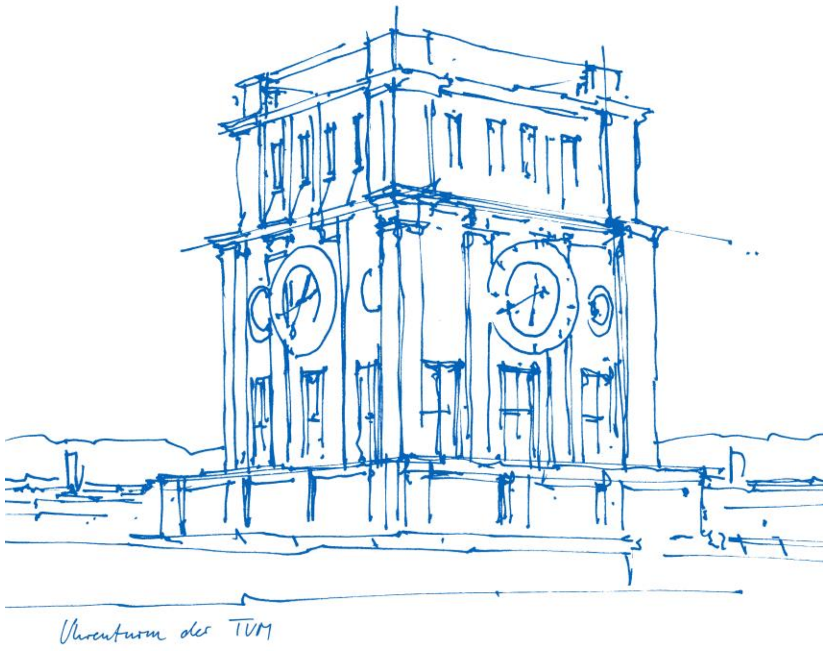
Fast harmonic analysis for PHIL experiments with decentralized real-time controllers

Erhan Sezgin[†], Anurag Mohapatra*,
Thomas Hamacher*, Özgül Salor[‡], Vedran S. Peric*

*Center for Combined Smart Energy Systems (CoSES),
Technical University of Munich

[†]Kafkas University, Turkey

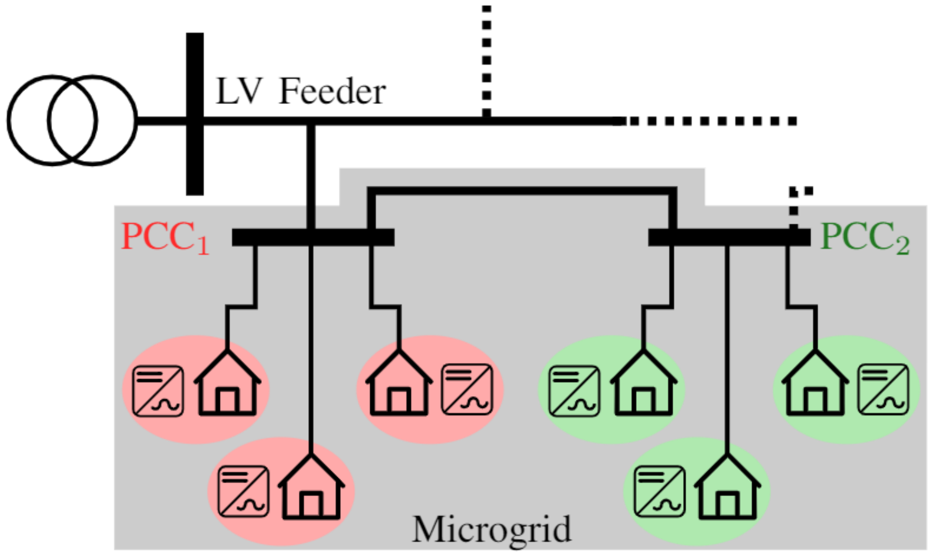
[‡]Gazi University, Turkey



Motivation

In LV distribution grids

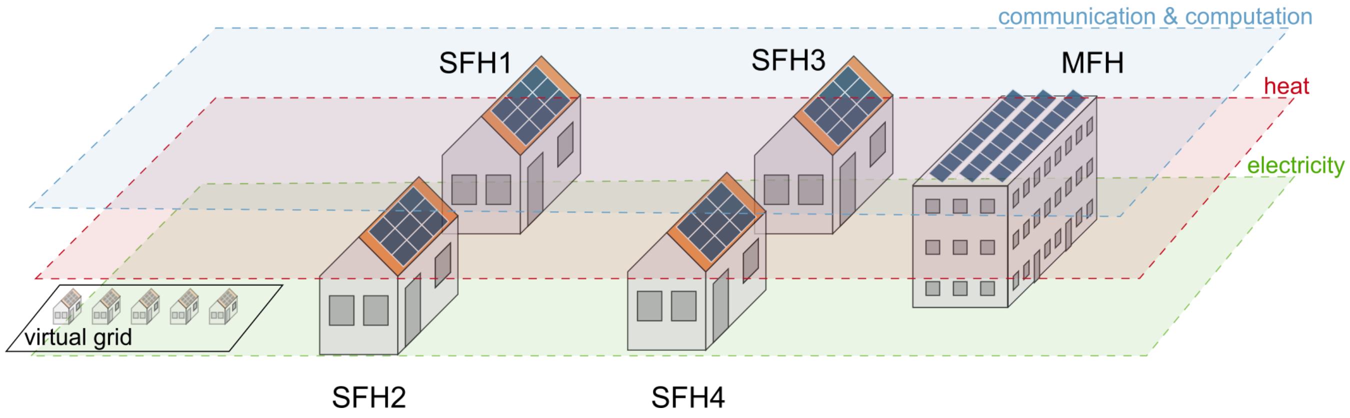
- Increased individual control of prosumers in distribution grid.
- Relevant PCC voltage can be too far for direct measurements.
- Instrumentation changes are necessary.



Motivation

In CoSES microgrid lab

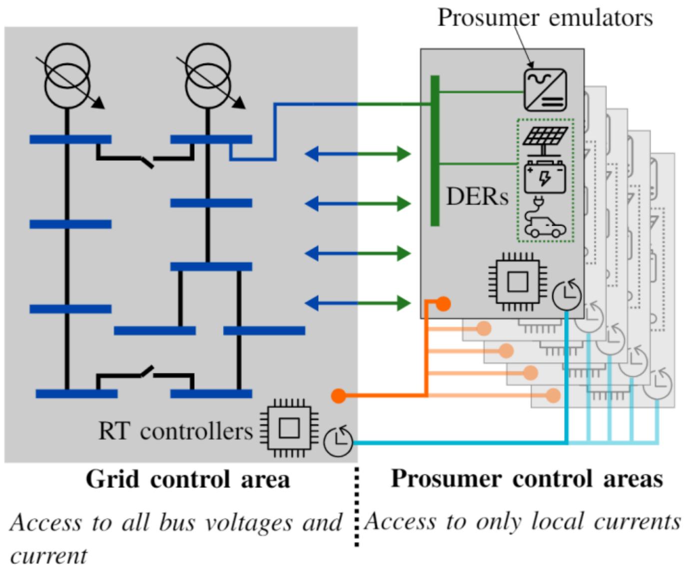
- Low-inertia, sector-coupled LV grid, ~1.5kms cable
- PHIL emulators, DERs, distributed controllers.



- Bus voltage measurement available in only LV substation room.

- PHIL prosumer controllers are far away for direct voltage feedback.

- Asynchronous data link and time synchronisation between RT controllers.



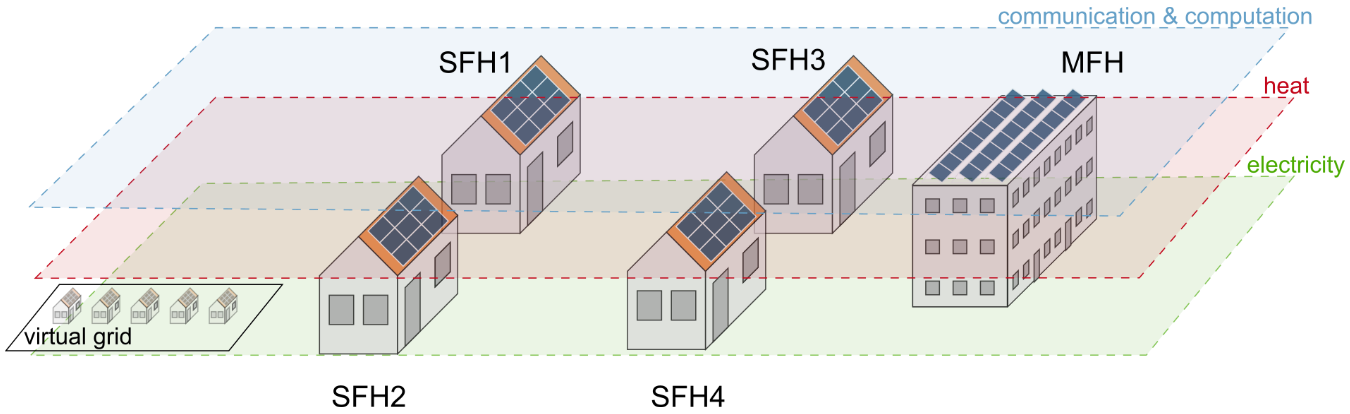
Motivation

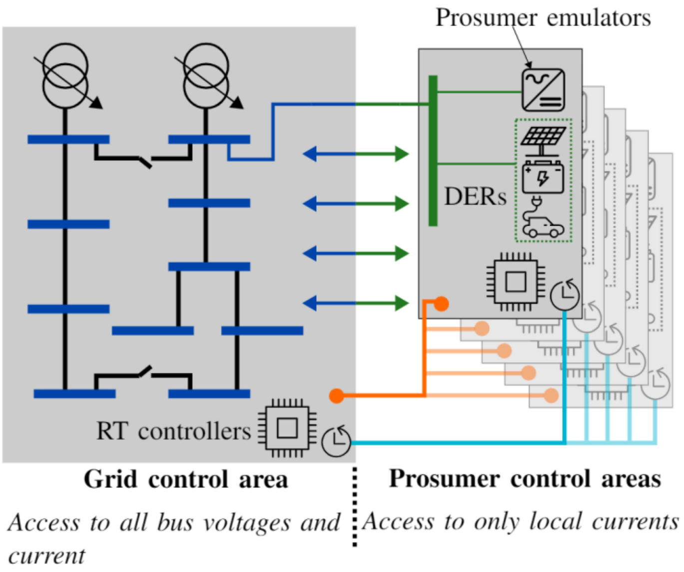
Requirements

- Continuous voltage measurements as feedback for prosumer power injection.
- Accurate fundamental harmonic analysis.
- Transfer measurement over asynchronous link.
- Low computation burden in RT.

Use cases

- Prosumer control in CoSES with distributed voltage and current measurements.
- Prosumer controller in real world microgrids without direct access to PCC voltage





Literature review

State-of-the-art for harmonic analysis for RT power measurements

	Computation burden in RT	Need for Buffering	Time Localisation	**Step Changes**	**Unknown Harmonics**	Time domain output	**Decentralized Implementation**
Discrete Fourier Transform	-	-	-	+	+	-	-
Fast Fourier Transform [1]	+	-	-	+	+	-	-
Discrete Wavelet Transform [2]	-	+	+	+	+	-	-
Second Order generalized integrator [3]	+	+	+	-	-	+	+
Kalman Filters [4]	-	+	+	-	-	-	-
Frequency Shifting* [5] **+** **CIC Filtering** [6]	+	+	+	+	+	+	+

*This approach is also known as Coulon Oscillator [7], Quadrature Amplitude Modulation [8], Complex Exponential Modulation [9] in literature.

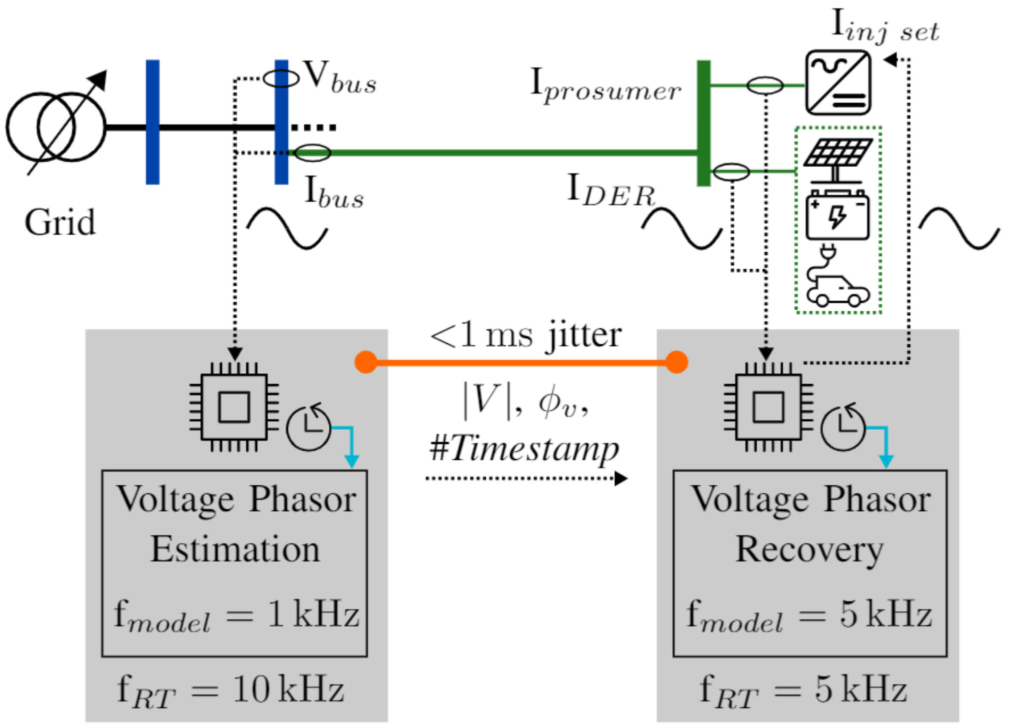
Implementation

Proposed Solution* (in the following order)

1. Estimate voltage magnitude and phase at Grid RT controller.
2. Send information over async. data link.
3. Compensate for the data transfer delay.
4. Compensate for phase shift in model clocks.
5. Reconstruct the voltage waveform in prosumer controller.

Contributions

- Easy to synchronize measurements from independent RT controllers.
- Estimation and recovery models can be run at different RT rates.
- Local timestamp is enough to recover the measurement.
- Phase shift for PLL is directly calculated, no additional computation needed; reduces RT burden.



**The solution is similar to mSDFT [10] with output in time domain.*

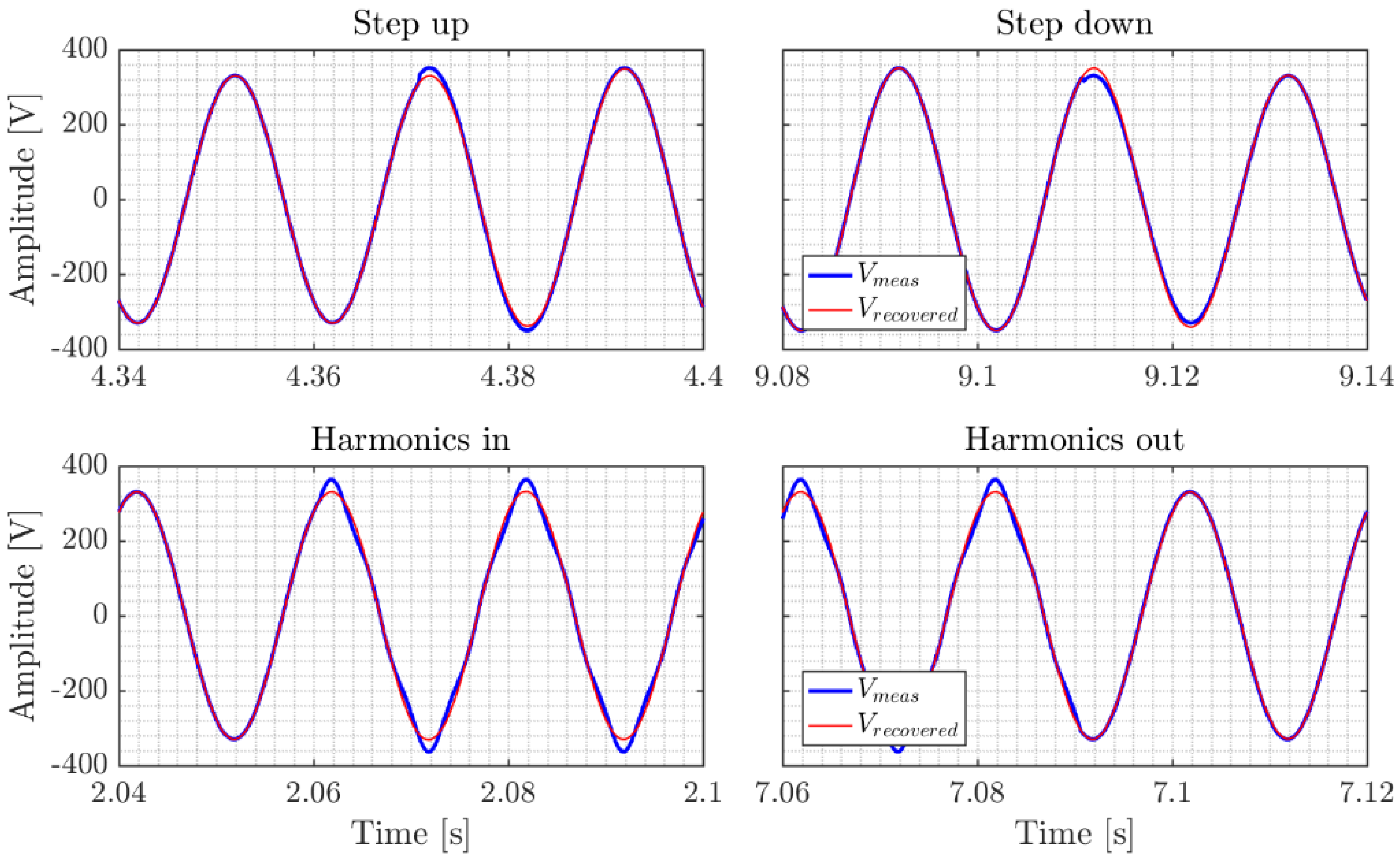
Results - Validation

Step change sequence

- 330 → 350 → 330 (V_{peak})

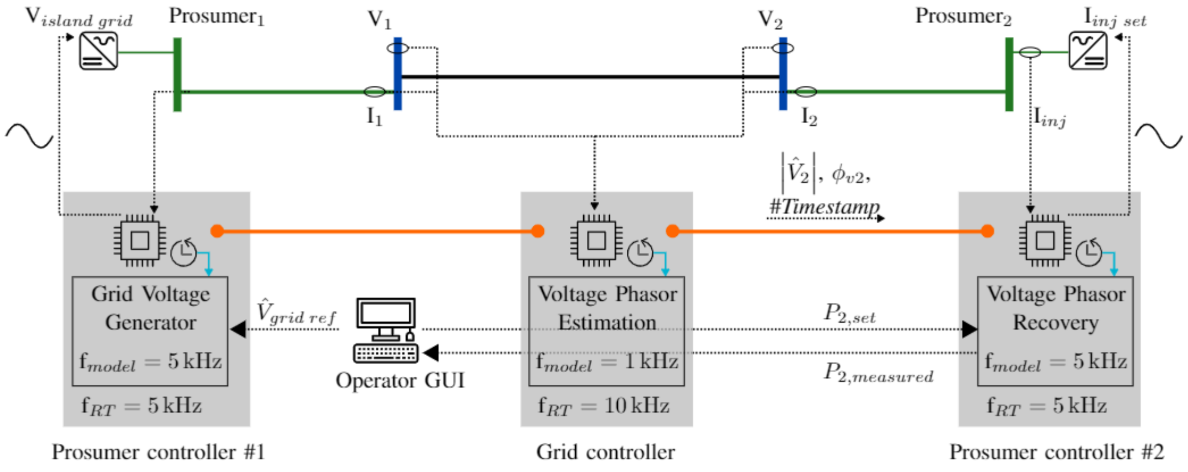
Unknown Harmonics

- 3rd order – 5% Fund. magnitude
- 5th order – 5% Fund. magnitude



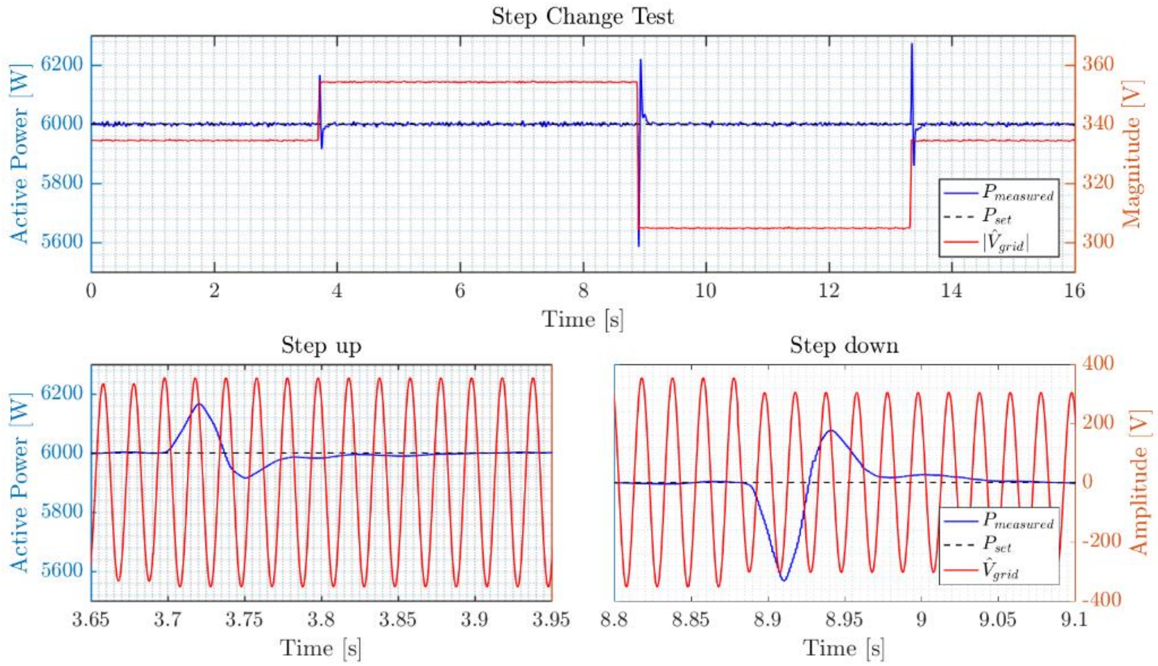
Results - Demonstration

PHIL Experiment #1



*Schematic of the PHIL experiment for **constant power injection** under **step change** or **distortion** of **grid voltage** in **islanding mode**.*

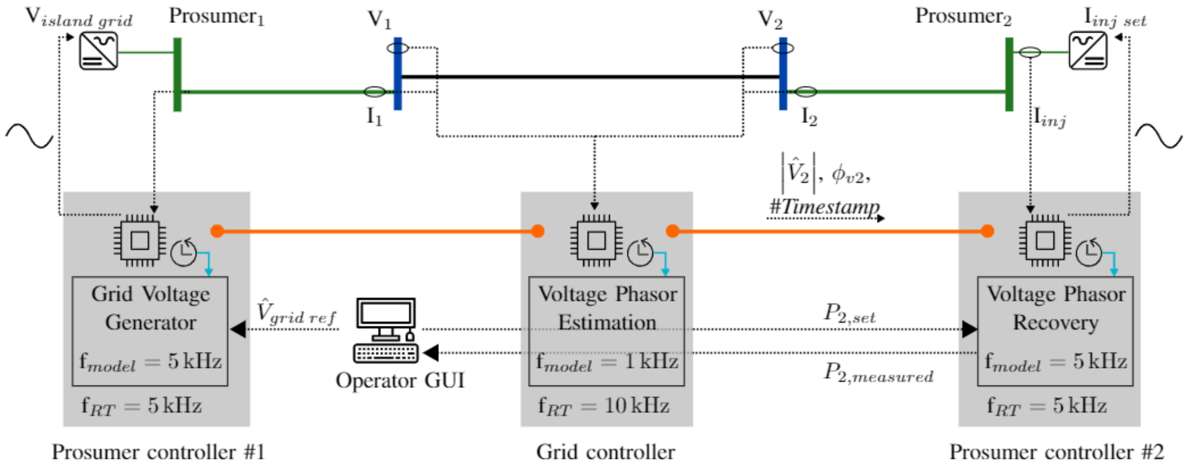
Prosumer#1 acts as the grid forming inverter and Prosumer#2 as grid following inverter with a fixed active power setpoint. Grid controller measures and analyses the voltages



Step change test on voltage with power control loop

Results - Demonstration

PHIL Experiment #1



Schematic of the PHIL experiment for ***constant power injection*** *under* ***step change*** *or* ***distortion*** *of* ***grid voltage*** *in* ***islanding mode****.*

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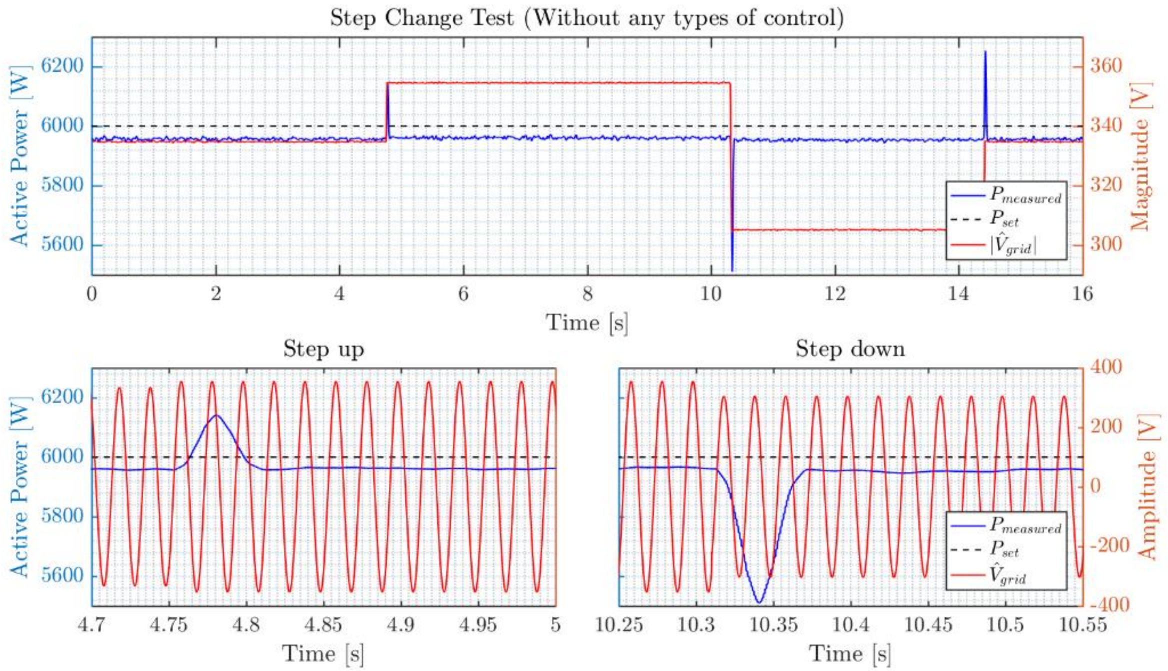
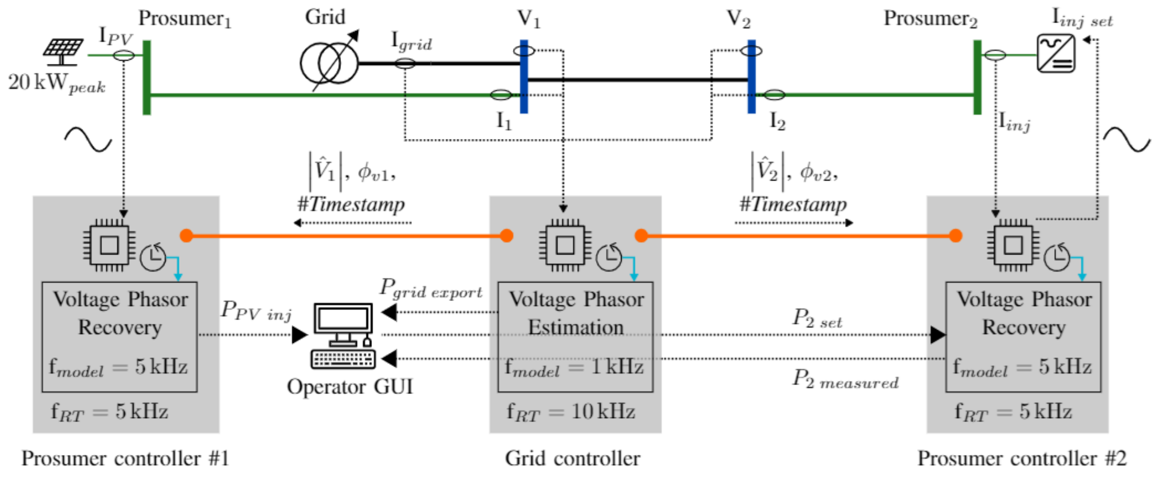


Step change test on voltage without power control loop

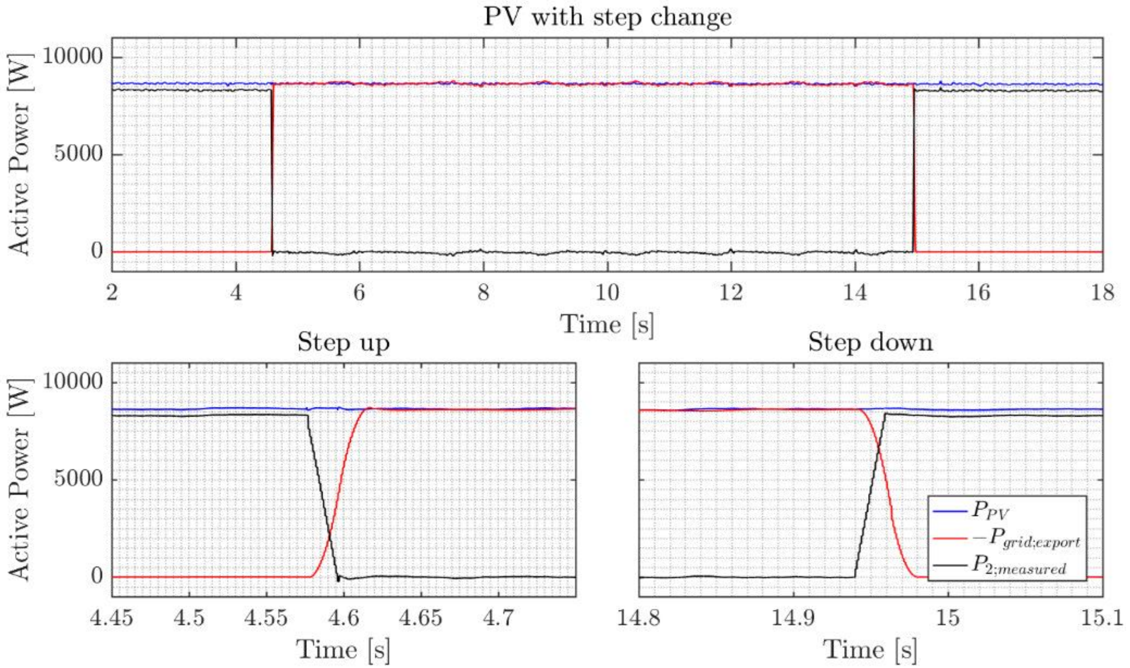
Results - Demonstration

PHIL Experiment #2



*Schematic of the PHIL experiment for **matching the PV production** as a dynamic load to make **net export zero** in **grid connected mode**.*

Prosumer#1 is connected to 20 kW_{peak} PV and Prosumer#2 is programmed as a dynamic load with a power setpoint. Grid controller measures and analyses the voltages.



Grid export with Prosumer#2 matching the PV Power

Conclusion

- Gap identified in PHIL literature for systems with distributed measurement schemes, eg. – prosumer too far from PCC in real world.
- Proposed and validated a frequency shifting and recursive filtering based signal analysis and recovery method for synchronized RT controllers
- Method has good convergence, handles unknown harmonics, variable communication delay.
- Model rates can be modulated to reduce computation burden by increasing convergence time.
- Tool is currently being used for power measurements in CoSES lab.

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Center for Combined Smart Energy Systems

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Contact

Anurag Mohapatra, M.Sc.

anurag.mohapatra@tum.de
Tel. +49 89 289 52767
Fax +49 89 289 52749

Lichtenbergstr. 4a, 85748 Garching b. München
Munich School of Engineering
Technical University of Munich
https://www.mep.tum.de/mep/coses/