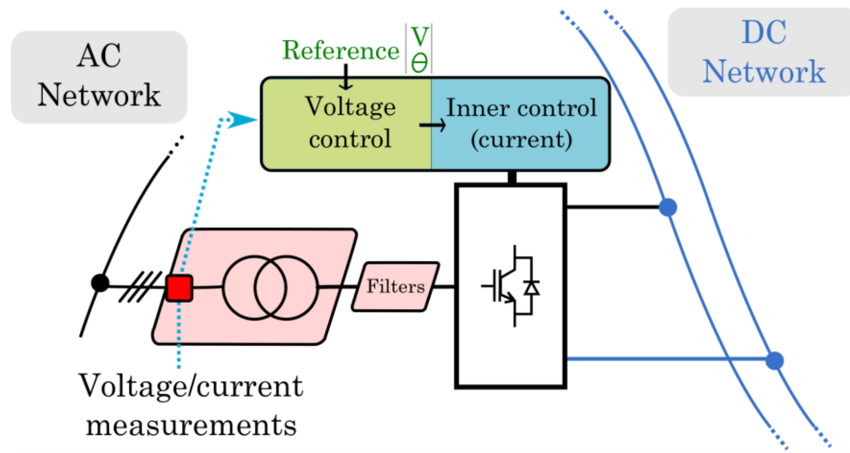
A **Grid-Following** converter:

- **Matches the AC grid voltage and frequency**
- **Faults: provide reactive current equal to the** steady state **rated current during AC faults**.



A **Grid-Forming** converter:

- **Can regulate both instantaneous AC frequency and AC voltage**.
- **Faults: Provide reactive current equal to the** steady-state **rated current during AC faults**.



*Definitions extracted from CIGRE B4, TF77/WG87

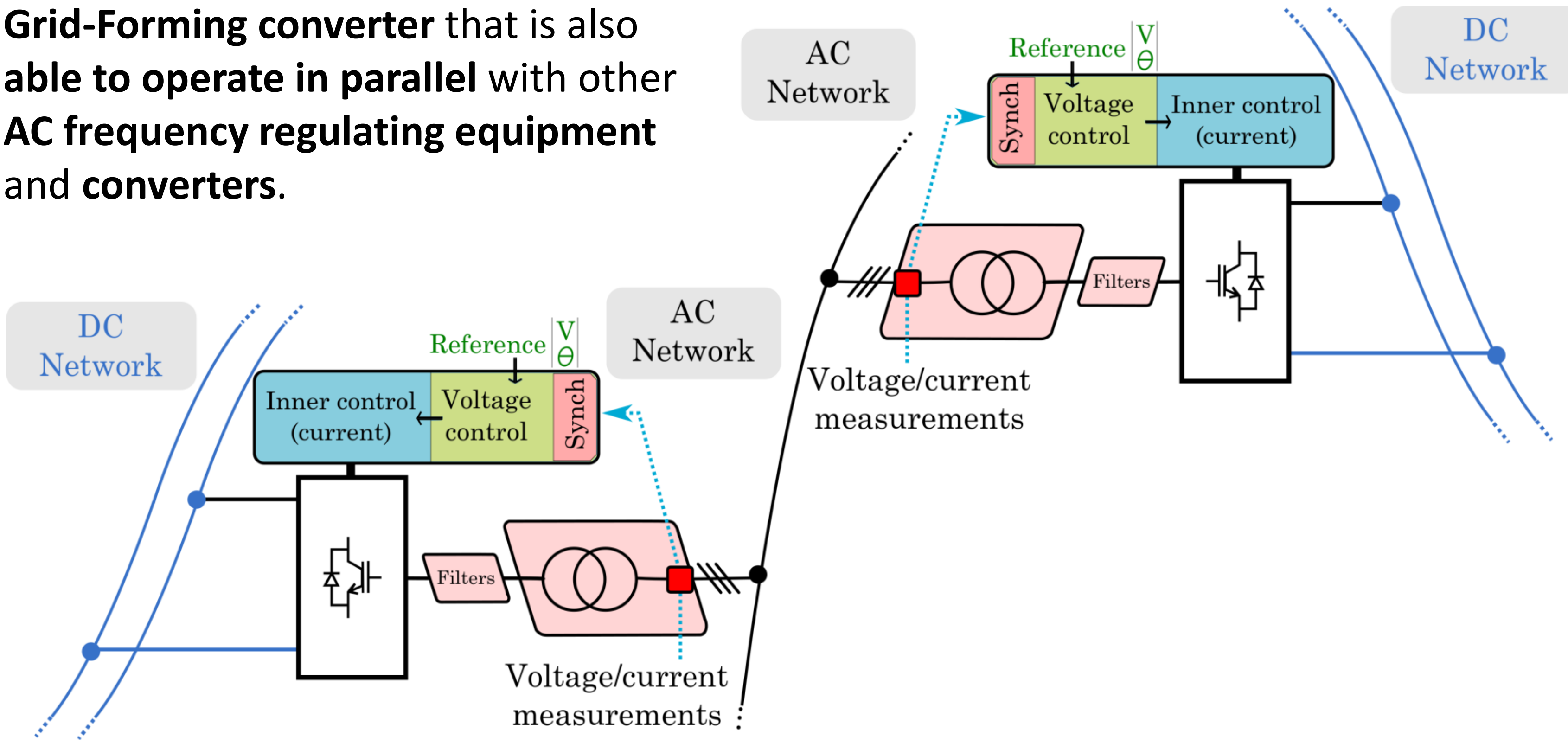
Power electronics vs Synchronous generators

VSC control modes – Programmable modes

The terminologies for **VSC operation modes** are widely used but lack any strict definition*:

A **Synchronous Grid-Forming:**

- **Grid-Forming converter** that is also **able to operate in parallel** with other **AC frequency regulating equipment** and **converters**.



*Definitions extracted from CIGRE B4, TF77/WG87

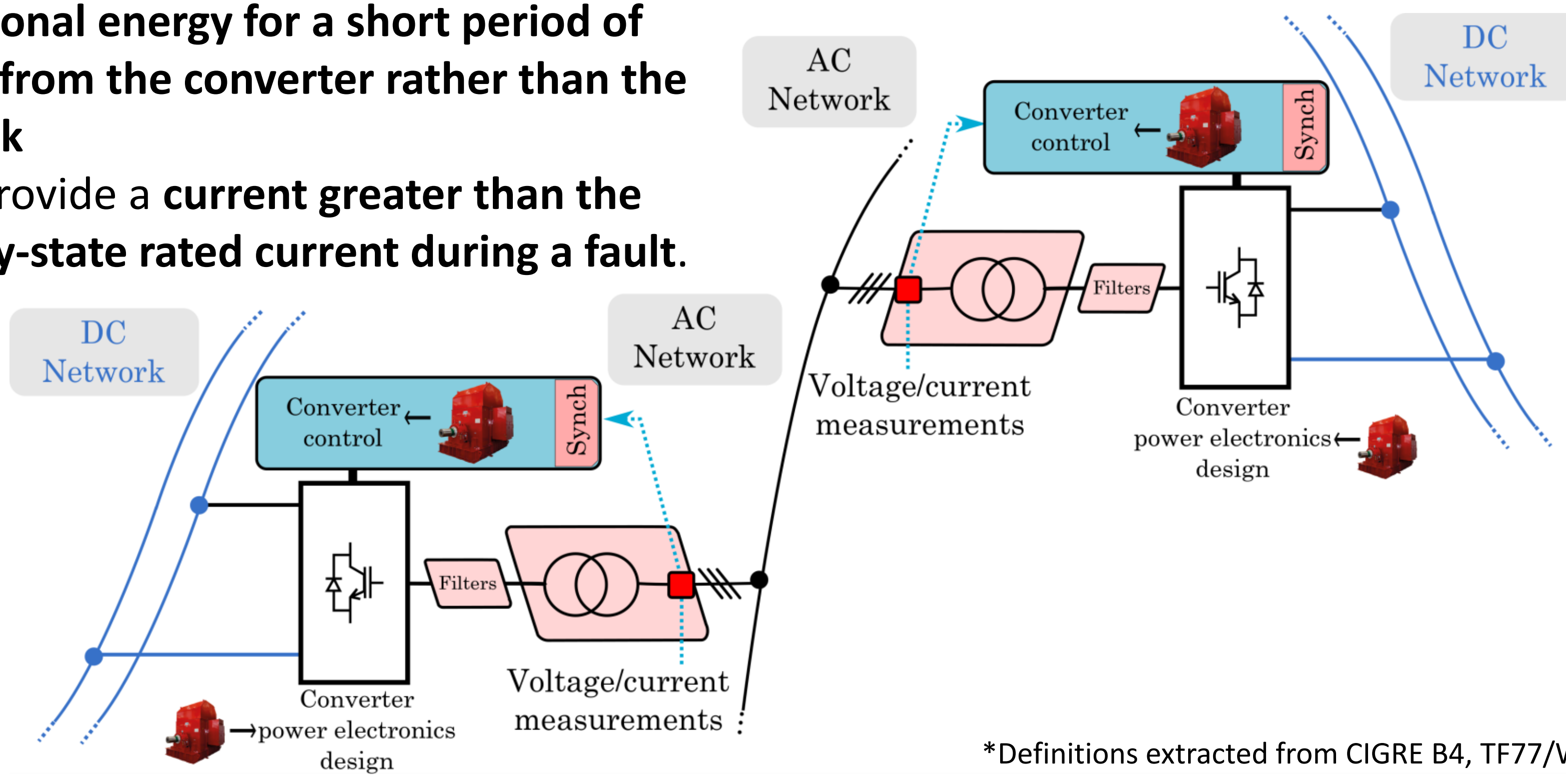
Power electronics vs Synchronous generators

VSC control modes – Programmable modes

The terminologies for **VSC operation modes** are widely used but lack any strict definition*:

Virtual Synchronous Machine (VSM) is a:

- (Synchronous) **Grid-Forming converter**
- **Has energy storage** capable of **delivering additional energy for a short period of time, from the converter rather than the DC link**
- Can provide a **current greater than the steady-state rated current during a fault**.

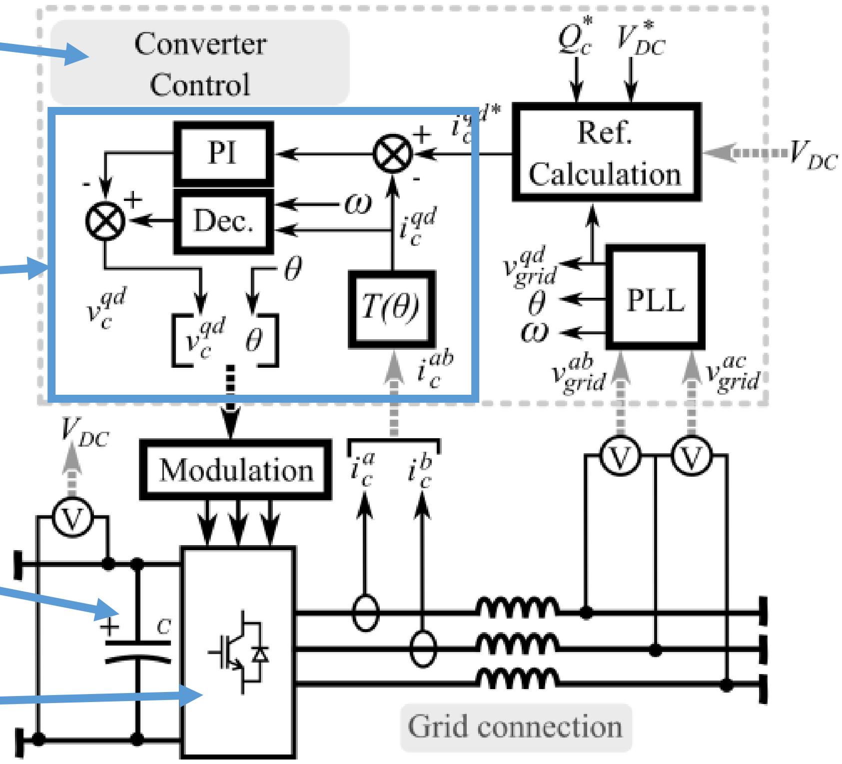


*Definitions extracted from CIGRE B4, TF77/WG87

Power electronics vs Synchronous generators

Main differences

- **Power Electronics**
  - Programmable response – control strategy implemented in uC. Interoperability?
  - Fast response (certain control loops in the ms range)
  - **Limited inertia contribution**, compared to SGs.
  - **Limited short-circuit** contribution, compared to SGs.
  - Difficulties when handling short circuits

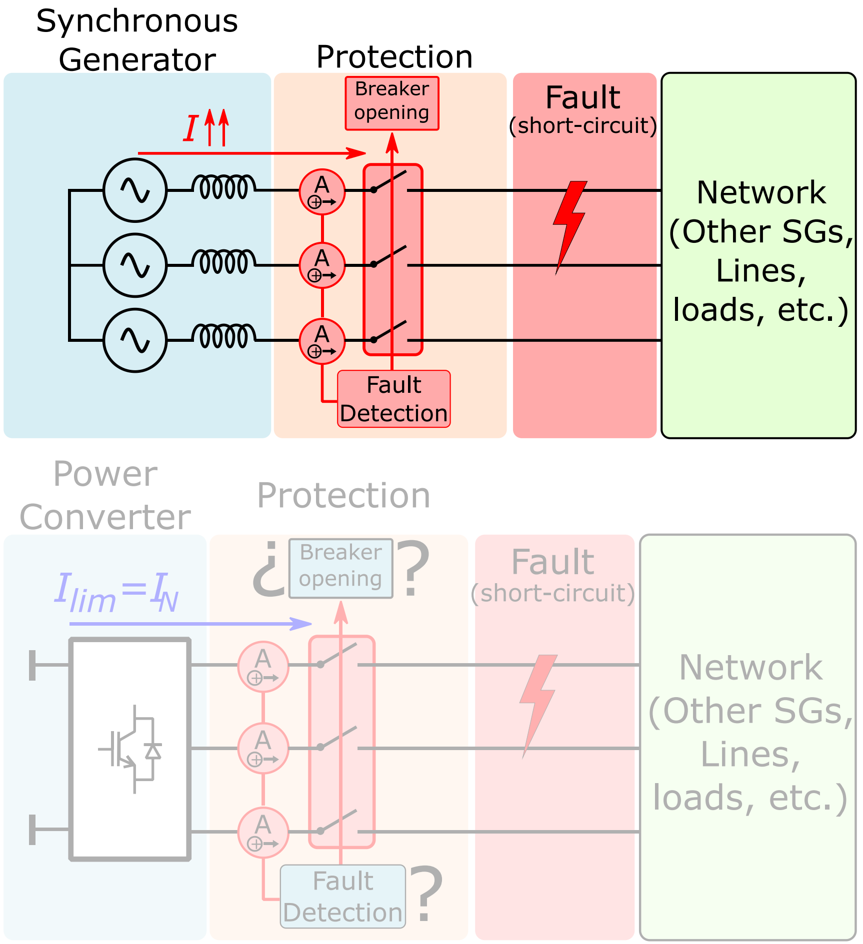


Power electronics vs Synchronous generators

Fault response

- When an **AC system fault occurs**, a **synchronous generator** will **inherently produce a large fault current.**

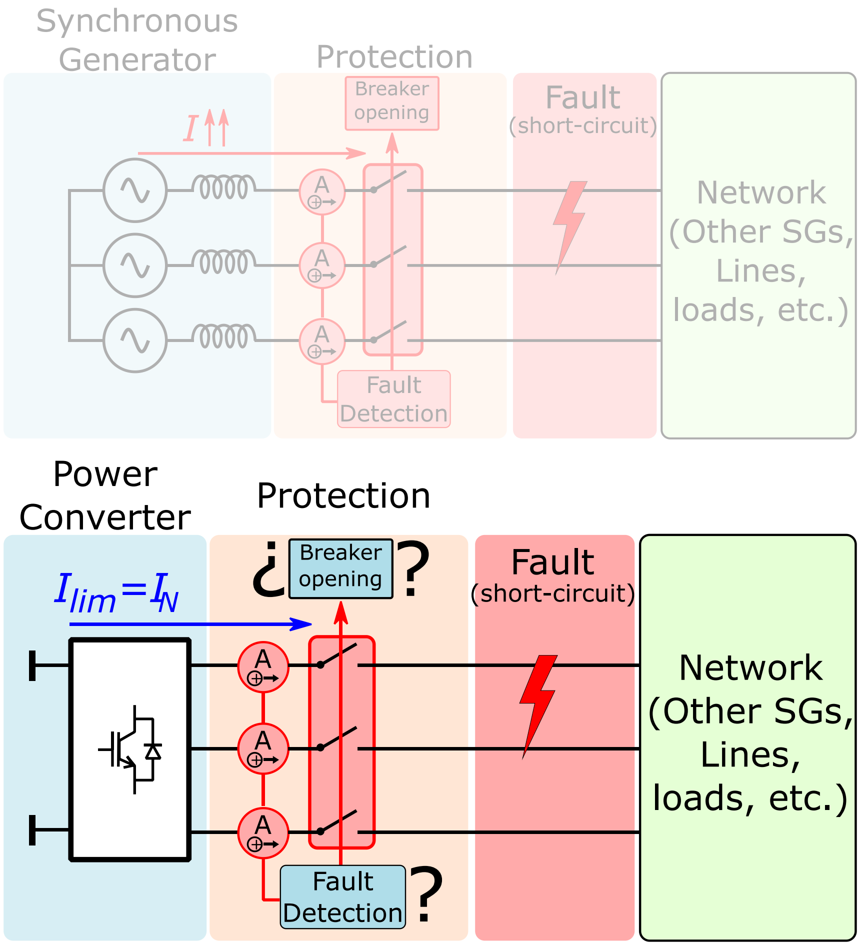
- Whilst this **fault current can be problematic** for the grid in terms of the maximum fault current **to be interrupted by AC switchgear**, the fault current can also provide some benefit to the AC system, namely:
    - **Fault current flowing through the impedance** of the AC system will **raise the AC voltage**, improving the AC voltage profile
    - Measurement of the **high fault current** can be **used to detect the** presence of the **fault**



Power electronics vs Synchronous generators

Fault response

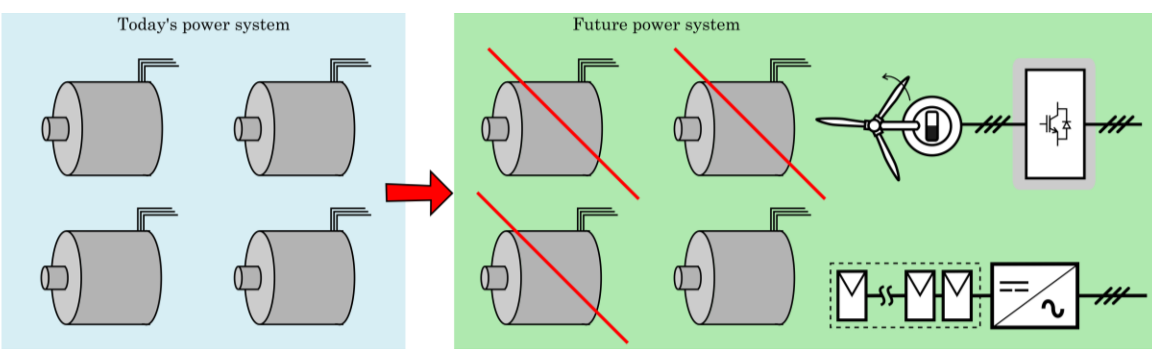
- A **converter** that has been **designed/** optimized for a **particular voltage and current** will **not be able to respond** to a **disturbance** by **providing more than rated current.**
- **To mandate PE converters to supply fault current beyond their rated current** capacity **would require their** effective **rating to be increased**, operating it with a curtailment.
- This might lead to **increased capital cost, losses and footprint**.
- Also, the **converter is typically current controlled** to **avoid exceeding the limitation**, which adds an inherent response delay.

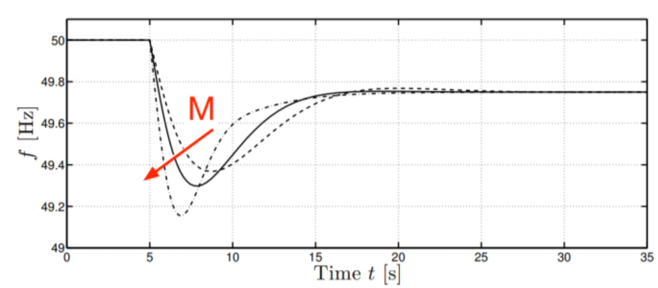


Power electronics vs Synchronous generators

Post fault response

- In a **sudden loss of generation** within the AC **grid, the remaining generation must compensate it** by providing **additional power**
- **Generators respond 'instantaneously'** to the AC disturbance, **taking energy from their inertia**
- With **reduced synchronous generation**, the **AC frequency can fall faster** at some parts of the grid, compromising the system stability.
- What should converters do?
  - **Injecting real power** to **avoid high RoCoF** and excessively low values of system frequency?
  - Avoid participating in low-frequency interactions?
  - Provide damping? Keep pre-fault constant power?





Source: Prof. Florian Dörfler (ETH)

RoCoF (Rate of Change of Frequency)

*RoCoF – Rate of change of Frequency

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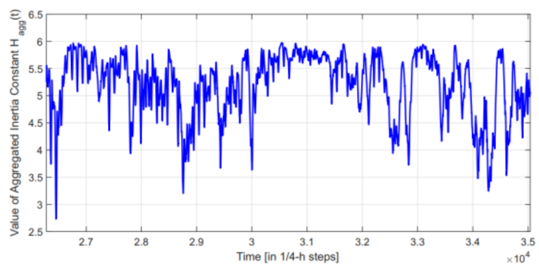
New power system issues

Real/relevant examples to show these differences!

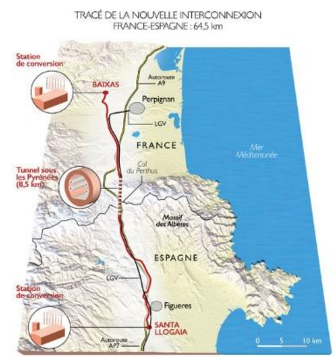
These differences are arising new power system issues that need to be solved!

El Hierro island (low inertia system)

German inertia variability



INELFE interactions (participation after faults+ Harmonic interaction)



South Australia Blackout (fault management)

Borwin 1 (oscillatory)

Luxi Back-to-back (harmonic interaction)

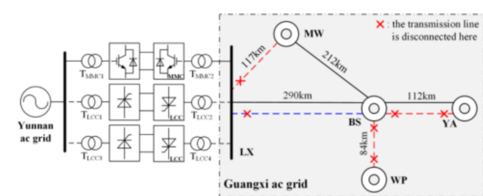
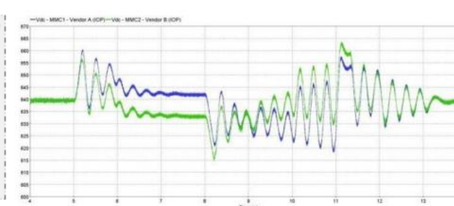


Fig. 1. Luxi back-to-back HVDC project.

Best paths project (interoperability)



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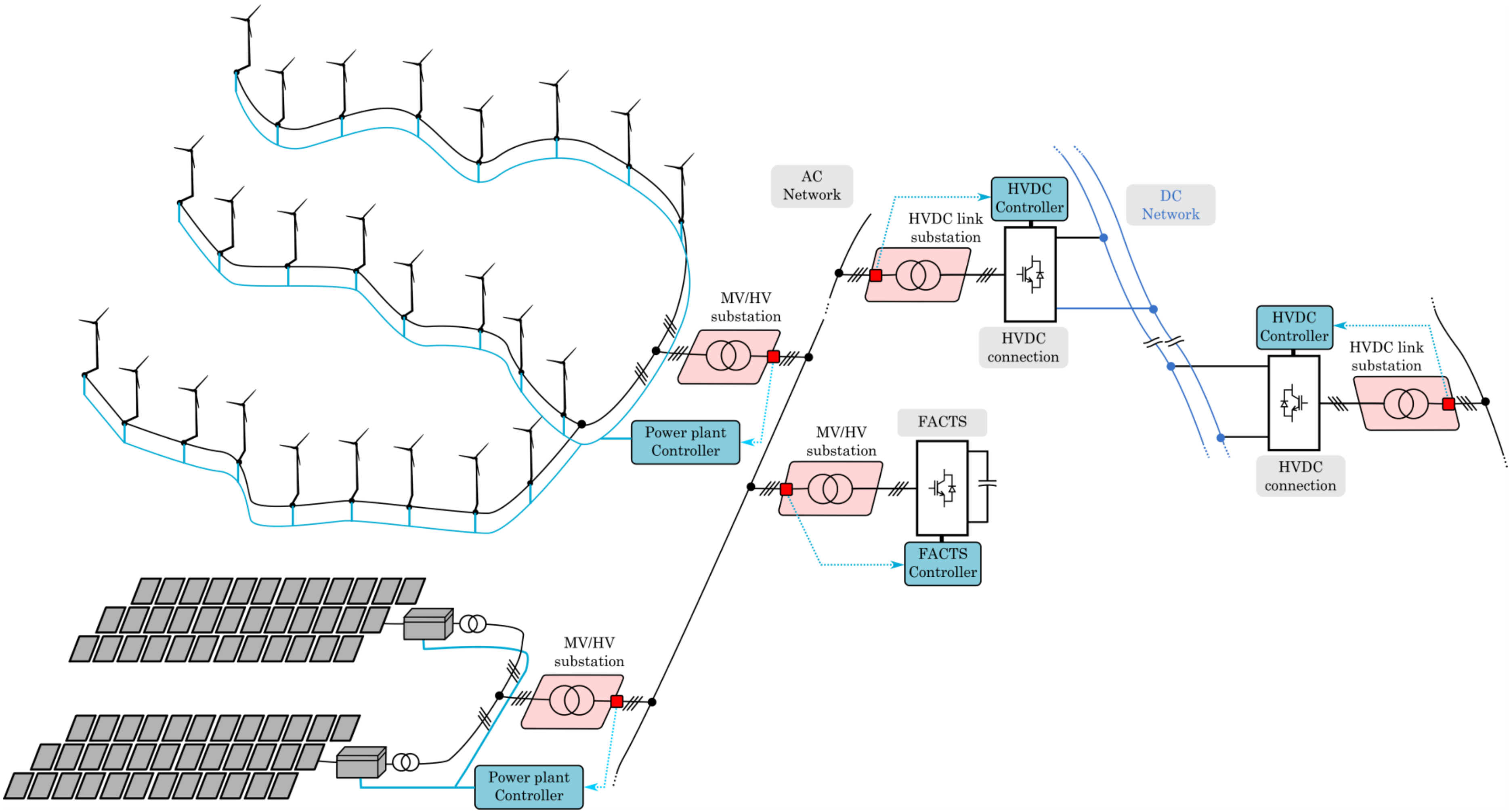
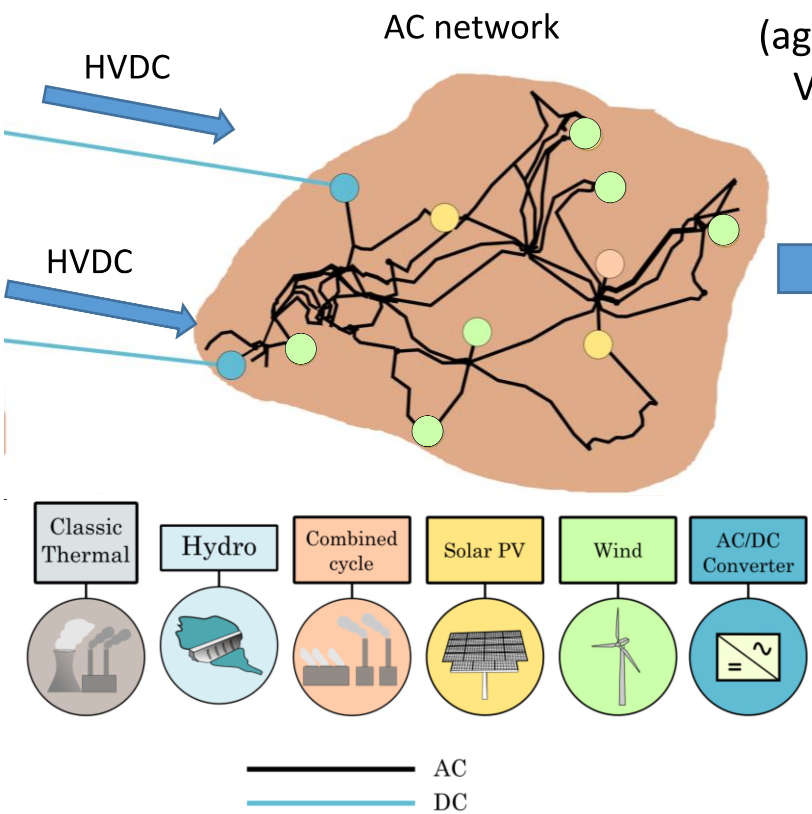
UPC ‘research map’



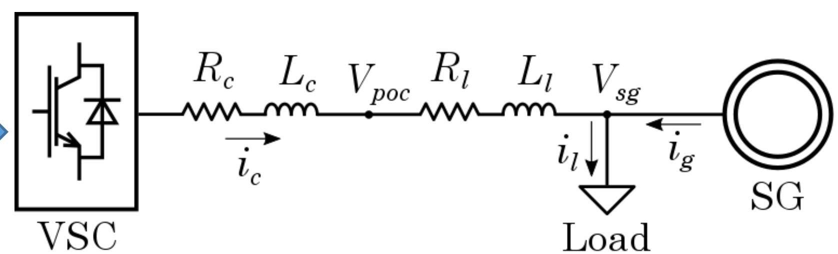
Islanded system – Interaction analysis

VSC + Synchronous generator



System simplification (aggregation of all VSC, including wind)

Understand the general behavior of a PE-dominated system



Objectives of the model:

- Understand the fundamentals of interactions between both systems
- Impact of different controllers
- Identify the minimum generation limit (small-signal) assuming grid following converters.

Methodology developed

Description

Complete system analysis

Derivation of **mathematical model** of the entire system including the power system elements

- Linear and simplified models
- Equations and mathematic analysis
- Capture the system essential dynamics

Study possibilities

- Conventional analysis (eigenvalues, participation factors, frequency models, etc.
- Find mathematic relations between variables
- Sensitivity analysis (different operation points, control modes, etc.)

Derivation of an **EMT-based model** of the entire system including all the power system elements

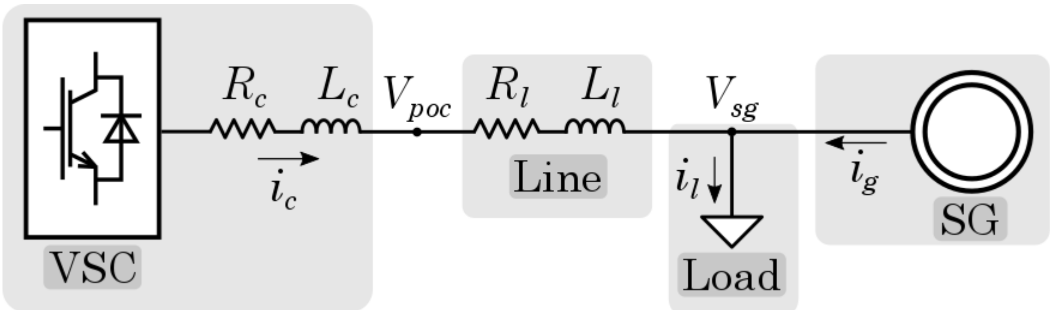
- Use detailed models (cables, converters, transformers, etc.)
- Include system non-linearities (switching strategies, saturations, control modes, etc.)
- Use of black-box models

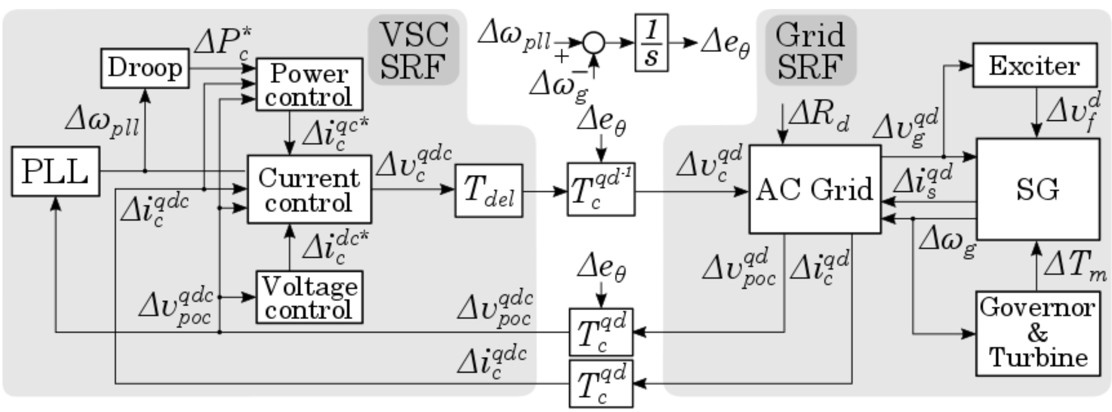
Study possibilities

- Simulations of a single case study
- Large transient analysis (faults, etc)
- Parametric studies
- …

Mathematic analysis example

VSC-HVDC converter + Synchronous generator





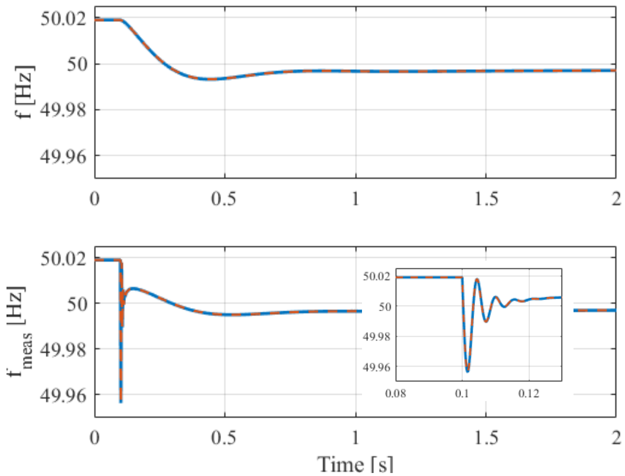
Model (linear) derivation:

- Thermal power plant
  - Governor and exciter (voltage and frequency controllers)
  - Synchronous machine equations (electrical and mechanical)
- VSC-HVDC converter
  - PLL
  - Current control
  - Active and reactive power controllers (P-Q mode)
  - Frequency controller

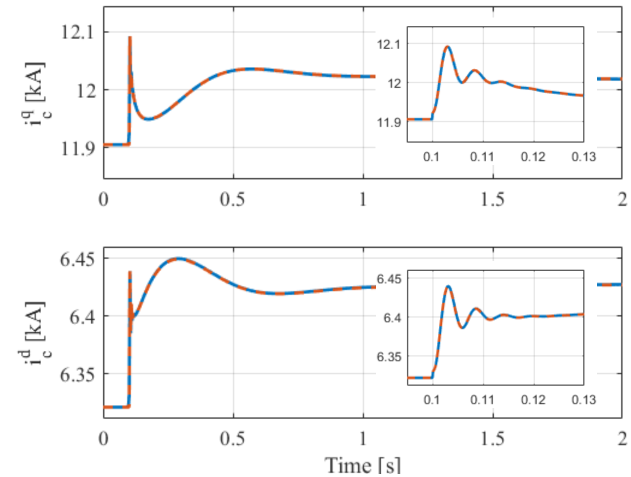
*Additional control modes can be implemented, as well as more complex networks

Mathematic analysis example

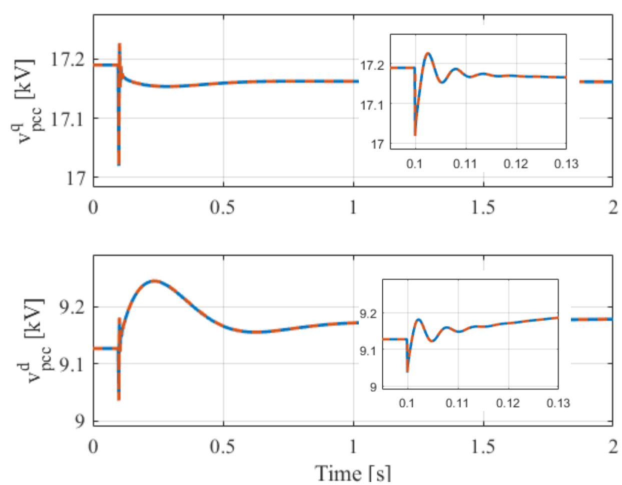
Linear vs non-linear complete model (small disturbance) – Load change



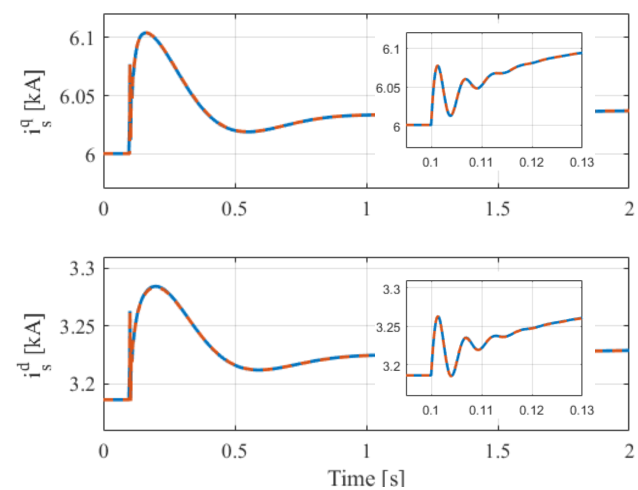
Real and measured frequency



Converter currents



POC AC voltage



Generator currents

Mathematic analysis example

Sensitivity analysis

Increasing the VSC nominal power

Increasing the VSC injected power

Reduce the generator nominal power

Increasing the VSC droop gain

Decreasing the PLL loop speed

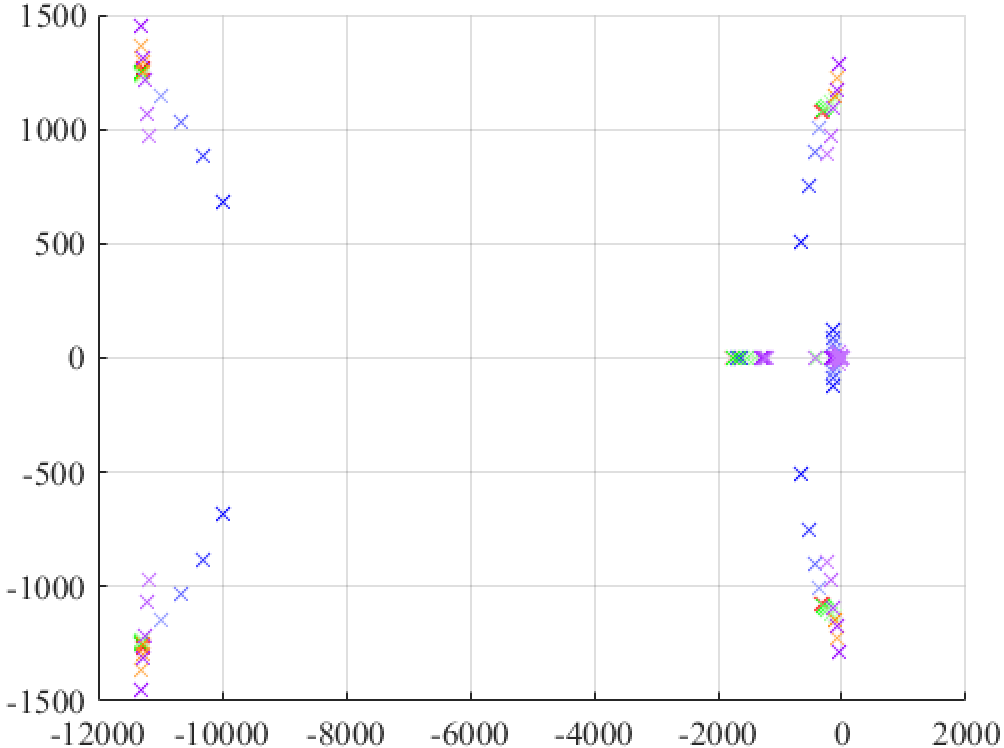
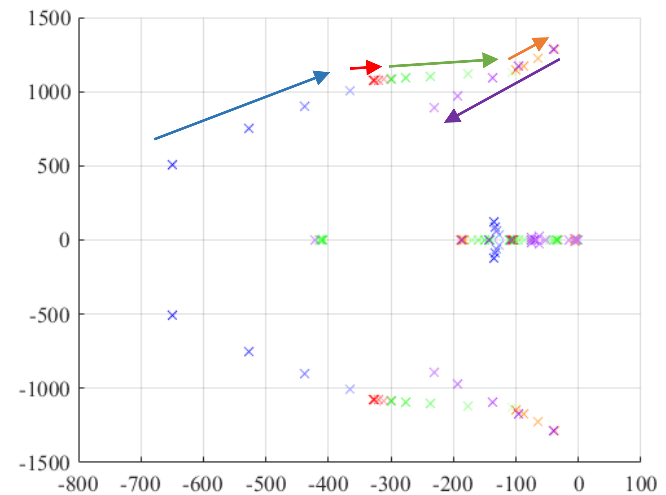


Diagrama de polos del sistema VSC + SG

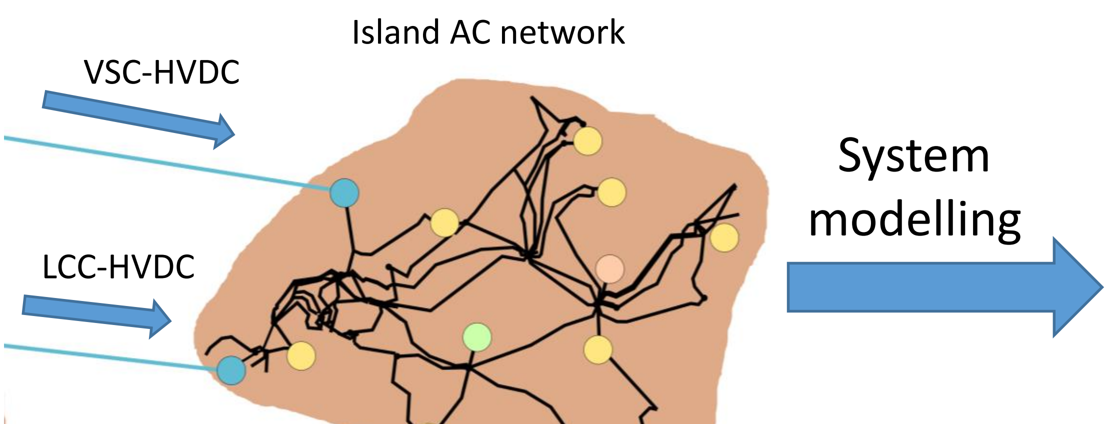


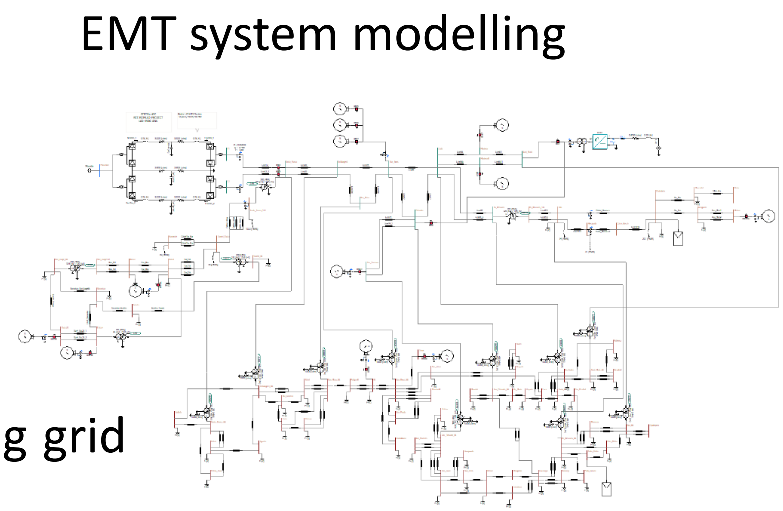
Colors:
- Dark: initial value
- Light: final value

Example:
- Dark blue (P_{VSC} low), light blue (P_{VSC} high)
- Dark green ($P_{generator}$ high), light green (P_{gen} low)

Model development

Detailed modelling of different components



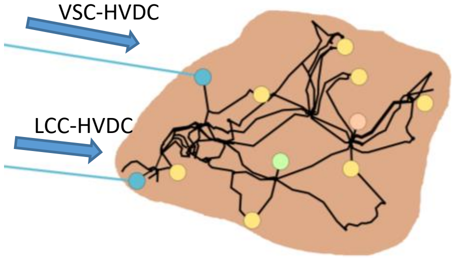


Objectives:

- Identify the minimum generation limit assuming grid following converters
- Detect converter interactions
- Scenarios simulated (systematic analysis):
  - Reduction of the SGs
  - Reduction of the SGs + Network faults
- Entire system is modelled including secondary networks

Model development

Results – SG disconnection – Higher share of power electronics

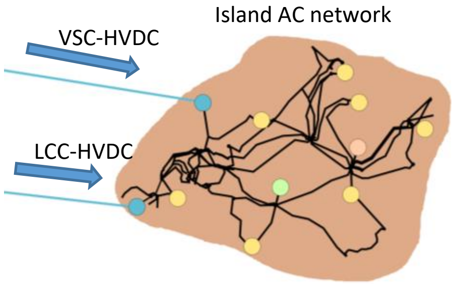


LCC		MMC		Generators in G1			SG Prop	Instability?	
P_{LCC} (MW)	P_{LCC}/P_{tot} (%)	P_{MMC} (MW)	P_{MMC}/P_{tot} (%)	#Gen	P_{GSR} (MW)	P_{G1}/P_{tot} (%)	S_{SG}/S_{tot} (%)	P-Q	P-V
0	0	728	55,4	3	189	14,4	42,2	No	No
200	15,2	528	40,2	3	189	14,4	42,2	No	No
400	30,4	328	25	3	189	14,4	42,2	No	No
0	0	791	60,2	2	126	9,6	38,6	No	No
200	15,2	591	45	2	126	9,6	38,6	No	No
400	30,4	391	29,7	2	126	9,6	38,6	No	No
0	0	854	65	1	63	4,8	34,9	Yes	No
200	15,2	654	49,8	1	63	4,8	34,9	No	No
400	30,4	454	34,5	1	63	4,8	34,9	No	No
0	0	917	69,8	0	0	0	31,3	Yes	Yes
200	15,2	717	54,6	0	0	0	31,3	No	No
400	30,4	517	39,3	0	0	0	31,3	No	No

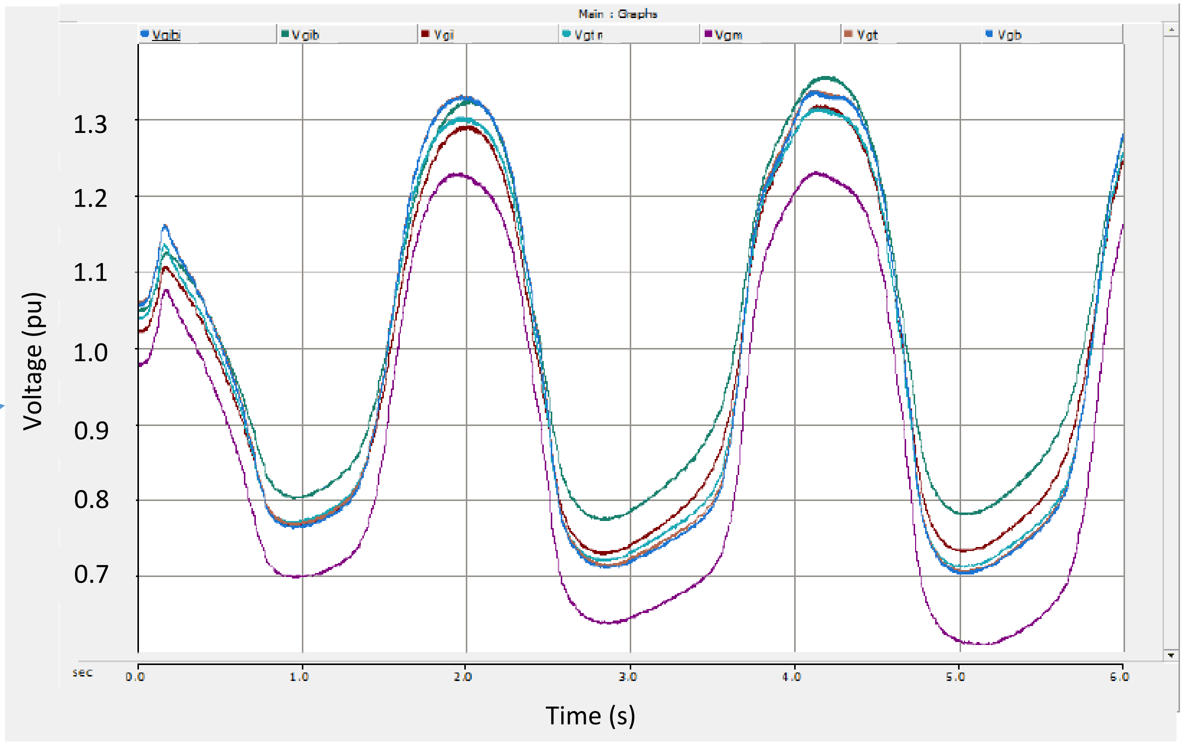
- First analysis
  - Changing the LCC/VSC production share and the #Gen connected
- Results
  - For the majority of the scenarios simulated, the system is 'stable'
  - Instability found around 30% of SG, when LCC is disconnected
  - The instability depends on control performed by the MMC

Model development

Results – SG disconnection – Higher share of power electronics



System voltages at different system buses



- Preliminary results simulations
  - Low frequency oscillation within the islanded system
  - Accurate VSC control tuning might be required

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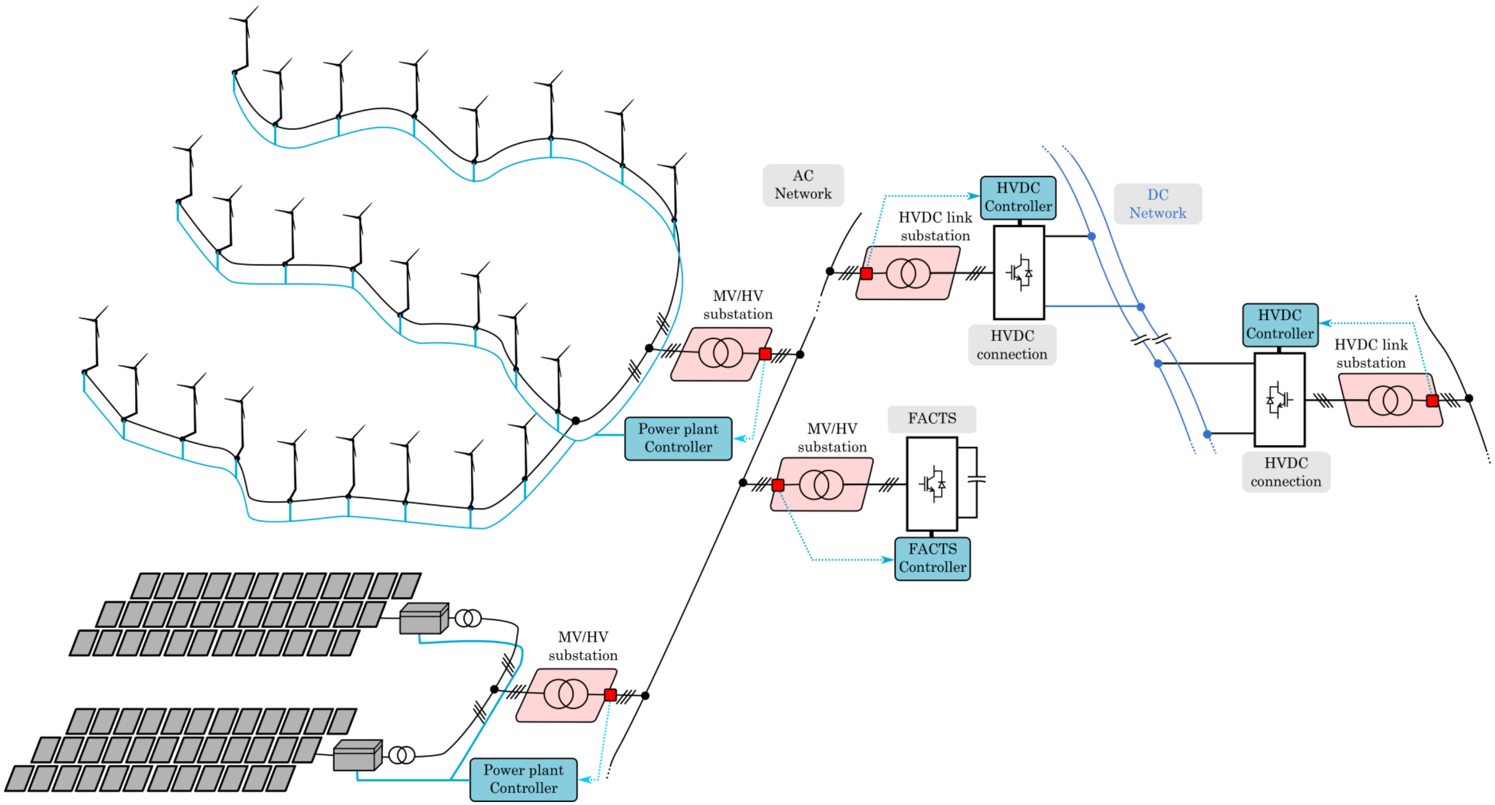
Conclusions

- Power electronics are different from SGs.
- We need to rethink (fast) how power electronics dominated power systems are designed, operated and controlled.
- Power electronics can facilitate the energy transition, supporting the network, but we have to design and program them properly.
- Converter roles will be different from today in the 'near' future power network.
- Rethink the 'classic' analysis tools and procedures (stability, etc.)

Thank you for your attention



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UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

CITCEA UPC

The research group

CITCEA UPC

- UPC research center
- Founded in 2001
- Part of the TECNIO network, by ACC1Ó
- Over 60 people: 11 academics, 25 engineers, 3 administrative staff, 15 PhD students, 20 Master and Bachelor students
- **1 spin-off** company (teknoCEA)

MECHATRONICS
- Power electronics and electrical drives.
- Automation, industrial ICTs.

ENERGY
- Generation, transmission and distribution.
- Economics, market and regulation of electrical energy.

LIFE LONG LEARNING
- LLL Masters in Mechatronics and Enertronics.
- Courses and Seminars for professionals.