DER inverter development and testing using HIL simulation

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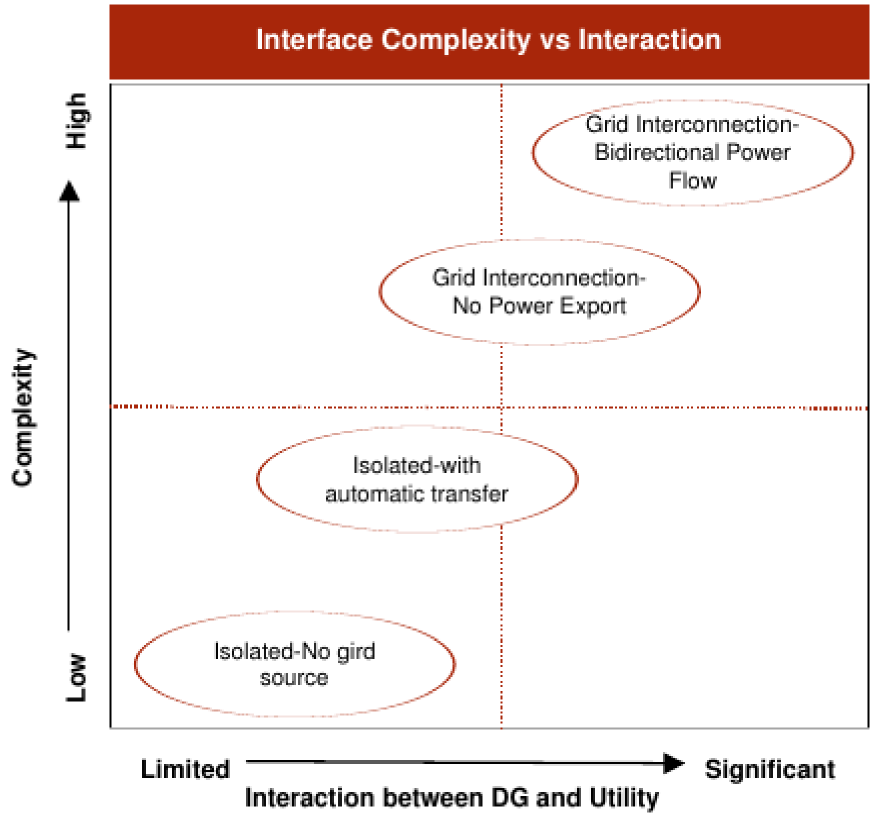
Power interfaces for DG and storage

Power interfaces are the point of physical interaction between DG and the electrical infrastructure, usually the local electric grid.

- The power interface is designed to interact with and serve between the DER and the power system.
- The DG unit studied in this presentation is a **battery systems**.

Distribution networks are becoming increasingly ‘**smarter**’, as well as more **complex**:

- Advanced control strategies to manage such networks are becoming necessary.
- These strategies need to be thoroughly tested and validated, before they can be implemented in a real network.



*Electrical Interface Complexity with Respect to Interface Configuration *.*

Arthur D. Little, “Electrical Interface Complexity with Respect to Interface Configuration”, White Paper, 1999.

Development Overview of Battery Inverter and test procedure

Design

- **Design Requirements**
  - *Interfacing Lead-acid battery bank with AC bus*
  - *Grid connected Operation*
  - *Islanded Operation*
  - *Bidirectional Power flow*
  - *Grid Support Functions*
  - *Battery Management System (BMS)*
  - *Integrated protection functionalities*
  - *Communication interface*

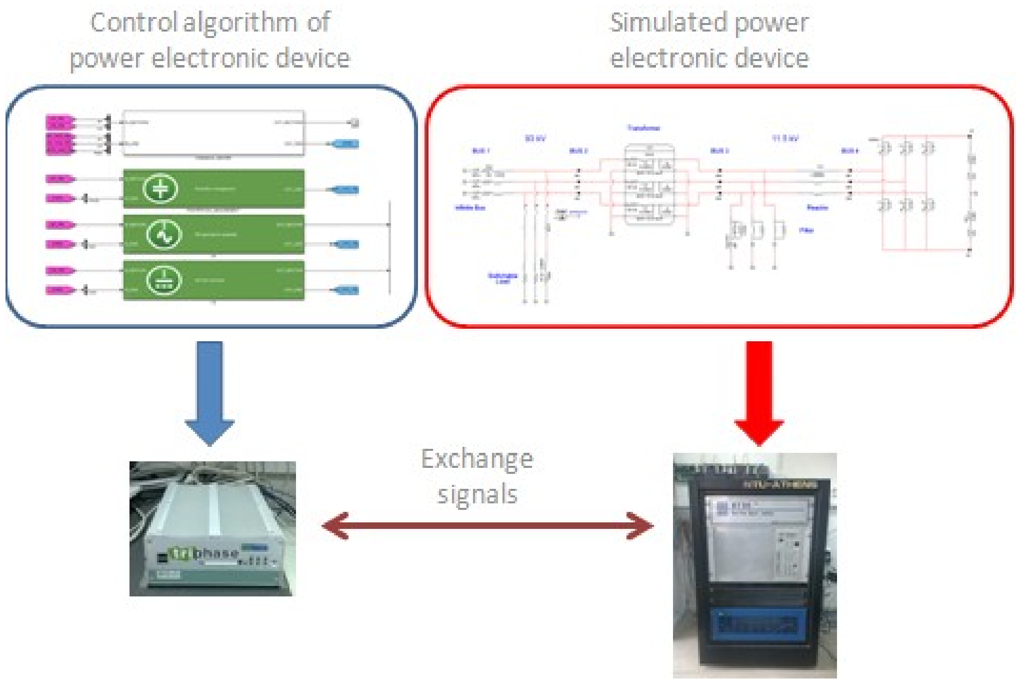
Testing

- **Simulation Validation**
  - *Islanded mode*
    - PI SRRF Voltage Contro
    - PR Voltage Control
    - H-Infinity Control
  - *Grid-connected mode*
    - PI SF Voltage Control
    - Virtual Resistance
    - 2-DoF
- **CHIL Tests**
  - *Island operation*
  - *Grid connected operation*
  - *Grid support functionalities*

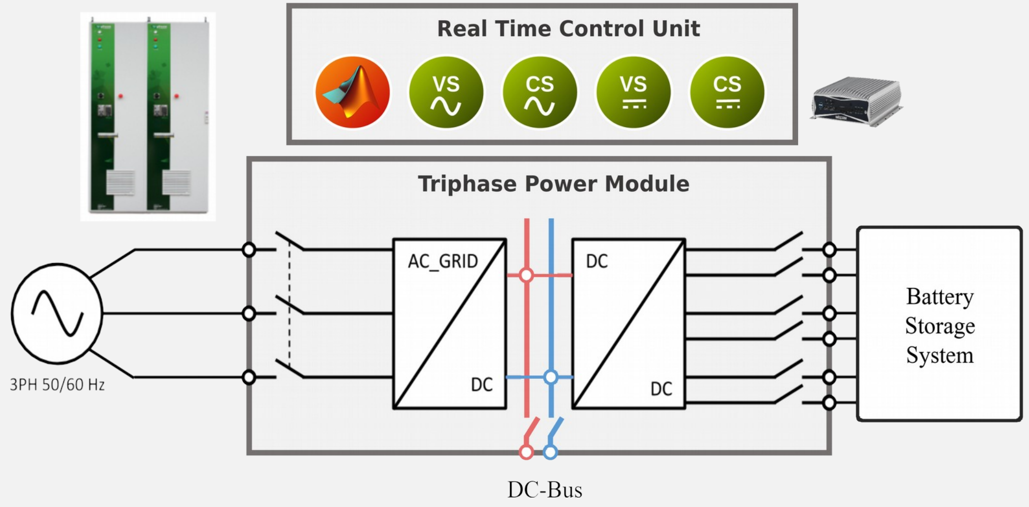
- **Hardware tests**
  - *Island operation*
    - PI SRRF Voltage Control
    - PR Voltage Control
    - H-Infinity Control
  - *Grid connected operation*
    - PI SF Voltage Control
    - Virtual Resistance
    - 2-DoF
- **Power-Hardware-in-the Loop Tests**
  - *Grid support functionalities*
  - *Integrated protection*
  - *Communication interface*

Overview of the CHIL & Hardware test setup

CHIL test set up in ICCS laboratory



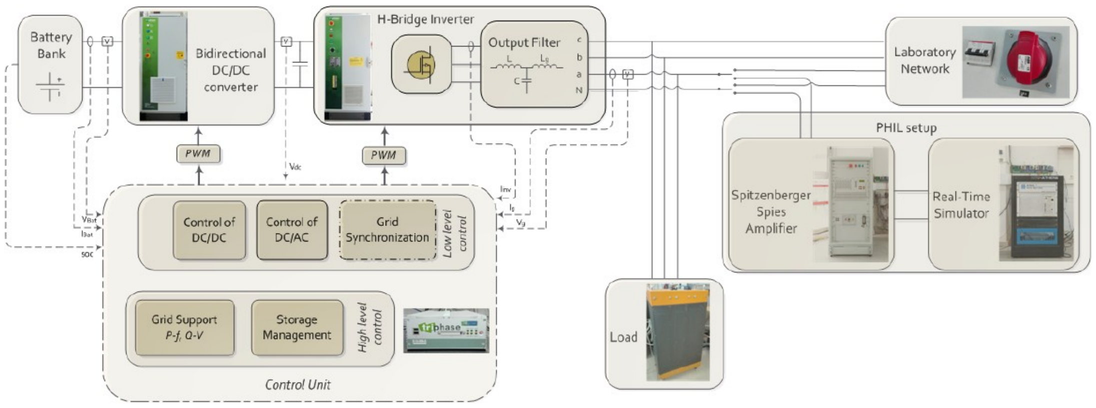
Hardware test set up in ICCS laboratory

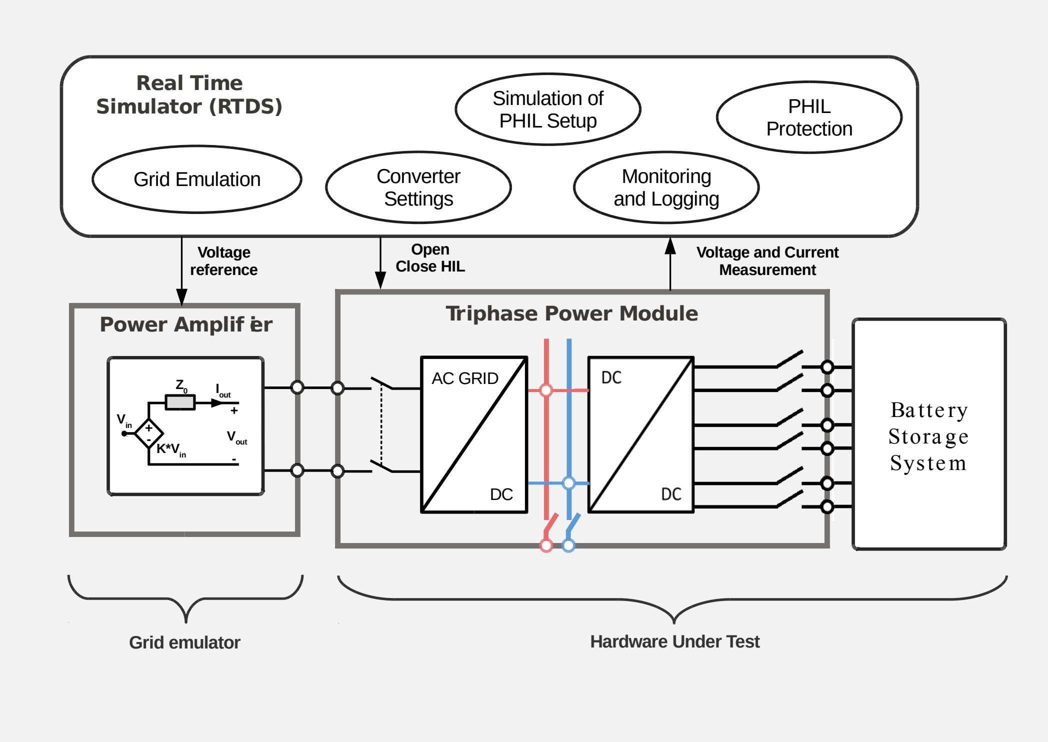


Overview of the PHIL setup

- The operation of the developed battery inverter have tested in the ICCS laboratory.

PHIL test set up in ICCS laboratory



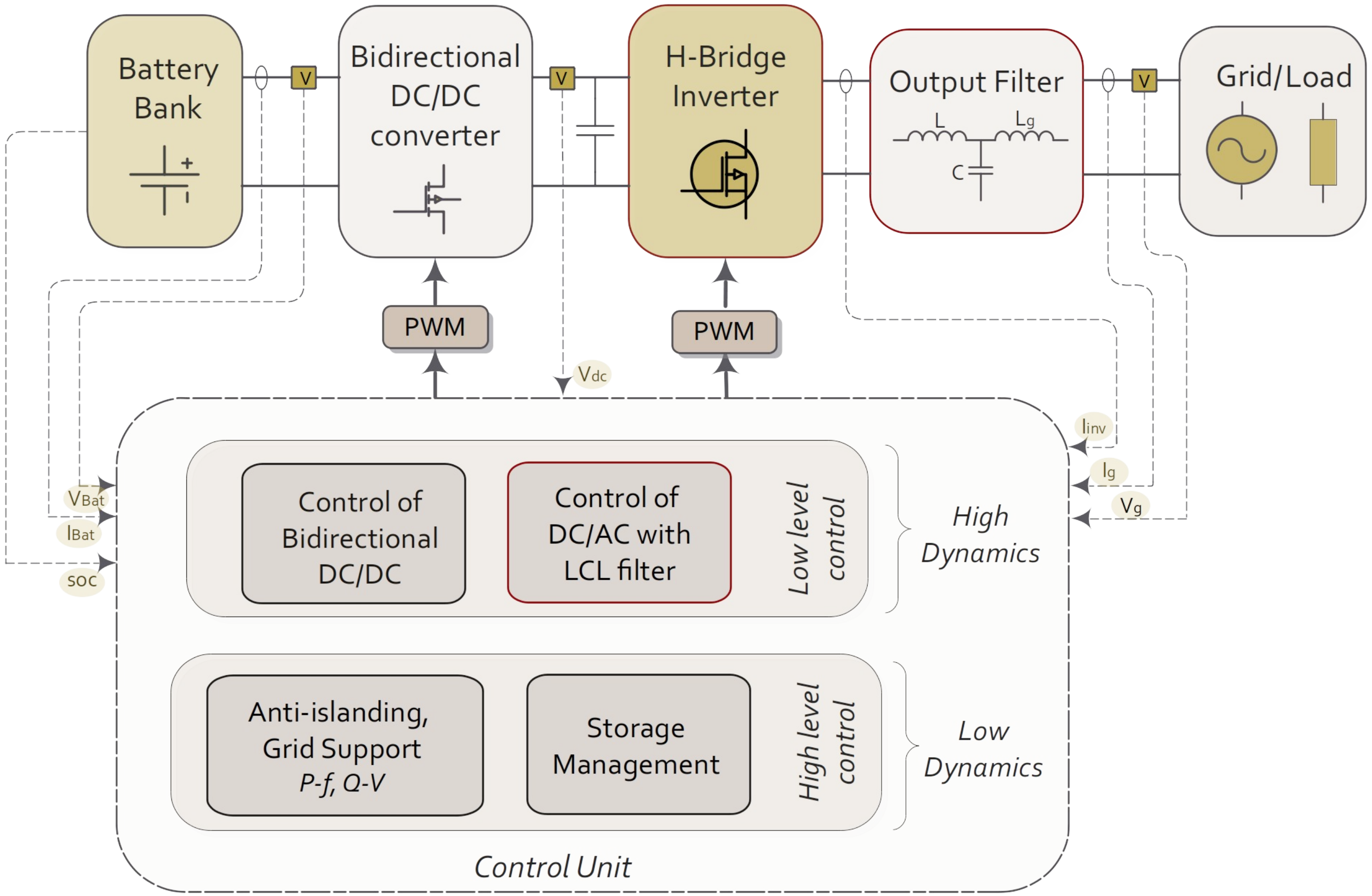


Battery Inverter - Storage Power Interface

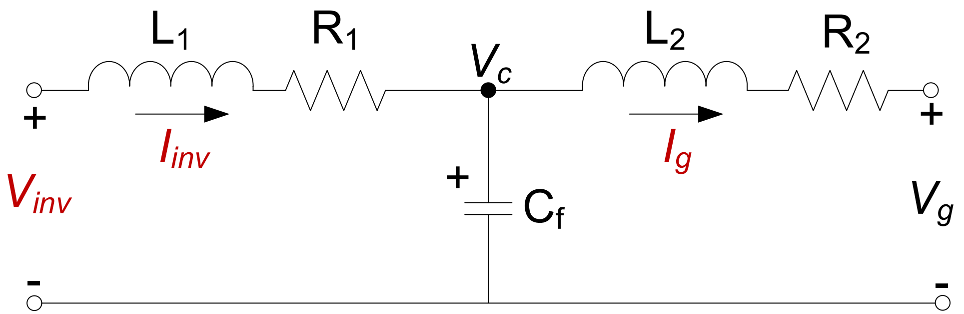
- Lead-acid battery bank
- DC-DC Bidirectional Converter
- DC-AC H-Bridge Inverter
- Low pass filter
- Control Unit (DSP, RT-PC, FPGA)

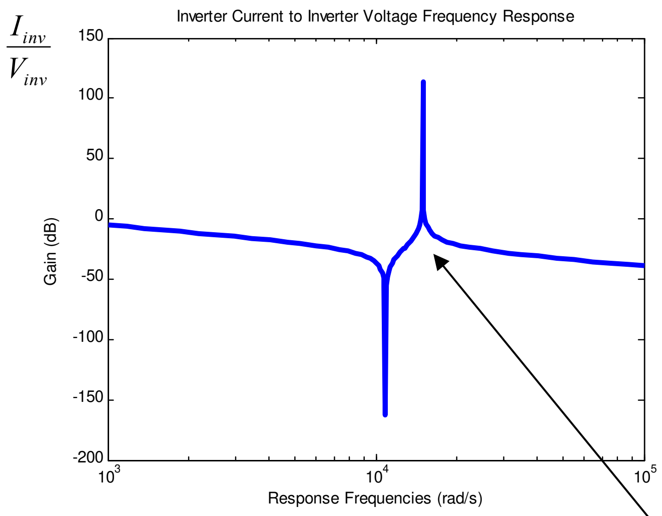
… Some Control Design Considerations…

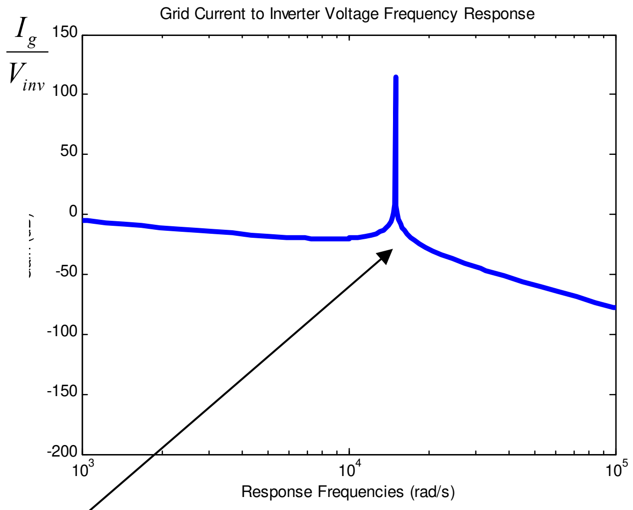
- Stability under all operational conditions (Resonance issues, Non-linearity issues, Time delays etc.).
- Low current harmonic distortion
- Good dynamic performance



Battery Inverter – LCL filter design considerations (1/2)







Resonance Peaks
(Zero Impedance)

For high power, low switching frequency applications **LCL filter** can provide *switching ripple reduction* with:

→ Lower *cost* & *weight*

→ Switching *ripples* reduction

....compared to **L filter**

Requires ***Damping***

...for power quality and stability improvement

BUT: *Current control stability* issues due to **resonance.**

Battery Inverter – LCL filter design considerations (2/2)

***Passive Damping** Techniques*:

Actual passive components placed on filter.

→ performance & efficiency degradation.

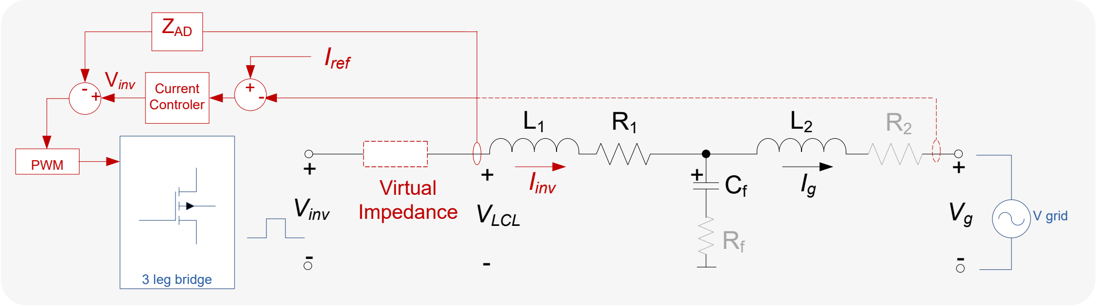
***Active Damping** Techniques:*

Modification of the current control algorithm.

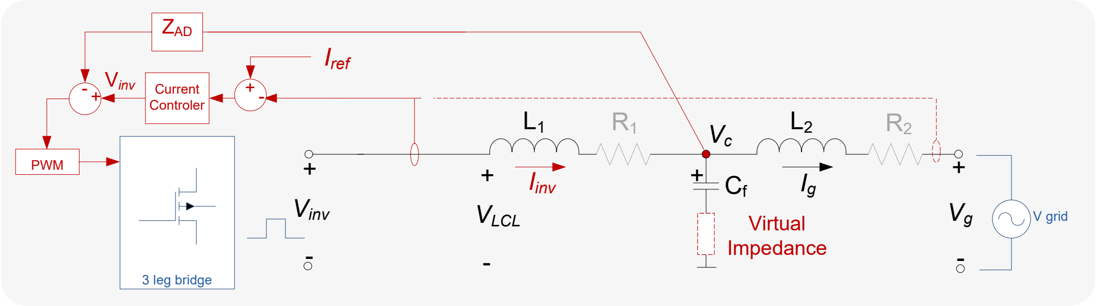
- Synchronous reference frame PI-based
- Cascaded double-loop
- Grid-side current only using HP feedback
- Filter-based (Notch Filters)
- Optimal control algorithms
- Virtual resistance

Implemented

Inductor Side Virtual Resistance

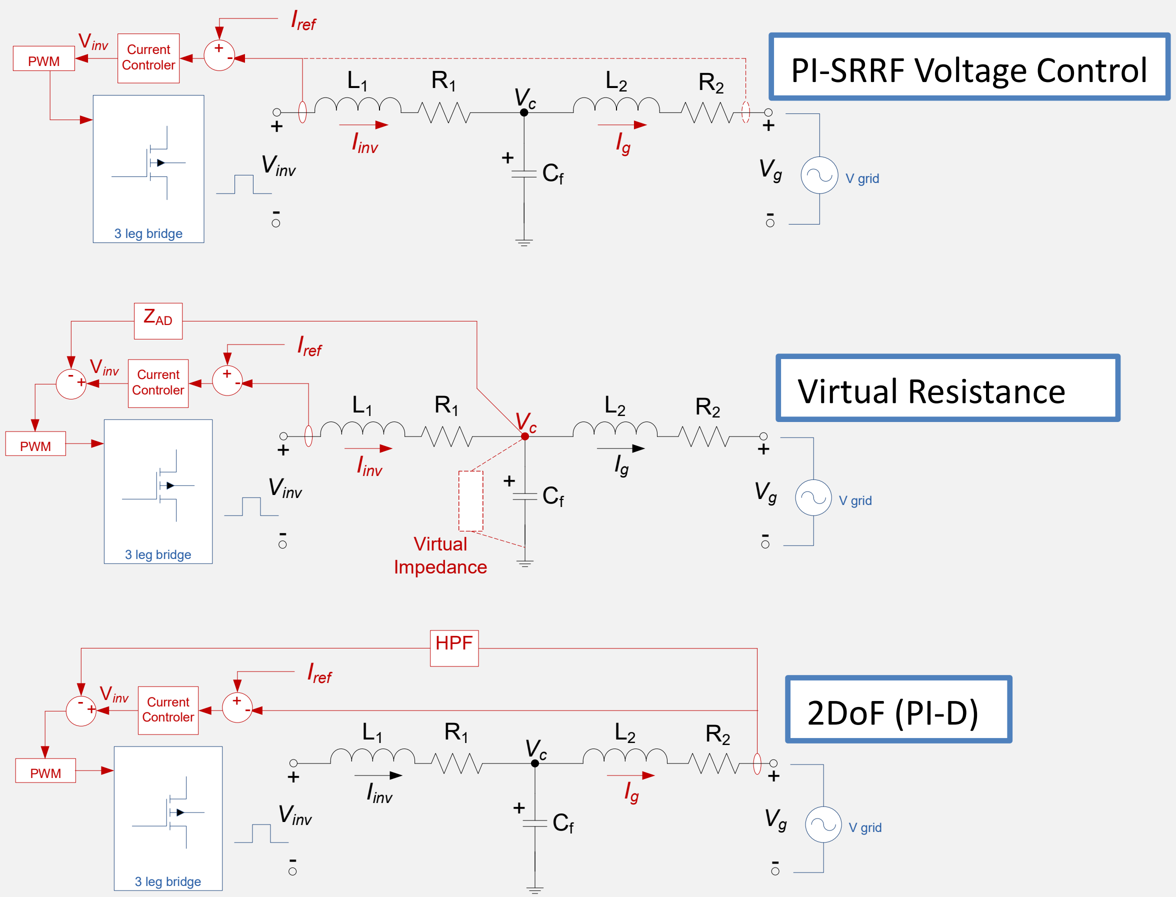


Filter Capacitance Virtual Resistance



Design of the power interfaces: Battery inverter (1/2)

- ***Grid connected operation***



***PI-SRRF** technique (without active damping)*:

- **Stable** with the inverter current feedback.
- **Unstable** with the grid current feedback.
- Stabile for low bandwidth controller.

***Virtual Resistance** technique*:

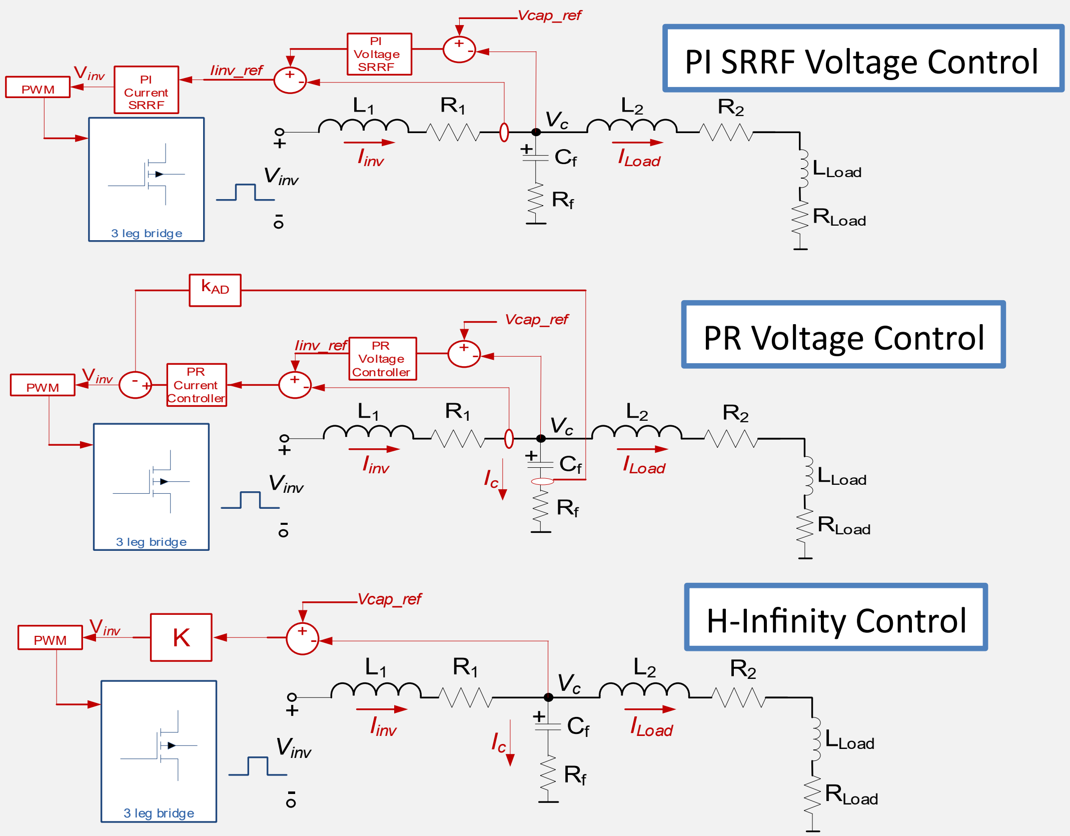
- **Capacitance** Virtual Resistance has **better damping performance** in regards to others.
- Grid current feedback stability is achieved
- **Extra sensor** is required (Voltage or current), or estimating the state variable (virtual flux)

2 Degree of freedom *technique*:

- **Excellent** damping performance (98%)
- Difficult tuning process
- Better THD performance

Design of the power interfaces: Battery inverter (2/2)

- ***Islanded operation***



$\min_K \|N(K)\|_\infty \qquad \|N(K)\|_\infty < 1$

$$\|N\|_\infty = max_\omega \sqrt{|T(j\omega)W_i(j\omega)|^2 + |S(j\omega)W_p(j\omega)|^2 + |K(j\omega)S(j\omega)W_u(j\omega)|^2}$$

PI-SRRF *technique (without active damping)*:

- Simple design
- Relatively good performance

Proportional - Resonant *control strategy*:

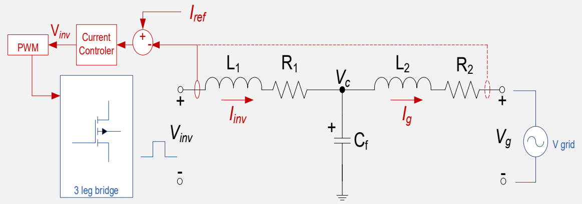
- Based on **αβ-frame** (stationary)
- Active damping with **capacitor current** feedback
- More robust behavior

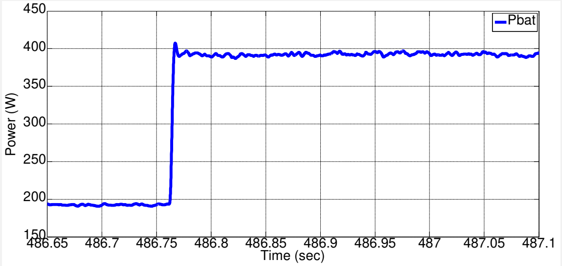
H-infinity Loop shaping *approach:*

- **Optimizes** the response near the system bandwidth.
- Based on **αβ stationary frame**
- **Multiplicative uncertainty**, taking in to concentration all the possible models
- Robust performance

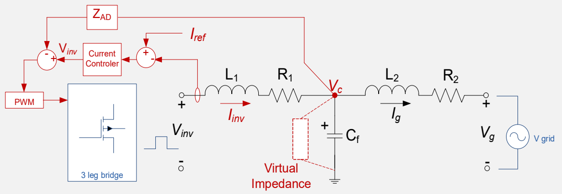
Hardware test results of the Battery inverter

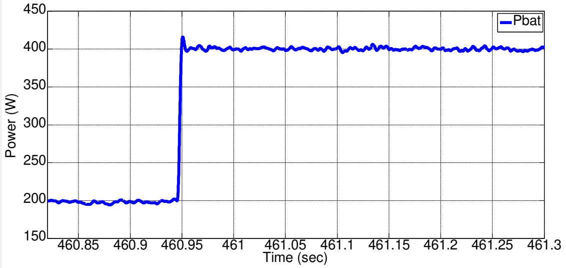
- **PI SRRF Voltage Control**



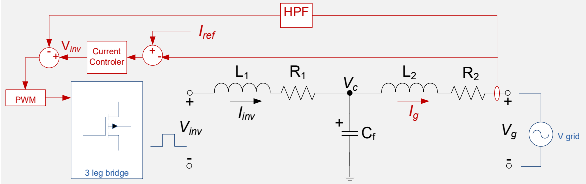


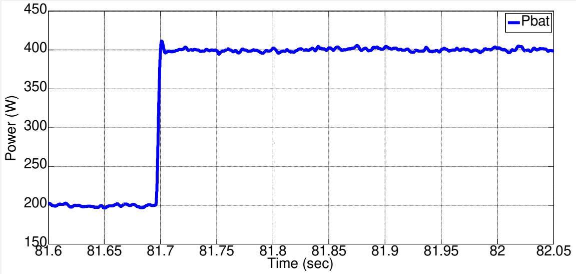
- **Virtual Resistance**



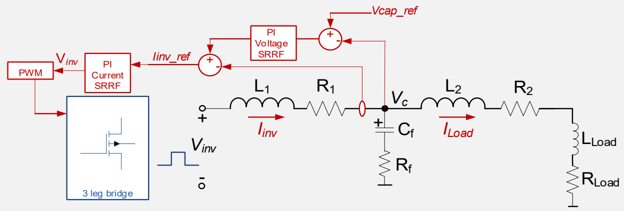


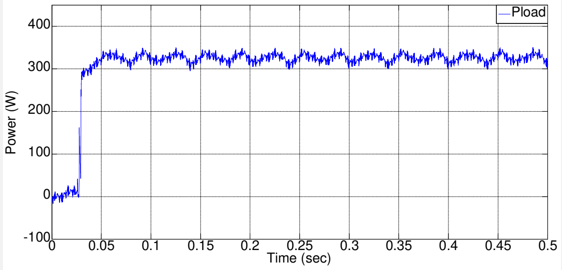
- **2DoF**



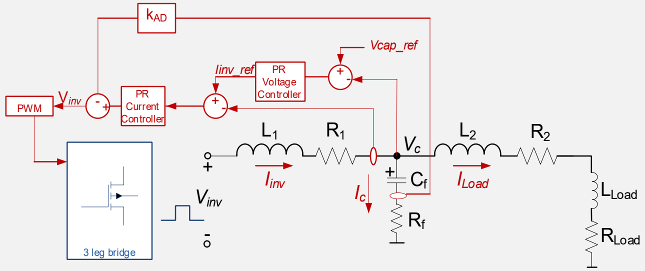


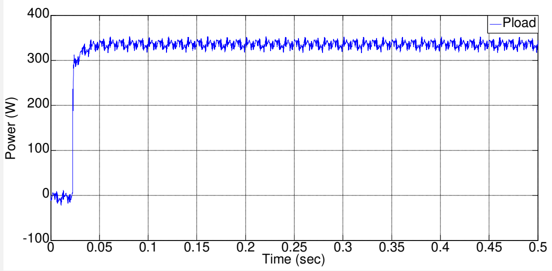
- **PI SRRF Voltage Control**



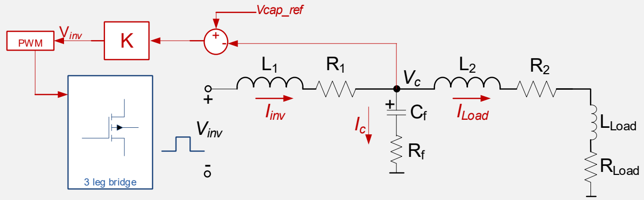


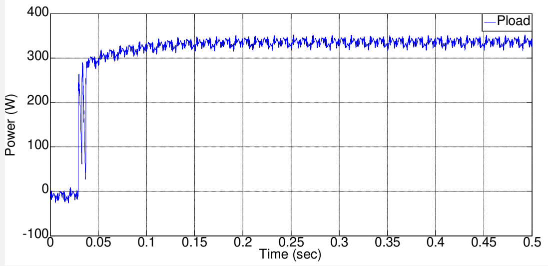
- **PR Voltage Control**





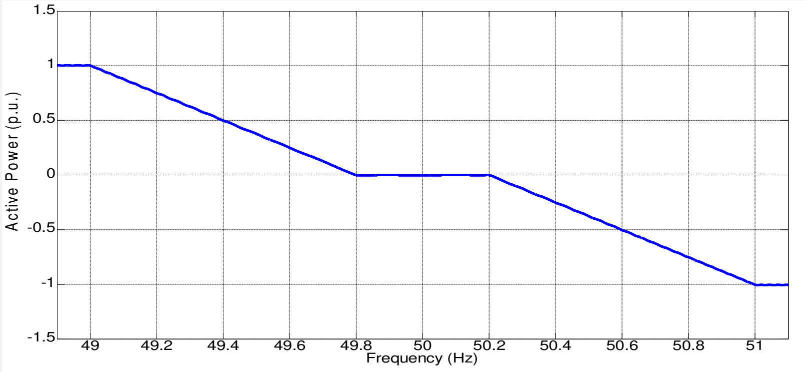
- **H-Infinity Control**



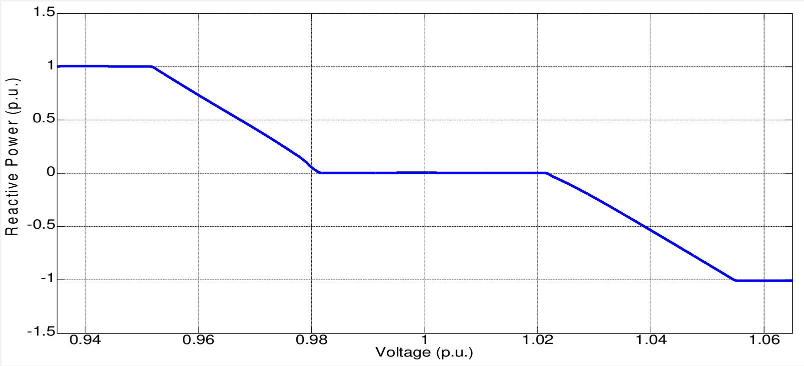


Tests for Droop Curves Verification

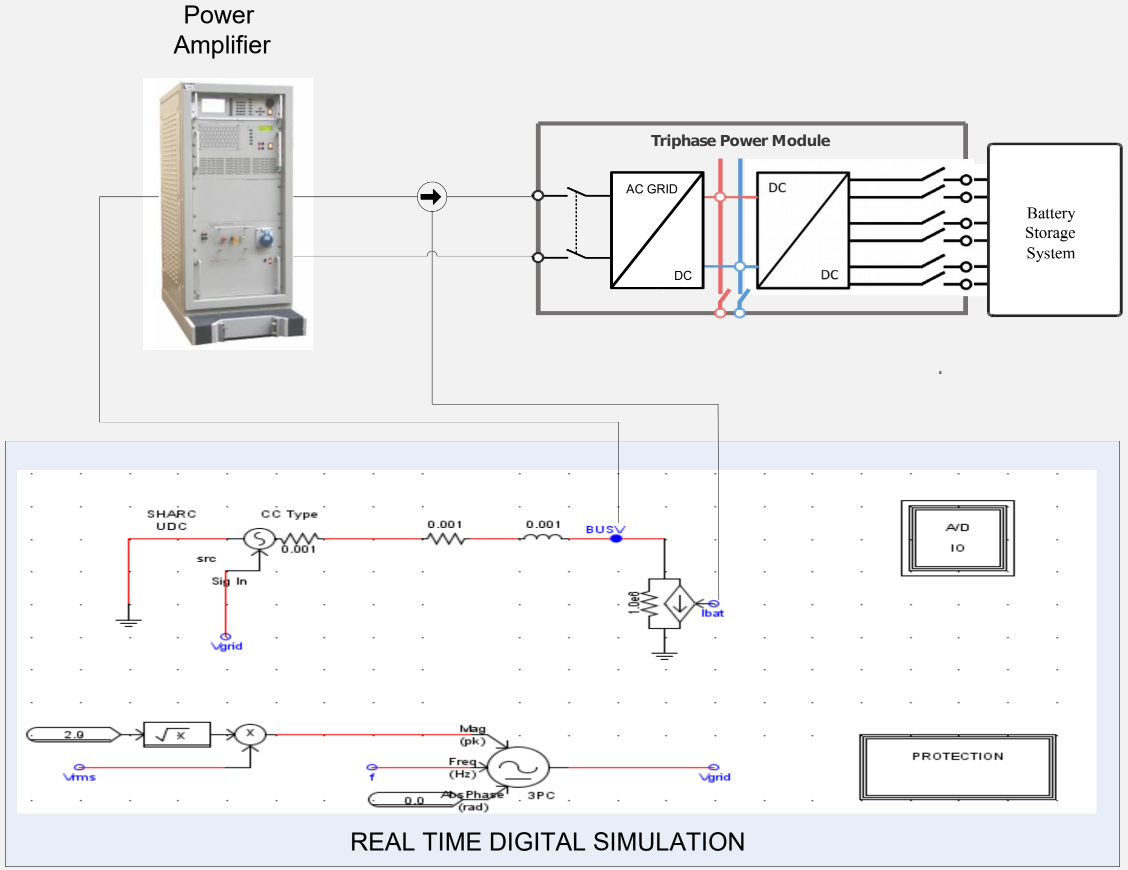
Measured P-f Curve



Measured Q-V Curve



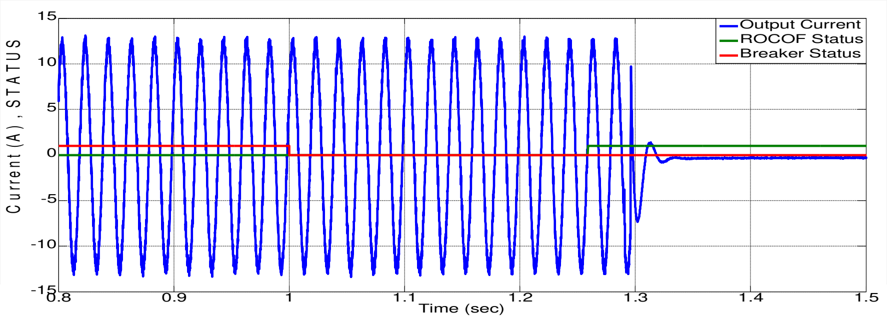
Setup for droop curve evaluation



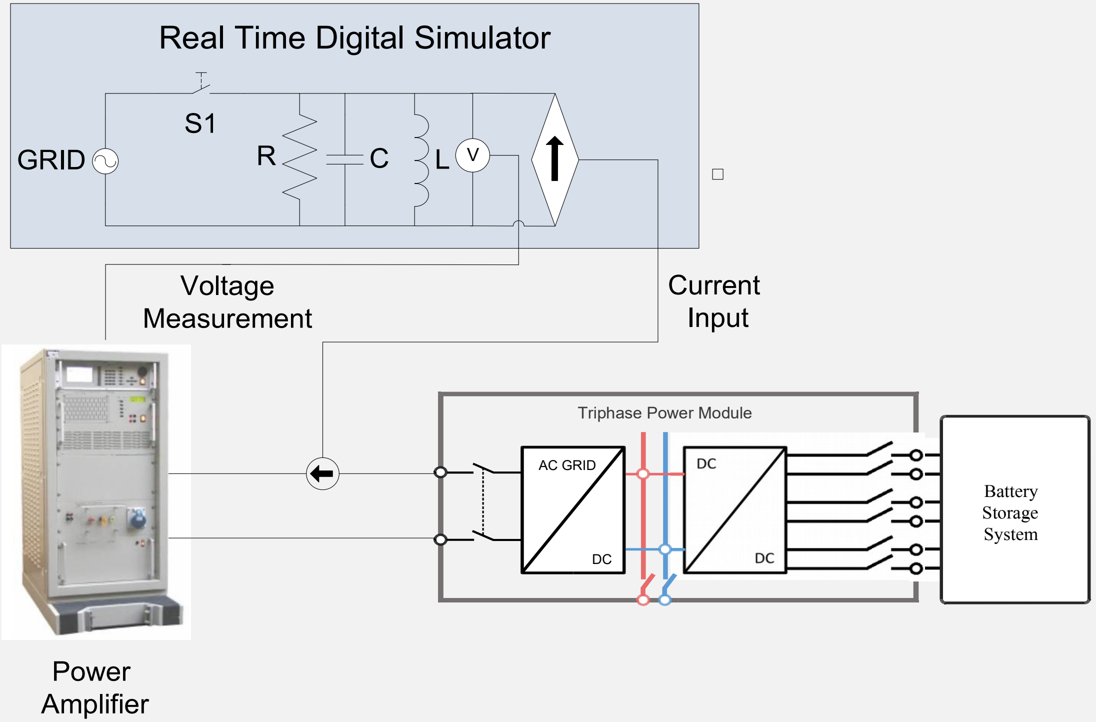
PHIL tests for Islanding Detection Methods Evaluation

Islanding detection

DP ≈ 0	UOV/UOF		ROCOF	
DQ/P_{DER} (%)	Island Detection	Detection Time (seconds)	Island Detection	Detection Time (seconds)
0	NO	-	YES	0.259
1	NO	-	YES	0.117
-1	NO	-	YES	0.108
2	YES	0.624	YES	0.056
-2	YES	0.986	YES	0.058
3	YES	0.402	YES	0.051
-3	YES	0.624	YES	0.047
4	YES	0.341	YES	0.044
-4	YES	0.431	YES	0.035
5	YES	0.280	YES	0.037
-5	YES	0.368	YES	0.043



PHIL setup for Islanding detection tests



Conclusions

- *A **design and testing methodology** that aims to test power electrinics components and control algorithms, in all their development stages, **using advanced laboratory setups** has been proposed*
- *The design process combines the **long-established** methods with **HIL approaches** in order also to combine the **advantages** of each method*
- *Power electronics **design is complex procedure** that need great attention by the designer on each development stage*
- *HIL simulation is an **efficient tool** for DER inverter testing*
- *The use of HIL simulation for **Loss of Main** detection can be considered for future standardized testing*

Thank You!

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