Comparison of Models and Implementation of Virtual Synchronous Generators

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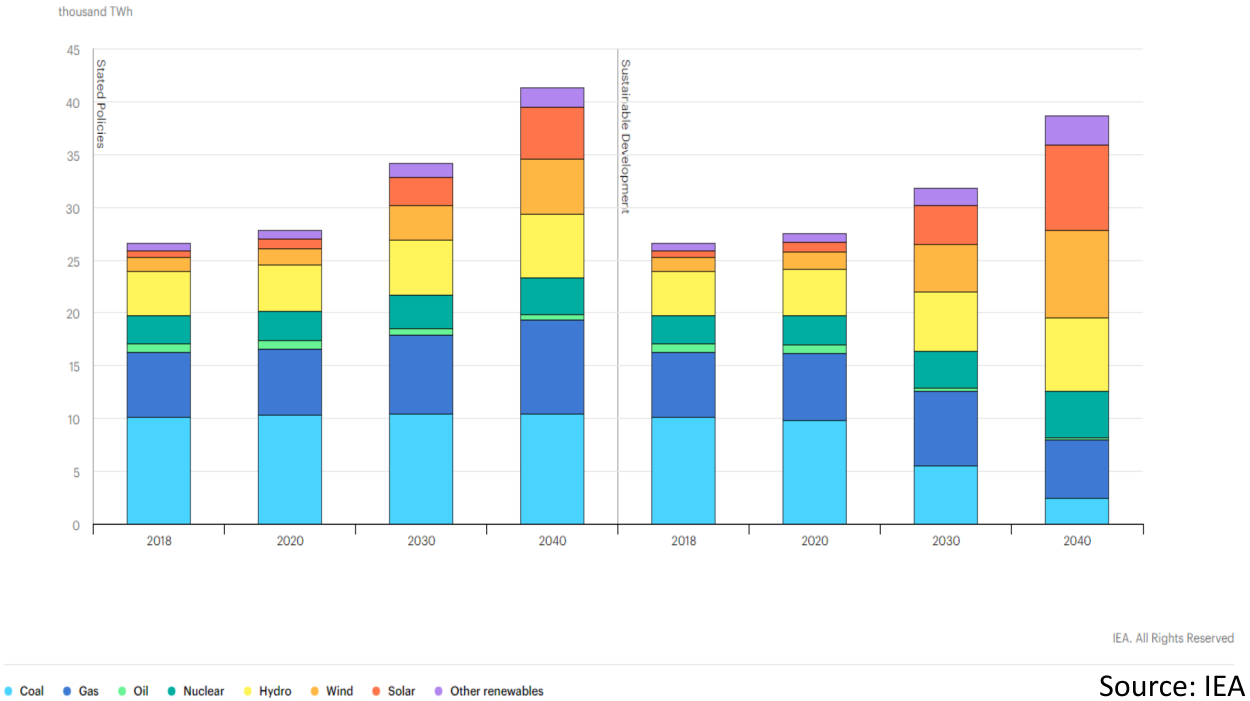
Outline

- Introduction
- Goal of the Master Thesis
- Description of the Models
- Experimental Results
- Conclusions

- The Electric System is going through a **revolutionary phase:**
  - A growing production of energy from renewable sources is expected
  - The distributed generation (DG) is increasingly widespread



Source: IEA

- Wind and solar interfaced with power electronics converters

Can the Electric System rely only on them?

Introduction

- The grid stability is strictly linked with the presence of the synchronous generators (SGs) of hydro/thermal power plants

- They can provide ancillaries services to the grid:
  - Frequency regulation (inertia and frequency control)
  - Reactive support (voltage regulation)
  - Support during faults (injection of short circuit currents)
  - Harmonics compensation

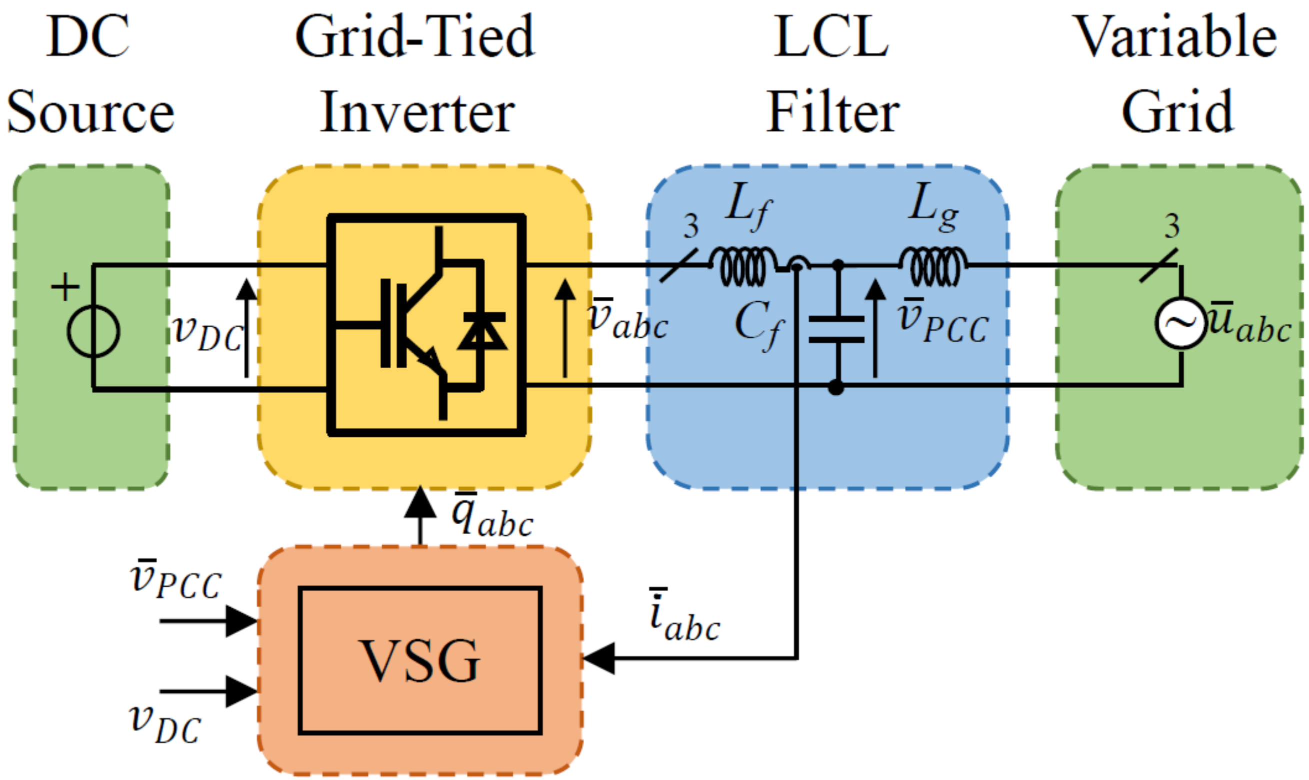
- The decarbonization process will reduce even more the number of conventional generators
- Static converters do not embed SGs' features and conventional control techniques are not suitable to solve this problem
- Many solutions were proposed in the literature, with a common goal: make static converters mimic synchronous generators

Goal of the Master Thesis

- **Bibliographical research** and study of the VSG solutions proposed in the literature
- Realization of **PLECS simulations** for each VSG model
- **C-code implementation** of the discrete-time version of each solution
- Evaluation of each considered VSG model by means of **experimental tests**
- **Comparison** between the analysed VSG models

- The analyzed VSG models available in the literature are:
  - Synchronverter
  - Osaka
  - VISMA
  - VISMA1
  - VISMA2
  - SPC
  - VSYNC
  - Kawasaki
  - CVSM

Block Diagram

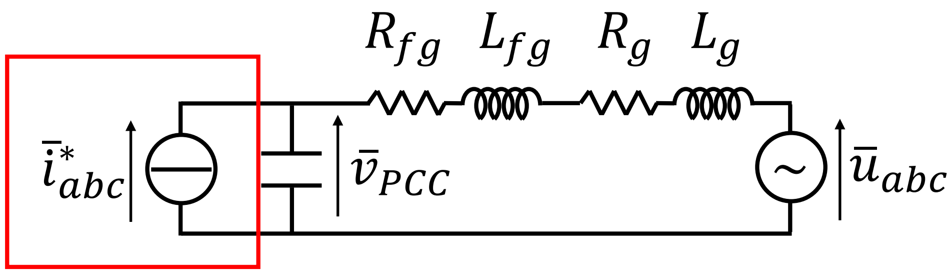


Description of the Models

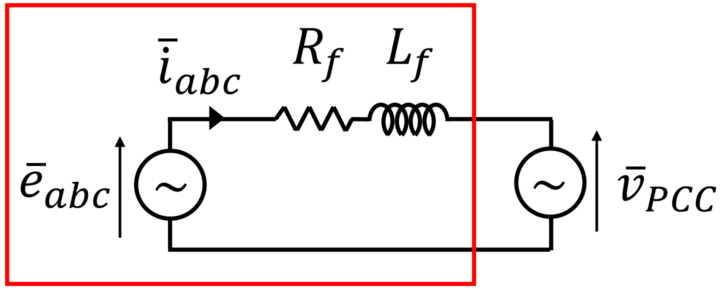
Two Categories

- Synchronverter
- VISMA
- VISMA1
- SPC
- VSYNC
- Kawasaki
- CVSM

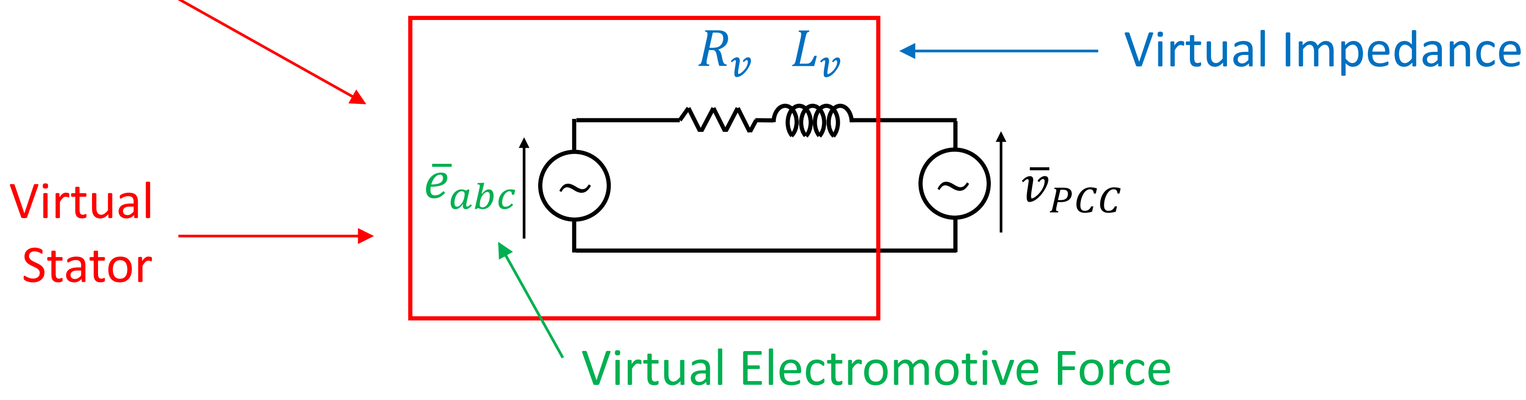
Current Output



Voltage Output



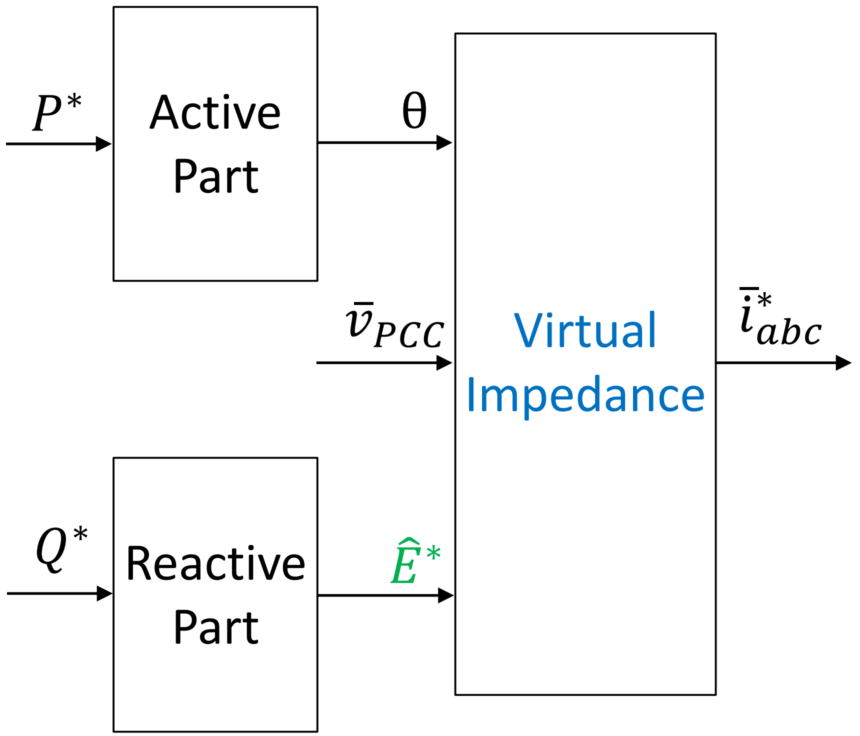
- Osaka
- VISMA2



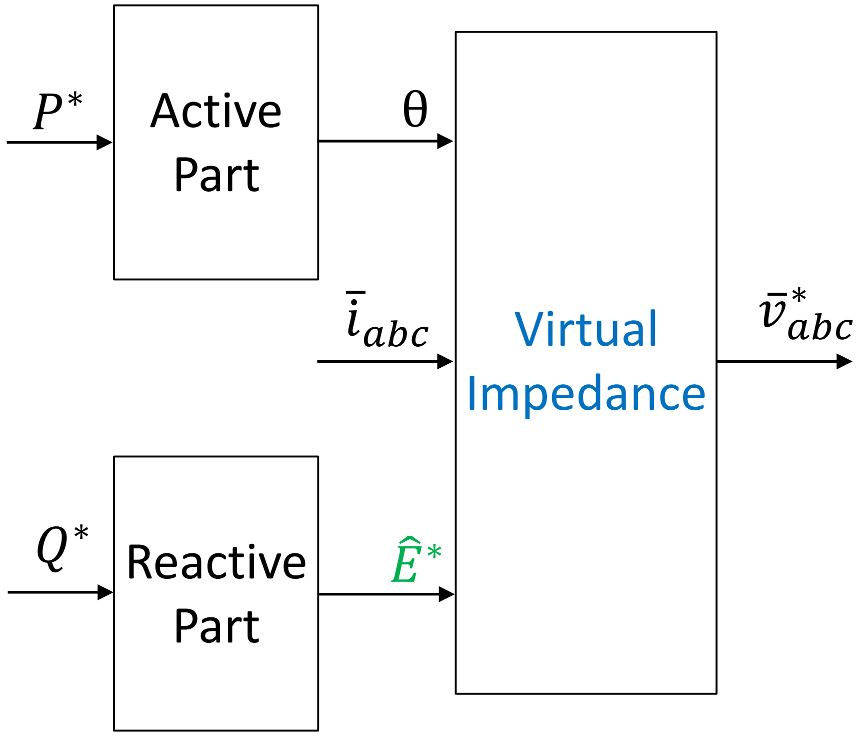
Description of the Models

Two Categories

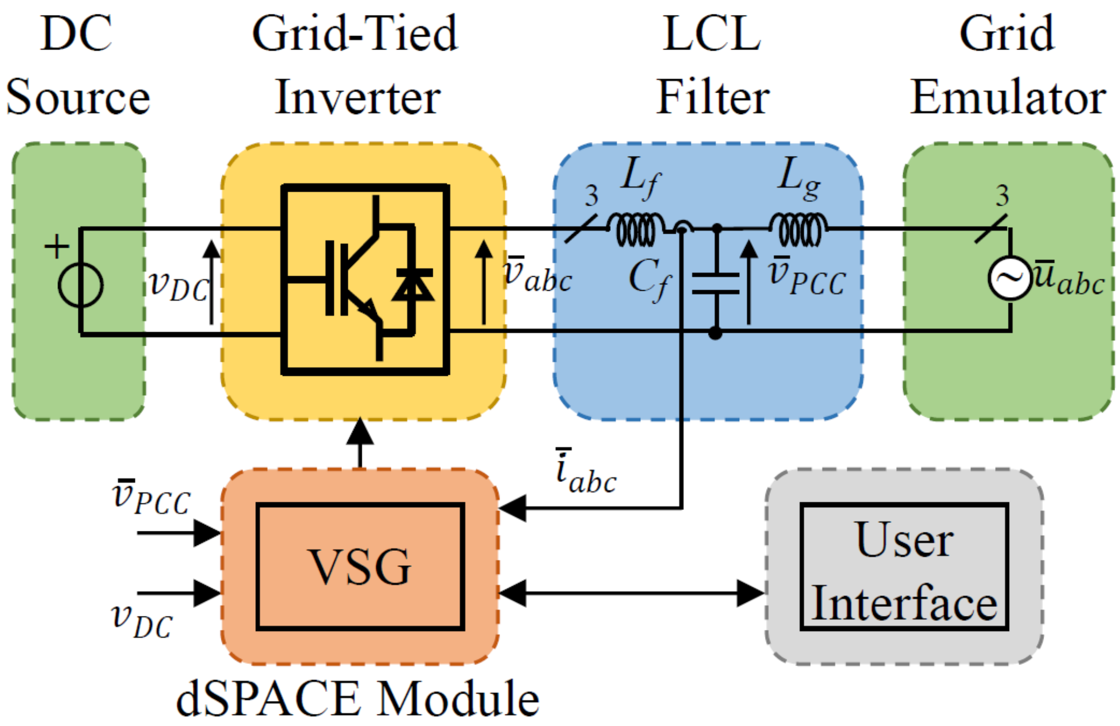
Current Output

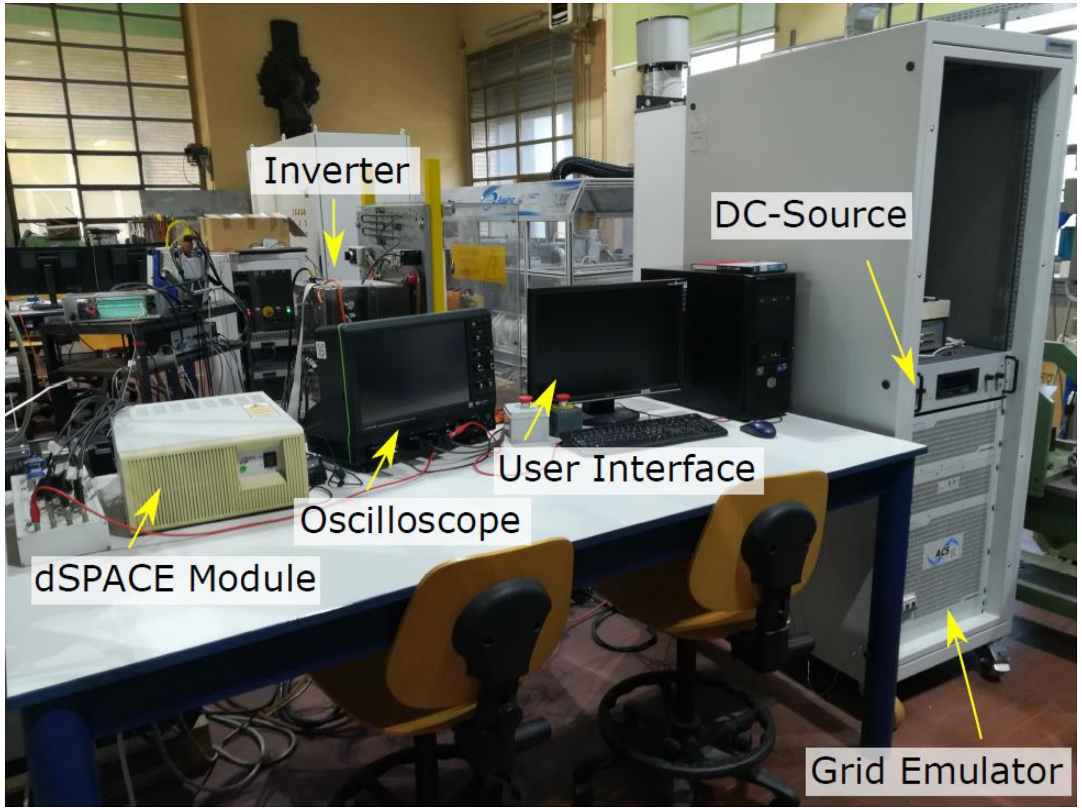


Voltage Output



- Experimental Setup

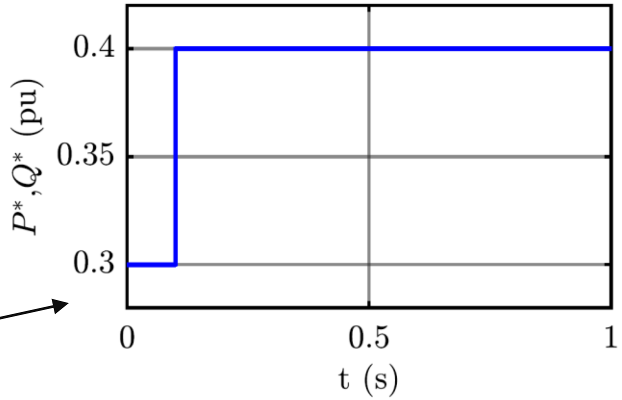


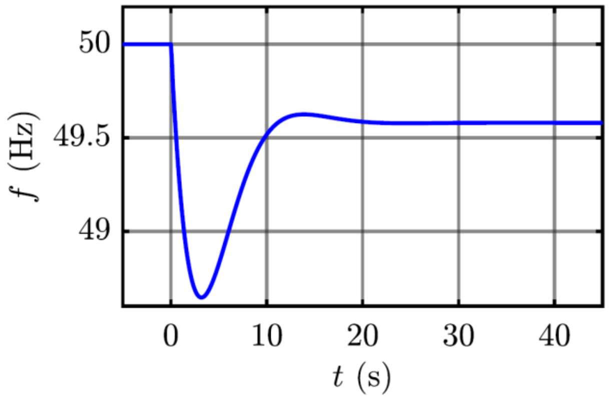


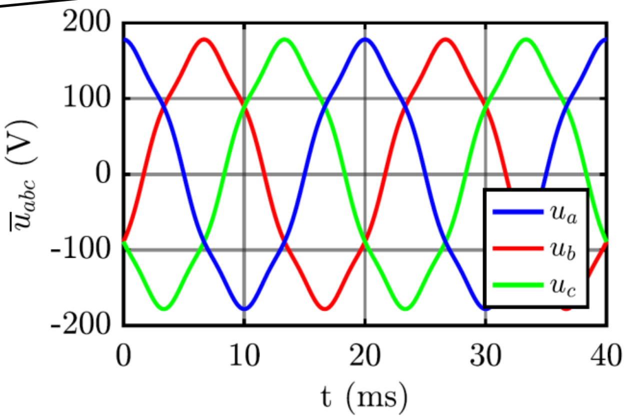
Main Data: $\begin{cases} \hat{U} = 120\sqrt{2}\ \mathrm{V} \\ S_N = 15\ \mathrm{kVA} \end{cases}$

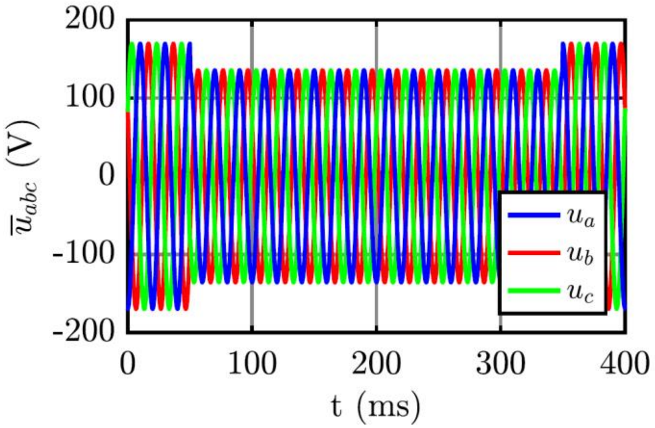
Experimental Results

- List of Tests:
  - Active and Reactive Power Reference Variation
  - Frequency Transient
  - Harmonic Distortion
  - Short Circuit Fault



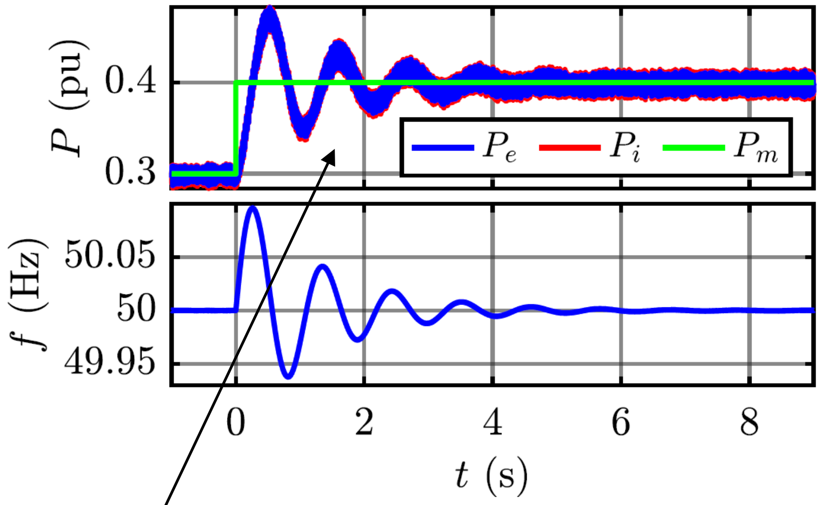




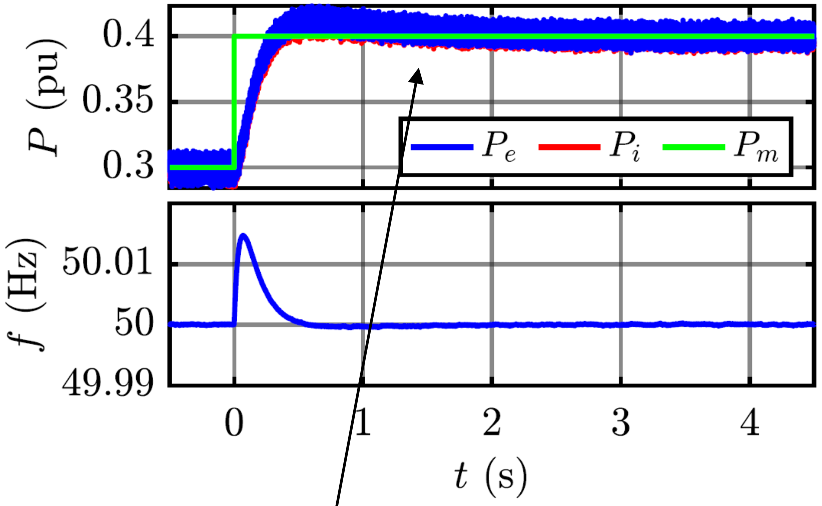


➢ Active Power Reference Variation

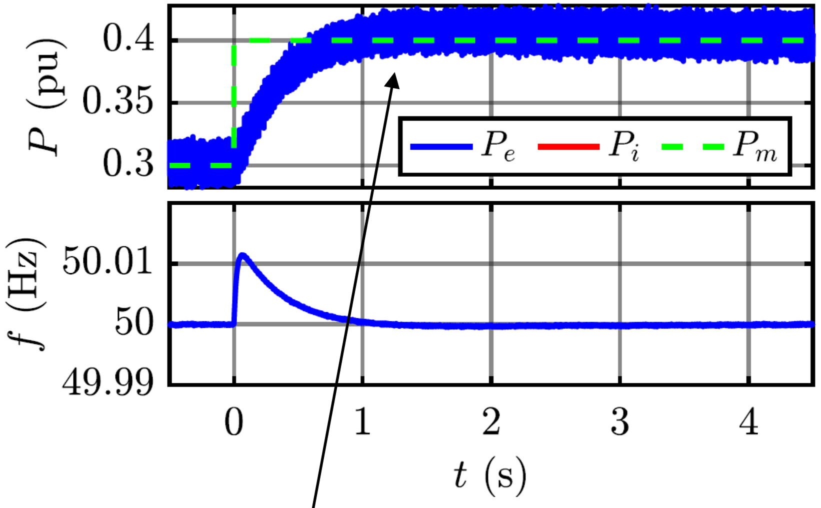
VISMA



VISMA1



VISMA2



Complete emulation of SGs (7th order)

⇓

Underdamped response

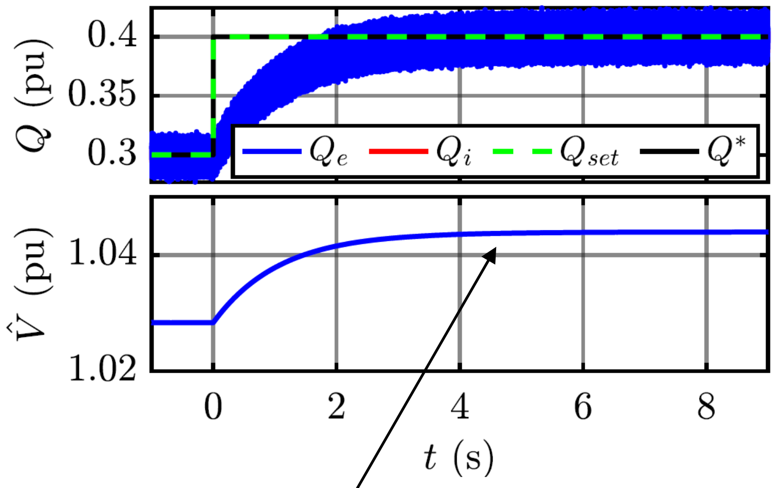
Slight overshoot

Damped response

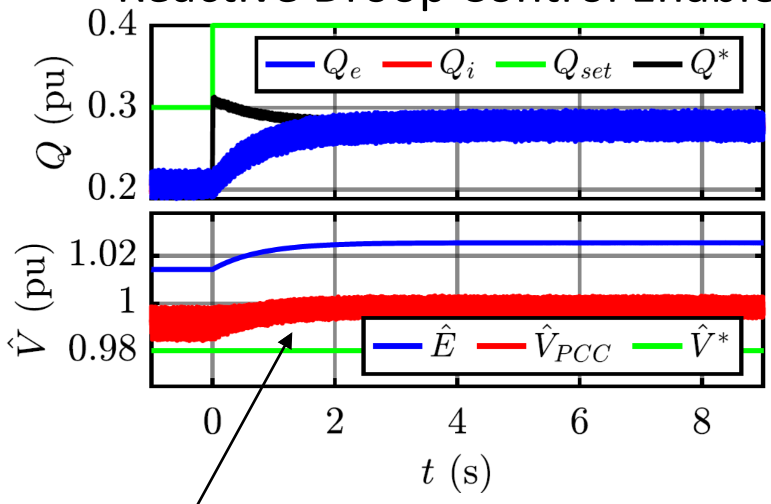
- Reactive Power Reference Variation

Synchronverter

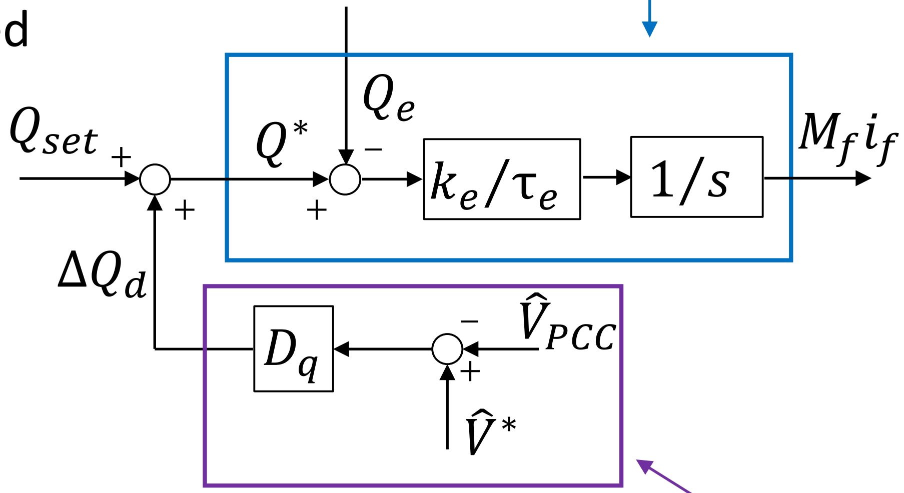
Reactive Droop Control Disabled



Reactive Droop Control Enabled



Excitation

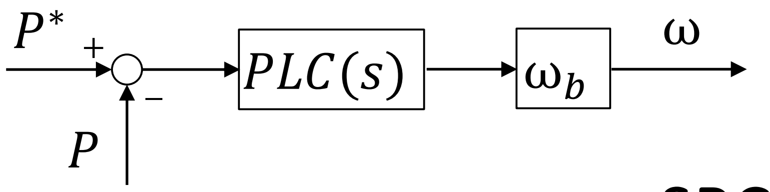


Reactive Droop Control

Time constant
$\tau_e = 1\ s$

Difference of voltage $\Rightarrow$ Reactive Droop Control

- Frequency Transient



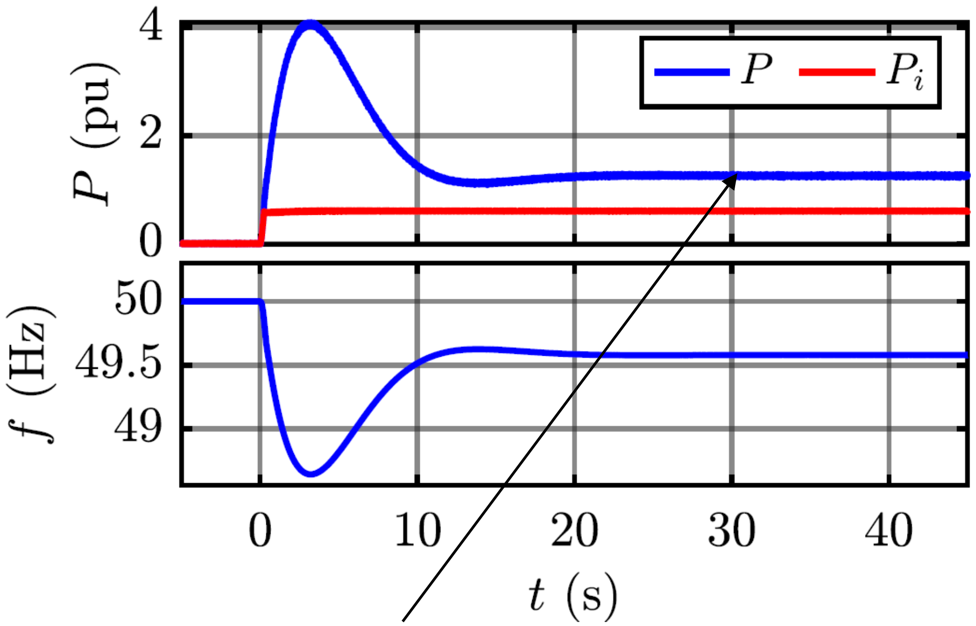
PLC:

$$\begin{cases} \text{SG:} & \dfrac{k\,\omega_c}{s+\omega_c} \\ \text{PI:} & \dfrac{k_p s + k_i}{s} \\ \text{LL:} & \dfrac{k_p s + k_i}{s+k_g} \end{cases}$$

Parameters:

$$\begin{cases} k_d = 153 \text{ pu} \\ b_p = 0.05 \text{ pu} \end{cases}$$

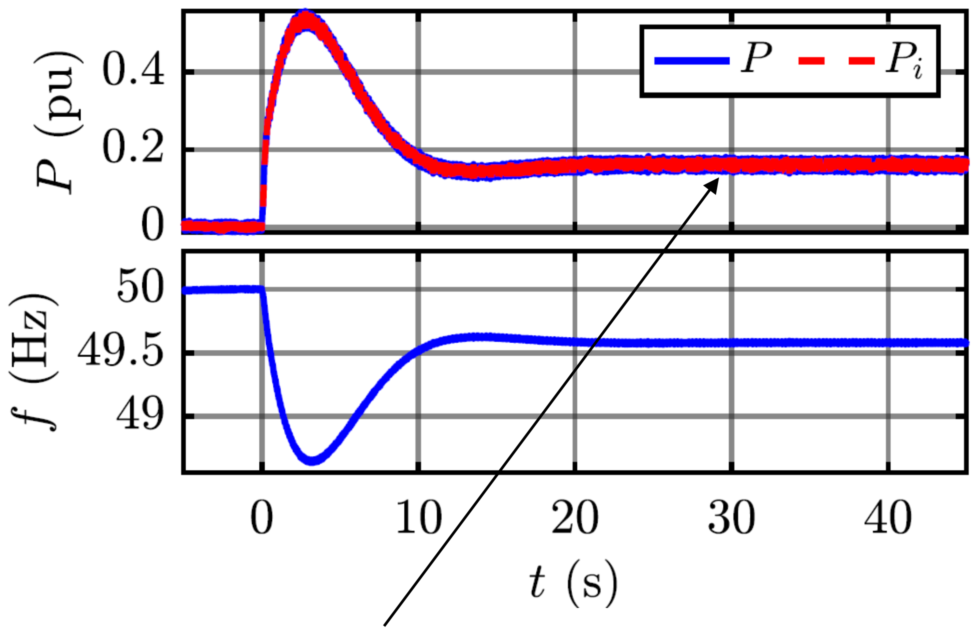
SPC SG



Damping-Droop Coupling

$$P = k_d \Delta f >> \frac{\Delta f}{b_p}$$

SPC Lead-Lag (LL)



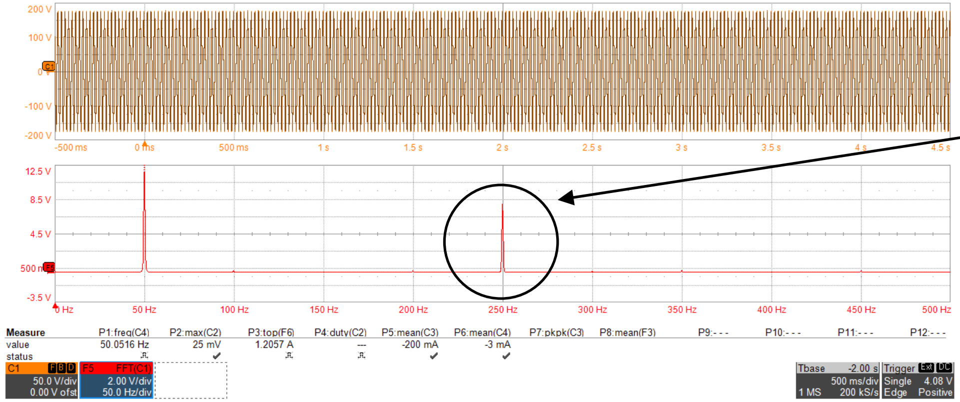
Damping-Droop Decoupling

$$P = \frac{1}{b_p}\Delta f$$

- Harmonic Distortion

5% of
5^{th} Harmonic

Current references disabled



8.5 V

Amplification of distortion

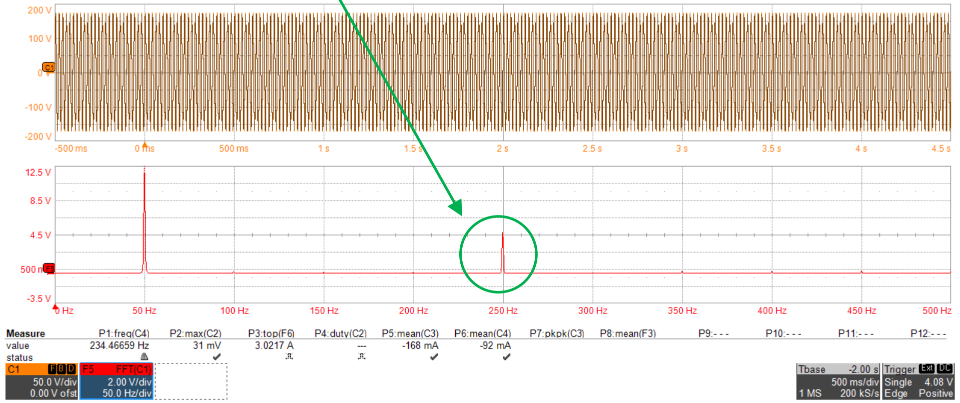
10.5 V

4 V

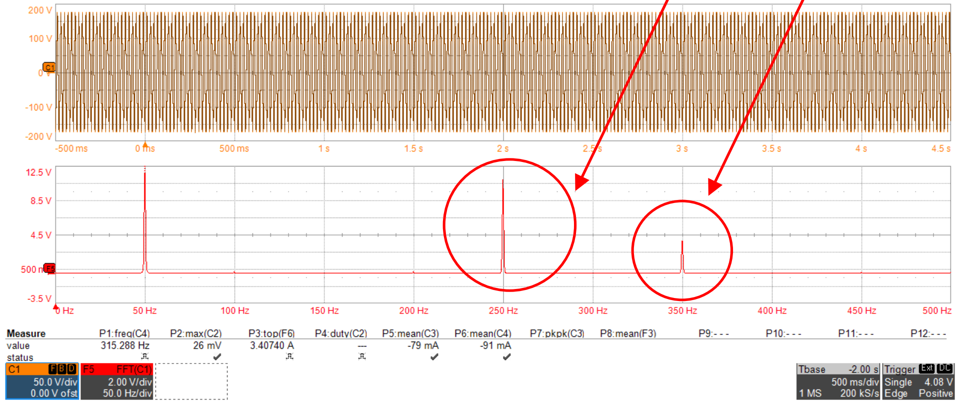
Active filtering behaviour

4.5 V

SPC



Kawasaki



Experimental Results

➢ Short Circuit Fault

Voltage-Output

⇓

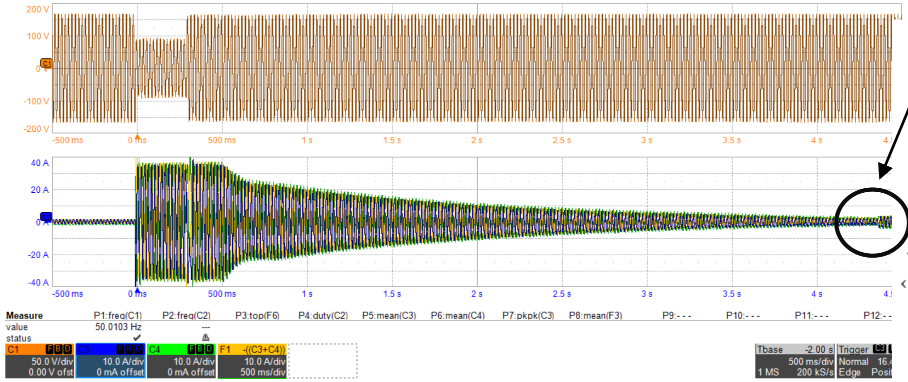
Complex Current Limitation System

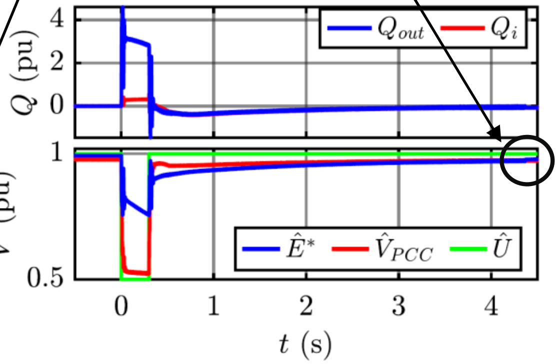
⇓

Transition to Current Control

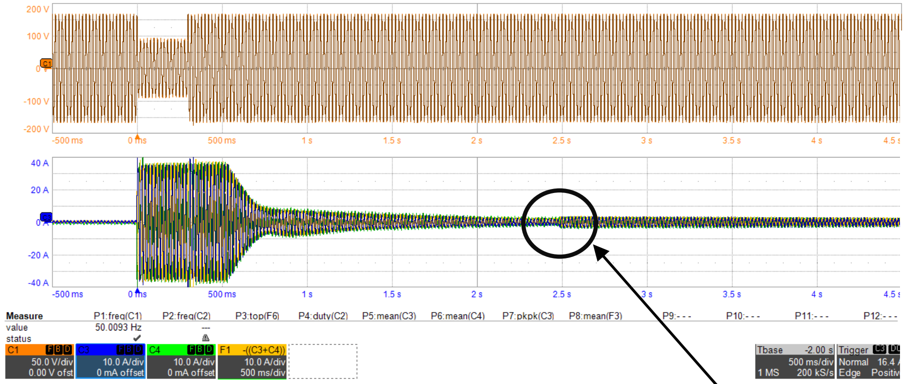
Osaka

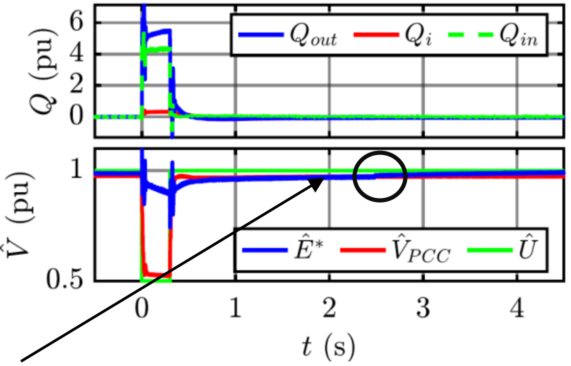
Transition at 4.37 s





Reactive Droop Control Disabled





Reactive Droop Control Enabled

Transition at 2.48 s

Model	Active Power Reference Variation		Reactive Power Reference Variation	Frequency Transient	Harmonic Distortion	Short Circuit Fault	Current Limitation
	Damping	Steady State Error	Steady State Error	Damping-Droop Decoupling	Filtering Capability	Grid Supporting	Simplicity
Synchronverter	✓	✓	✓	✗	✓	✓	✓
Osaka	✓	✓	✓	✓	✓	✓	✗
VISMA	✗	✓	✓	-	✗	✓	✓
VISMA1	✓	✓	✓	✗	✓	✓	✓
VISMA2	✓	✓	✓	✗	✓	✓	✗
SPC SG	✓	✓	✓	✗	✓	✓	✓
SPC PI/LL	✓	✓	✓	✓	✓	✓	✓
VSYNC	✗	✓	✓	-	✗	✓	✓
Kawasaki	✗	✓	✗	✓	✗	✓	✓
CVSM	✓	✓	✗	✓	✗	✓	✓

Conclusions

➢ **My contributions** have been:

- **Bibliographical research** and study of VSG solutions available in literature
- Implementation and tuning of each VSG control algorithm by means of **PLECS simulations**
- **Realisation of C-codes** for the discrete-time version of each solution
- Adaptation of C-codes for **dSPACE environment** and the real setup
- **Experimental testing** of every VSG model by means of the setup

Thank you
for your attention

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