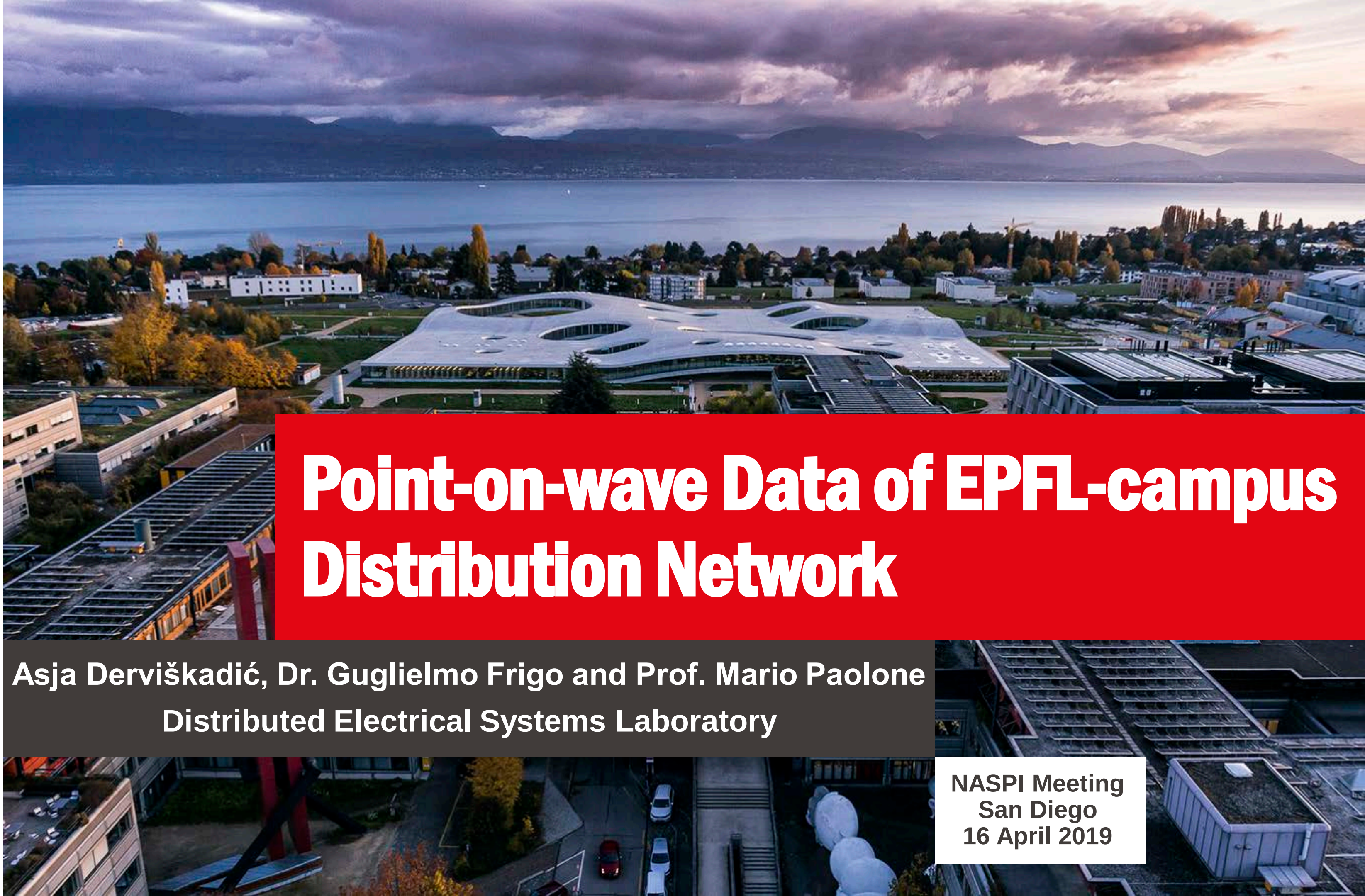
EPFL



Point-on-wave Data of EPFL-campus Distribution Network

Asja Derviškadić, Dr. Guglielmo Frigo and Prof. Mario Paolone
Distributed Electrical Systems Laboratory

NASPI Meeting
San Diego
16 April 2019

École
polytechnique
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EPFL

The Electric Network

- 20 kV
- 40 buses
- 30 MW peak
- 6 MW peak CHP
- 2.5 MW peak PV
- 1 MW peak, 0,5 MWh Li-Titanate Energy Storage System

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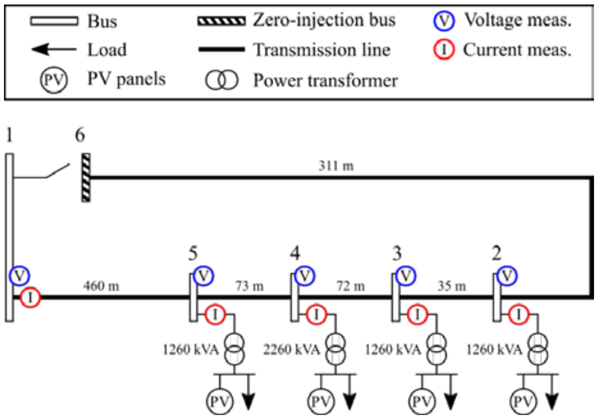
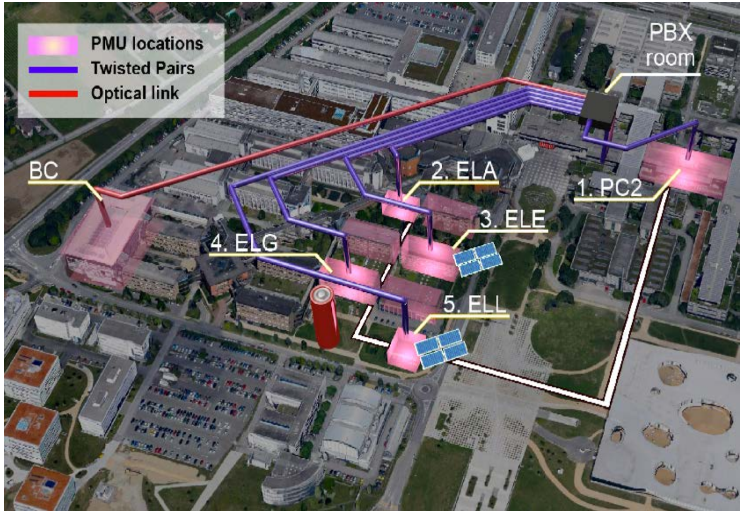
The Sensing Infrastructure

- 5 P-class PMUs
- FPGA-based ➔ National Instruments cRIO
- Synchrophasor Estimation ➔ e-IpDFT
- TVE ~ 0.0X %
- FE < 0.4 mHz
- GPS sync ➔ 100 ns accuracy
- Voltage sensors ➔ Capacitive 0.1-class
- Current sensors ➔ Rogowsky 0.5-class
- Communication ➔ Twisted pairs + fiber
- Data frames ➔ 50 fps – UDP
- 1 PDC





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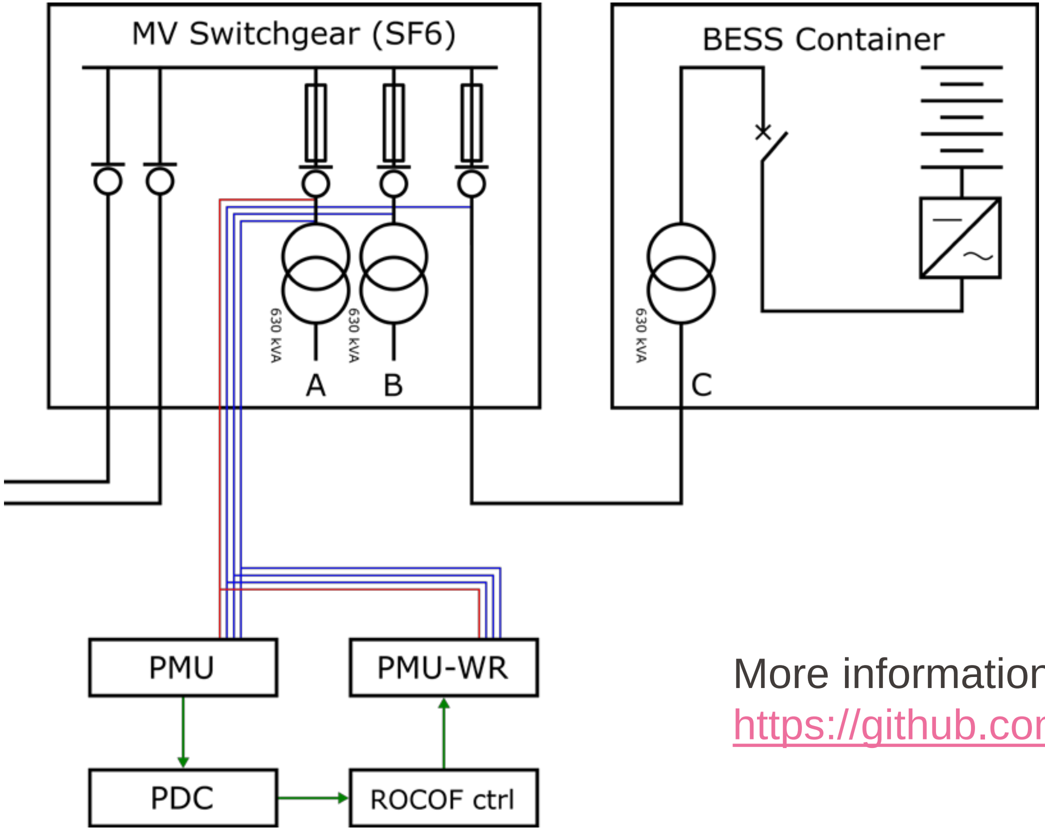
The Battery Energy Storage System (BESS)

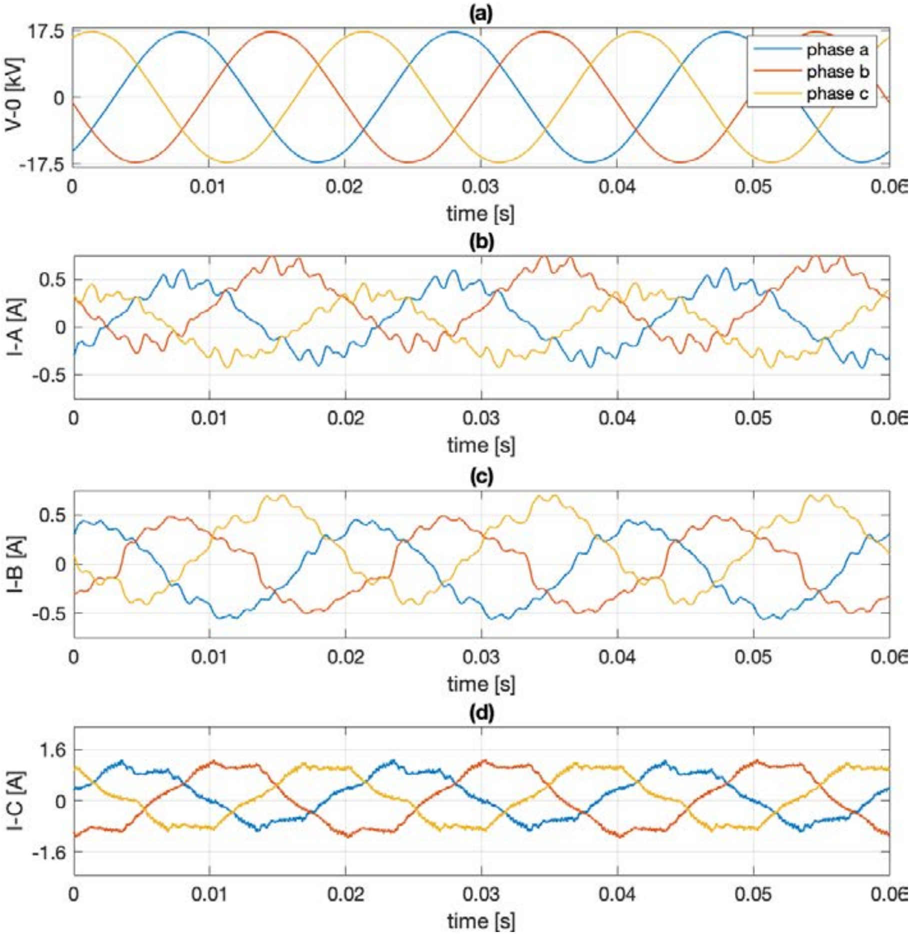
- 560 kWh/720 kVA BESS
- Lithium titanate oxide (LTO) cells
- Series and parallel to form 9 battery racks
- DC bus 590 : 810 V
- Four quadrant DC-AC converter
- 0.3/21 kV, 630 kVA transformer
- Active and reactive power setpoints request to the converter via ModBUS TCP

The Waveform Recorder Functionality



More information available at:
https://github.com/DESL-EPFL/

The Acquired Point-on-Wave Data



The Signal Model

The waveforms can be modelled as the sum of three main contributions:

$$y(t) = A_1(t) \cdot \cos\big(2\pi f_1(t)t + \varphi_1(t)\big) + \eta(t) + \varepsilon(t)$$

- A_1, f_1, φ_1 fundamental component time-varying parameters
- $\eta(t)$ narrow-band disturbances, i.e. (inter-)harmonics
- $\varepsilon(t)$ wide-band disturbances, i.e. measurement noise

The proposed PMU is able to identify also the disturbance contributions:

- (inter-)harmonic synchrophasors
- noise statistical model (e.g. PDF)

OBJECTIVE: accurate estimation of both fundamental and (inter-)harmonic synchrophasors in dynamic conditions over window lengths in the order of 10^2 ms.

Identification method

In order to track the signal time-variations, the proposed approach considers:

- a window length of 200 ms, i.e. 10 cycles at 50 Hz (as suggested by IEC Std 61000)
- a reporting rate of 100 fps, i.e. update every 10 ms (max rate of IEEE Std c37.118.1)

- Given a signal window, the identification method consists of the following steps:

1. DC identification and removal — $x = y - \mathrm{E}(y) = x - \mathrm{mean}(y)$
2. fundamental phasor estimation — $\{A_1, f_1, \varphi_1\} = x_1 = \text{i-IpDFT}(x)$
3. harmonic support definition — $\mathcal{S} = \{f_h = f_1 \cdot h \mid h = 2, \ldots 50\}$
4. Taylor-Fourier expansion basis — $B = \mathrm{TFM}(\mathcal{S}, 2)$
5. harmonic phasors' estimation — $\{A_h, f_h, \varphi_h\} = x_h = (B^H B)^{-1} B^H x$
6. estimation residual update — $r = x - \sum_h x_h, \quad h = 1, \ldots 50$
7. inter-harmonic peak search — $\{f_i\} = \mathrm{findpeak}(r) \rightarrow \mathcal{S} = \{f_i \cup f_h\}$
8. repeat steps 4 – 5 – 6 — $r = x - \eta = x - \sum_h x_h - \sum_i x_i$
9. noise model identification — $\varepsilon = \mathcal{N}\left(\mathrm{mean}(r),\ \mathrm{std}(r)\right)$

Harmonic Phasor Extraction

The (inter-)harmonic phasor extraction relies on the combined application of:

- Iterative Interpolated DFT (i-IpDFT)
- Taylor-Fourier basis expansion (cs-TFM)

i-IpDFT

- based on a static signal model (stationarity assumption)
- IEEE Std C37.118.1 class P + M
- compensation of spectral leakage effects (other tones, neg frequency)

cs-TFM

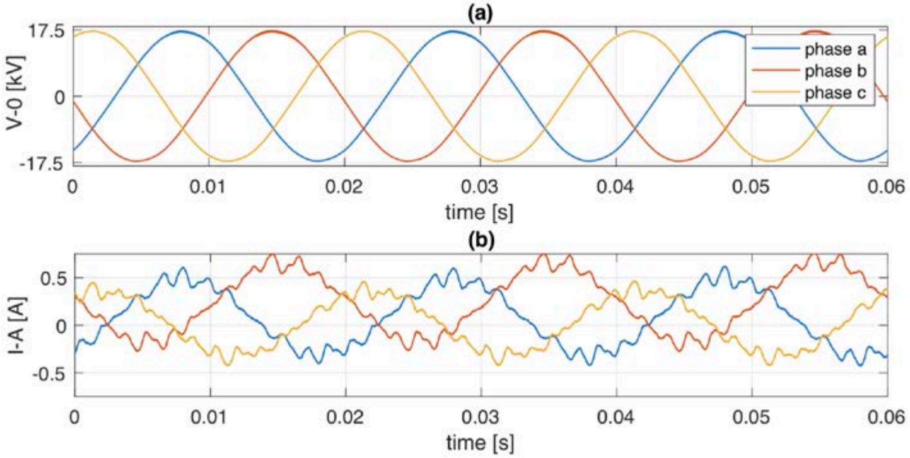
- based on a dynamic signal model (2nd order Taylor-Fourier expansion)
- IEEE Std C37.118.1 class M
- account for time-varying parameters within the observation window

The combined i-IpDFT + cs-TFM approach allows for a two-fold objective:

- i-IpDFT: accurate definition of fundamental frequency f_1 → spectral support $\mathcal{S}$
- cs-TFM: accurate estimation of time-varying harmonic phasors $A_h(t) \cdot \mathrm{e}^{j\varphi_h(t)}$

Results: Fundamental Frequency

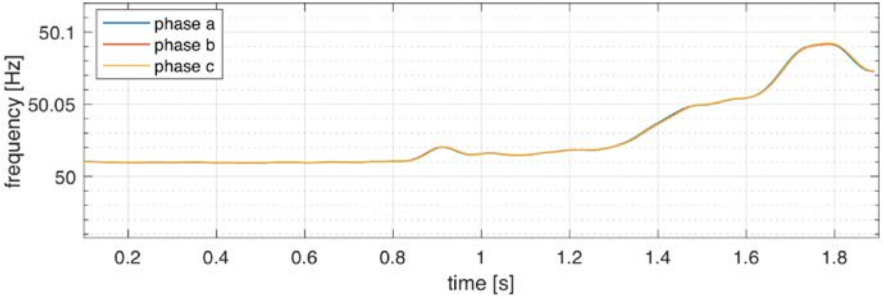
- Acquired three-phase waveforms of voltage V0 (a) and current I-A (b)



Waveform	Phase	SINAD [dB]	THD [%]
Voltage (V-0)	*a*	41.73	0.75
	b	41.21	0.73
	c	41.99	0.79

Waveform	Phase	SINAD [dB]	THD [%]
Current A (I-A)	*a*	15.89	15.86
	b	16.57	14.61
	c	15.67	16.20

- Fundamental frequency f_1 as estimated on V-0 (less distorted than current)

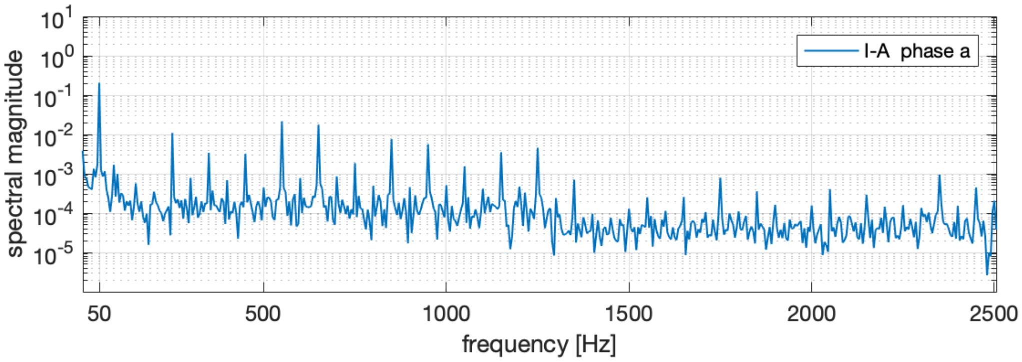


Fundamental frequency time-evolution:

- $t = [0,\ 0.8]s$ is stable around 50.01 Hz
- $t = [0.8, 2]s$ increases up to 50.09 Hz

Results: Harmonic Phasors

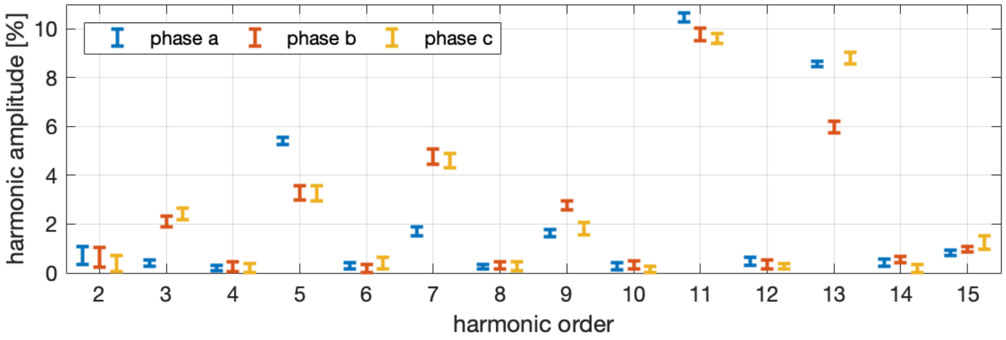
- Spectral representation of the current I-A phase a over a 100 ms window:



Harmonic content (THD ≃ 15%)

- highest harmonics within $[250, 1250]$ Hz
- higher amplitude for odd-order harmonics

- Harmonic phasor variability (min-max range) for the current I-A three-phase:



Harmonic amplitude range

- high variability also among odd-orders
- scarce correlation between the phases

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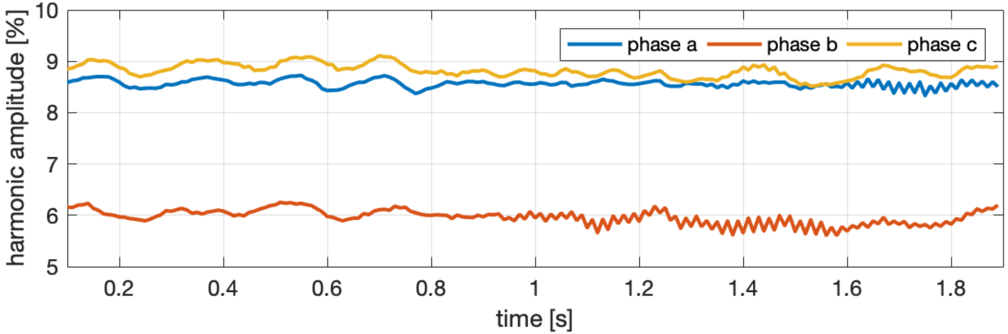
Results: Estimated THD

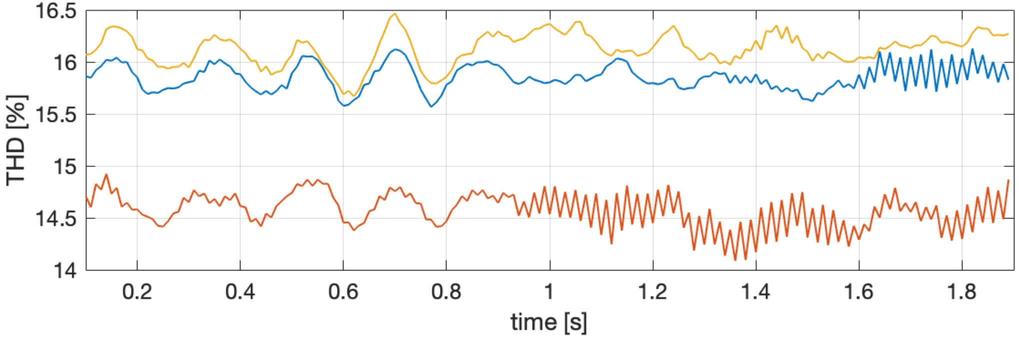
- Looking in more detail to the time evolution of 13th order harmonic amplitudes:



Uncorrelated random trends

- three-phases are not perfectly coincident
- mutual correlation lower than 90%

- Based on these harmonic amplitudes, we compute the corresponding THD:

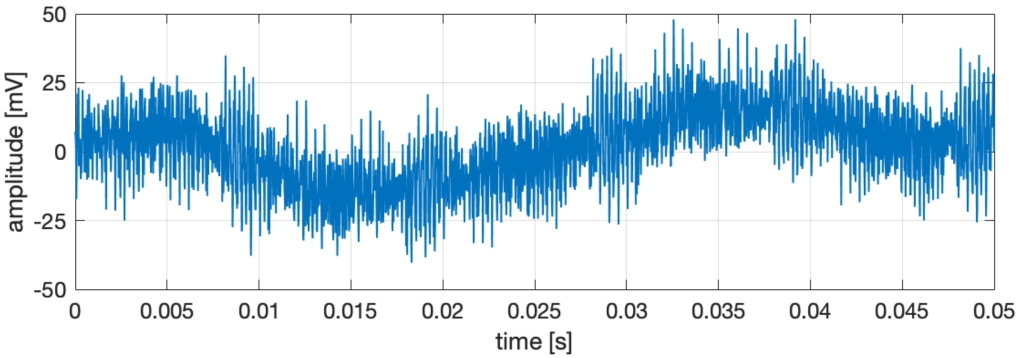


Total Harmonic Distortion variations

- different mean values, and std. devs. ≃ 0.15%
- results compliant with Matlab routine (SVD)

Measurement Noise Model

Once removed fundamental and (inter-)harmonics, the residuals are *just* noise:



Measurement noise

- nearly-stationary trend
- uncorrelated wideband noise

It is possible to identify two main components of the recovered meas. noise:

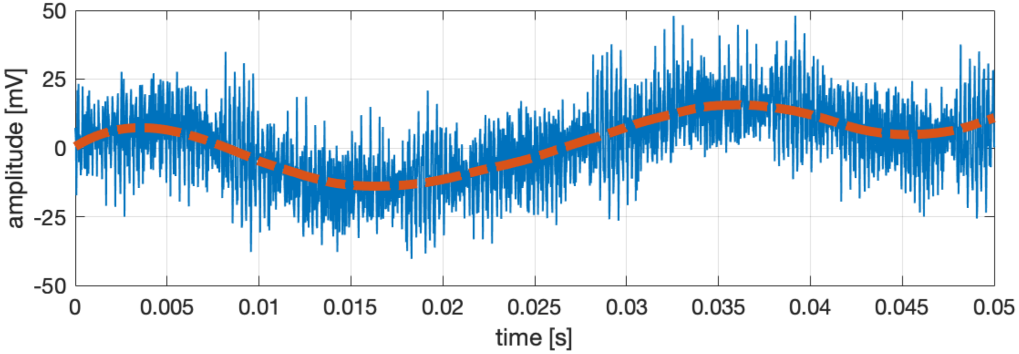
- nearly-stationary trend + DC
- uncorrelated wideband noise

Nearly stationary trend approximated by means of a low-pass filter (Savitzky-Golay filter, polynomial order 3, window length 20 ms).

Uncorrelated wideband noise approximated by means of a Gaussian random variable characterized by residuals' mean and variance.

Results: Noise Statistical Model

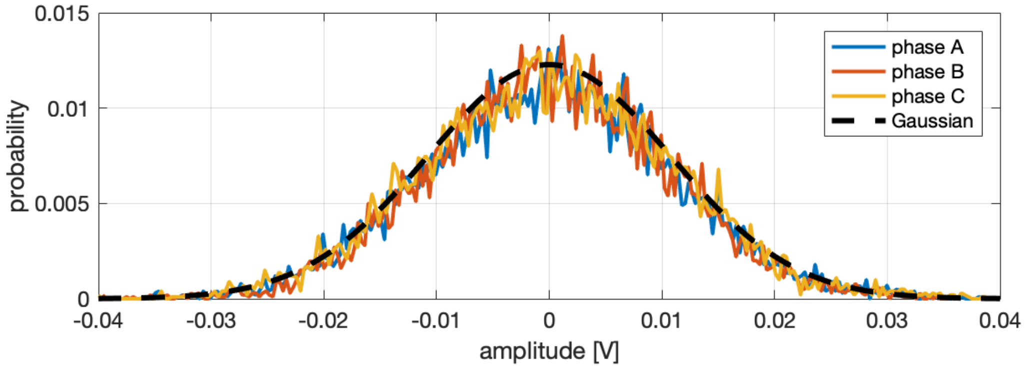
- Nearly-stationary trend:



Savitzky-Golay filter output

- capable of tracking low-frequency trend
- smoothened 3rd order approximation

- Gaussian random variable:



Gaussian noise model

- the model fits well all the three-phases
- comparable histogram distributions

Conclusions

We integrated the **waveform recording (WR) functionality** in our DESL-PMU:

- ROCOF measurements govern the recording action
- acquired data repository is available on Github

Acquired data processing enables us to determine the harmonic and inter-harmonic content and the statistical distribution of measurement noise:

- realistic disturbance levels for network modeling and control applications
- useful information for developing enhanced state estimators or for identifying possible non-linear effects in the acquisition system

In our experimental scenario we noticed:

- voltage waveforms → THD ≃ 1%, SNR ≃ 40 dB
- current waveforms → THD ≃ 16%, SNR ≃ 35 dB
- harmonic phasors with time-varying amplitudes
- harmonic phasors uncorrelated among phases

References

- **Dataset repository and network configuration:**

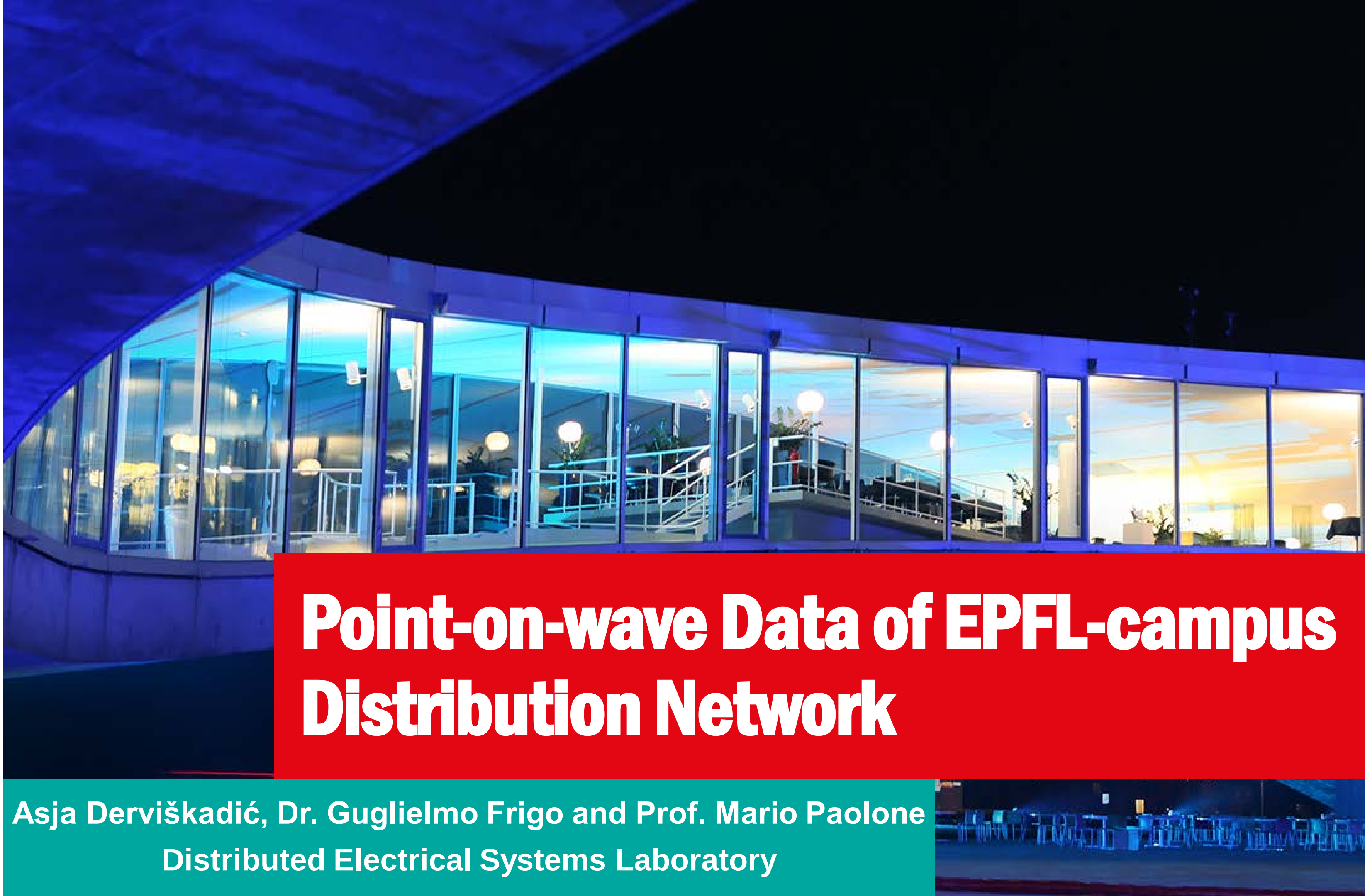
[1] *"Point-on-wave Data of EPFL-campus Distribution Network,"* [online] available at https://github.com/DESL-EPFL/

[2] F. Sossan, E. Namor, R. Cherkaoui, M. Paolone *"Achieving the Dispatchability of Distribution Feeders Through Prosumers Data Driven Forecasting and Model Predictive Control of Electrochemical Storage,"* in IEEE Trans. on Sustainable Energy, no. 7, vol. 4, pp. 1762-1777, April 2016.

- **Processing methods and results' discussion:**

[3] G. Frigo, A. Derviškadić, A. Bach, and M. Paolone, *"Statistical Model of Measurement Noise in Real-World PMU-based Acquisitions,"* 2019 IEEE SGSMA, accepted.

[4] G. Frigo, A. Derviškadić, A. Bach, P. A. Pegoraro, C. Muscas, and M. Paolone, *"Harmonic Phasor Measurements in Real-World PMU-Based Acquisitions,"* 2019 IEEE I2MTC, accepted.



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