Under-Frequency Load Shedding based on PMU Estimates of Frequency and ROCOF

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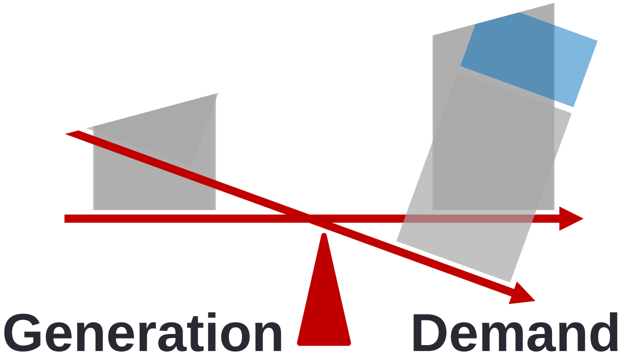
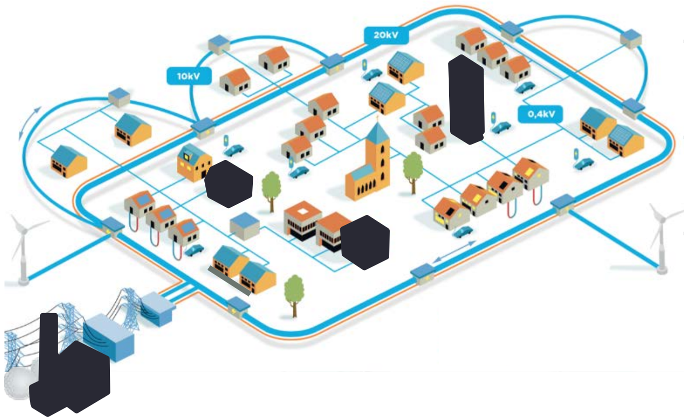
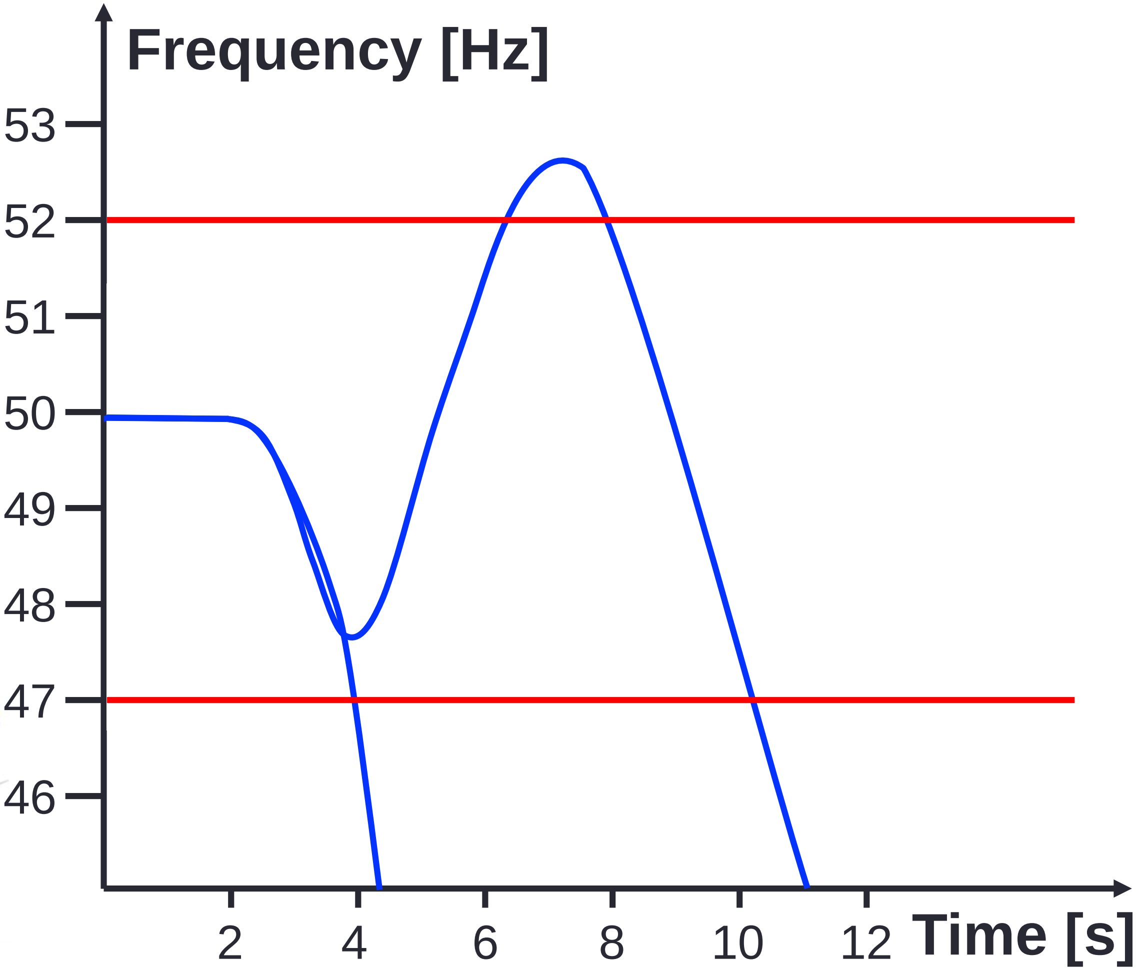
Under Frequency Load Shedding (UFLS)

Principles







Under Frequency Load Shedding (UFLS)

Frequency vs ROCOF relays

- The **amount of load shedding** and the **time of the shedding** are positively correlated with **restoration time**
- Traditional UFLS schemes ➔ frequency relays
- The recent literature has considered the adoption of centralized (WAMS) or decentralized (relays) methods relaying on the Rate of Change of Frequency (**ROCOF**)

ROCOF-LS ➔ Promptly detects critical conditions

✓ Higher nadir frequency

✓ Faster load restoration

✓ Smaller amount of curtailed energy

Outline

- PMU-based measurement of ROCOF
- Proposed ROCOF-based Load Shedding
- Description of the real-time simulation model
- Results

PMU-based measurement of ROCOF

IEEE Std. C37.118 definition

The frequency is computed as the first derivative of the synchrophasor phase angle, and ROCOF is computed as the second derivative of the same phase angle.

- Synchrophasor model assumption ➔ The acquired signal spectrum consists of one **narrow-band spectral component**
- In real-world ➔ During transient events the acquired signal spectrum consists of **several wide-band spectral components**

🡇

The definition of frequency and ROCOF associated to the fundamental component represents an open issue from the metrological point of view

- PMU observation interval <= 80 ms & reporting rate <= 50 fps ➔ ROCOF as frequency time derivative over 20 ms

🡇

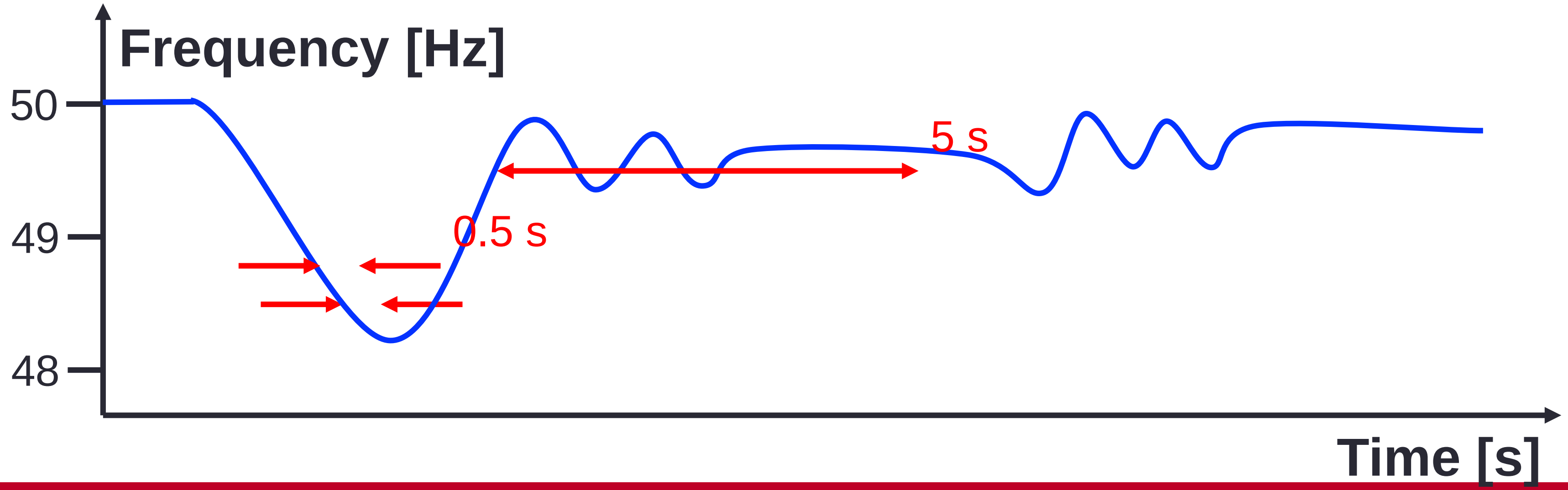
Low attenuation/filtering of electromechanical transients

ROCOF-based Load Shedding

Load Shedding (LS) and Load Restoration (LR) thresholds

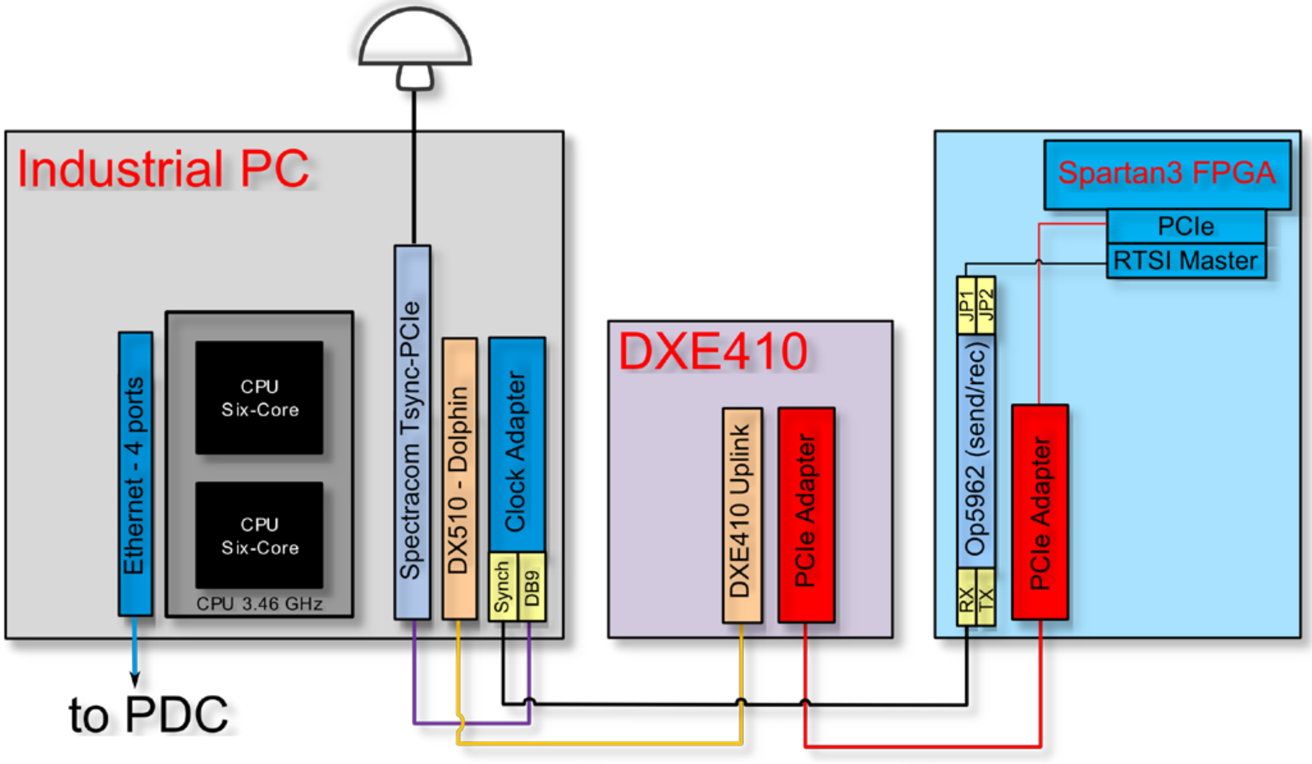
LS factor		**100 %**	**95 %**	**90 %**	**85 %**	**75 %**	**60 %**	**50 %**
f-LS *	[Hz]		48.9	48.8	48.6	48.4	48.2	48
ROCOF-LS **A**	[Hz/s]		0.2	0.4	0.6	0.7	1	1.3
ROCOF-LS **B**	[Hz/s]		0.2	0.3	0.4	0.5	1	1.3
f-LR *	[Hz]	49.7	49.6	49.5	49.4	49.2	49	

* European Network of Transmission System Operators for Electricity (ENTSO-E)



The Real-Time Simulator (RTS)

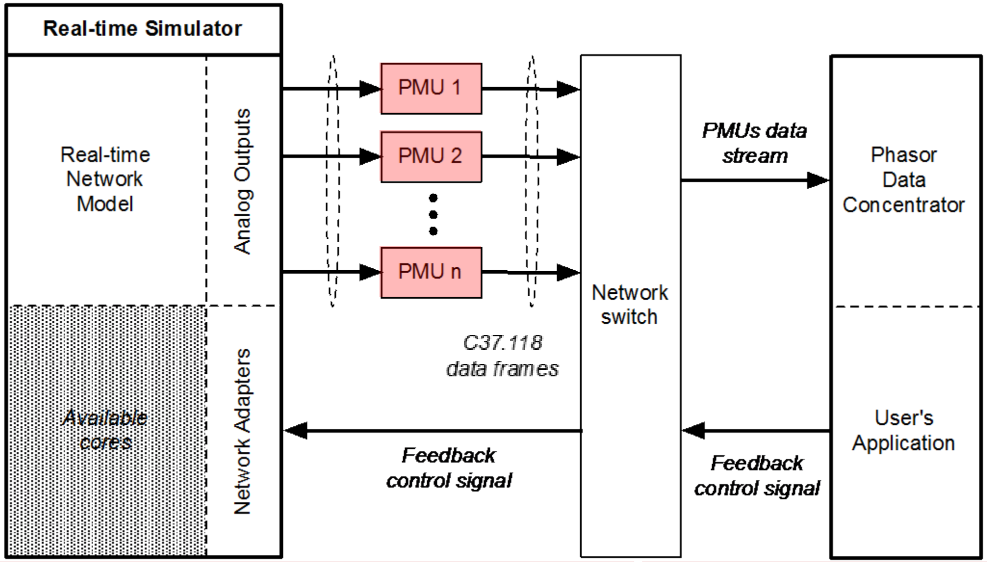
Opal-RT eMEGAsim PowerGrid Real-Time Digital Simulator



Industrial PC (12 cores) ➔ simulations ✚ hardware GPS sync
FPGA Spartan3 ➔ Stable integration time-step **10 μs**

The Real-Time Simulator (RTS)

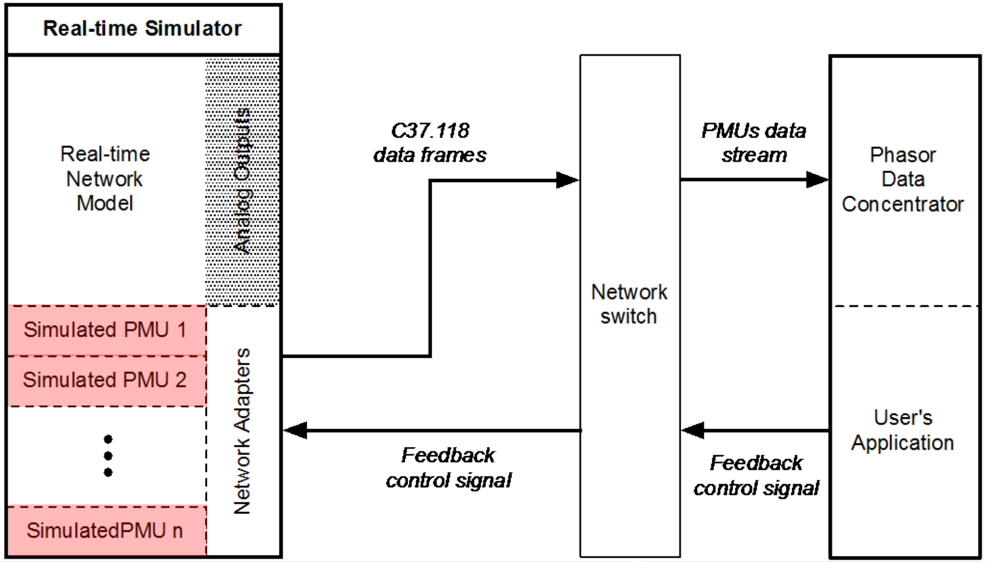
PMU testing using HIL setups



	Advantages	**Limitations**
Real devices	• Test real PMUs • Low RTS model complexity	• PMUs cost • AOs accuracy and availability • Cabling

The Real-Time Simulator (RTS)

PMU testing using HIL setups



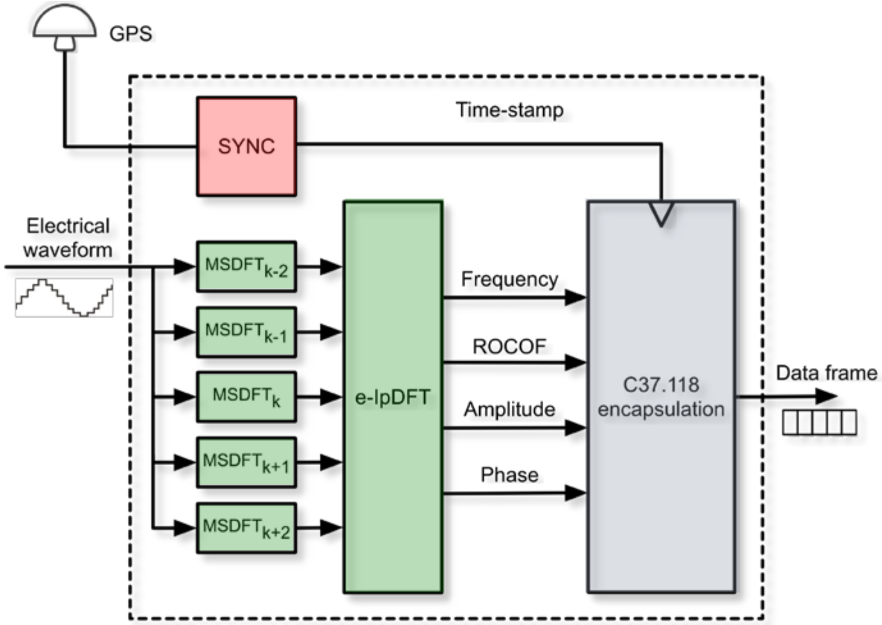
	Advantages	Limitations
Real devices	• Test real PMUs • Low RTS model complexity	• PMUs cost • AOs accuracy and availability • Cabling
Simulated devices	• **Extreme cost reduction** • Not limited by available AOs and PMUs	**PMU model complexity vs. RTS computational power**

The Real-Time Simulator (RTS)

Integration of an IEEE Std. C37.118 Compliant PMU into the RTS

Synchrophasor Estimation ➔ Enhanced Interpolated-DFT ➔ same metrological performance as real device TVE ~ 0.0X %

ROCOF error during frequency ramp **15 mHz/s**



Synchronization module

Synchrophasor estimation algorithm

- Modulated-Sliding DFT (MSDFT)
- Enhanced-Interpolated DFT (e-IpDFT)

Data encapsulation module

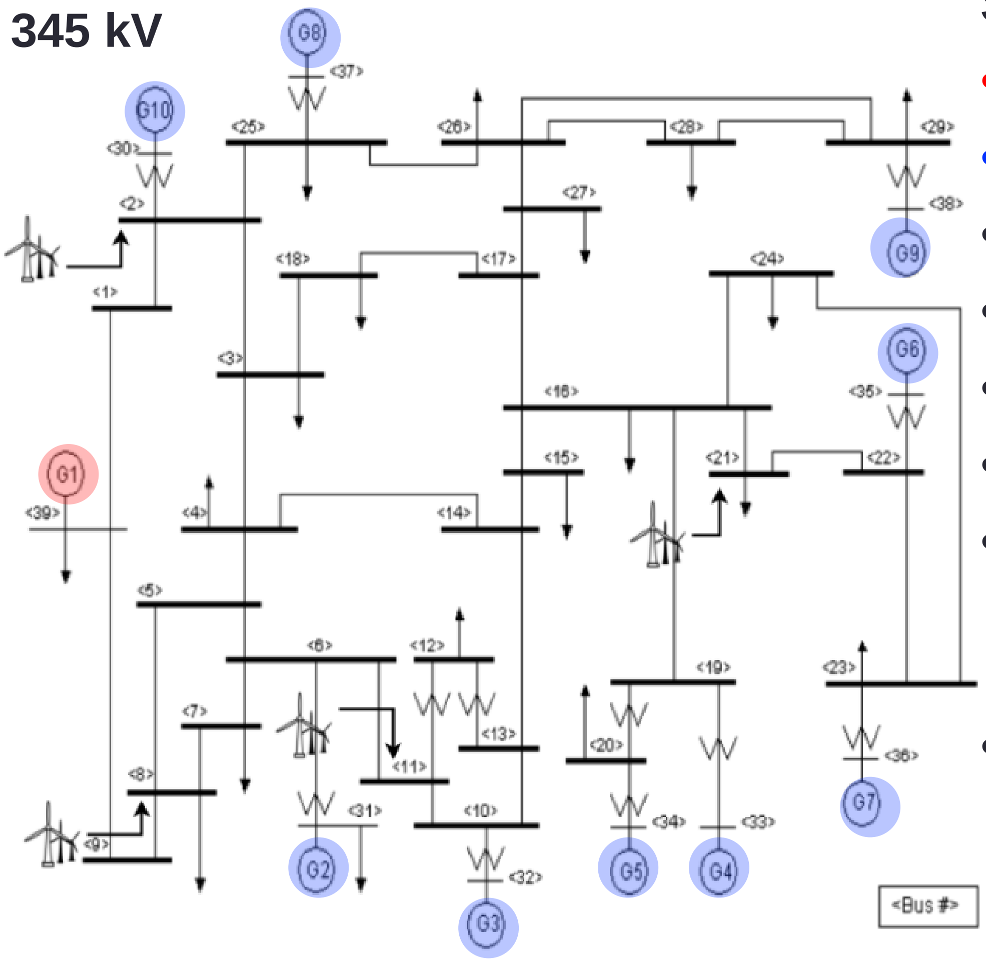
- IEEE Std. C37.118 compliant
- UTC-synchronized via GPS

 # PMUs ∀ core (12 cores) with integration time-step **100 μs**

1-ch ➔ 16 PMUs **6-ch ➔ 9 PMUs** **12-ch ➔ 5 PMUs**

The Simulation Model

IEEE 39-bus power system integrating renewables

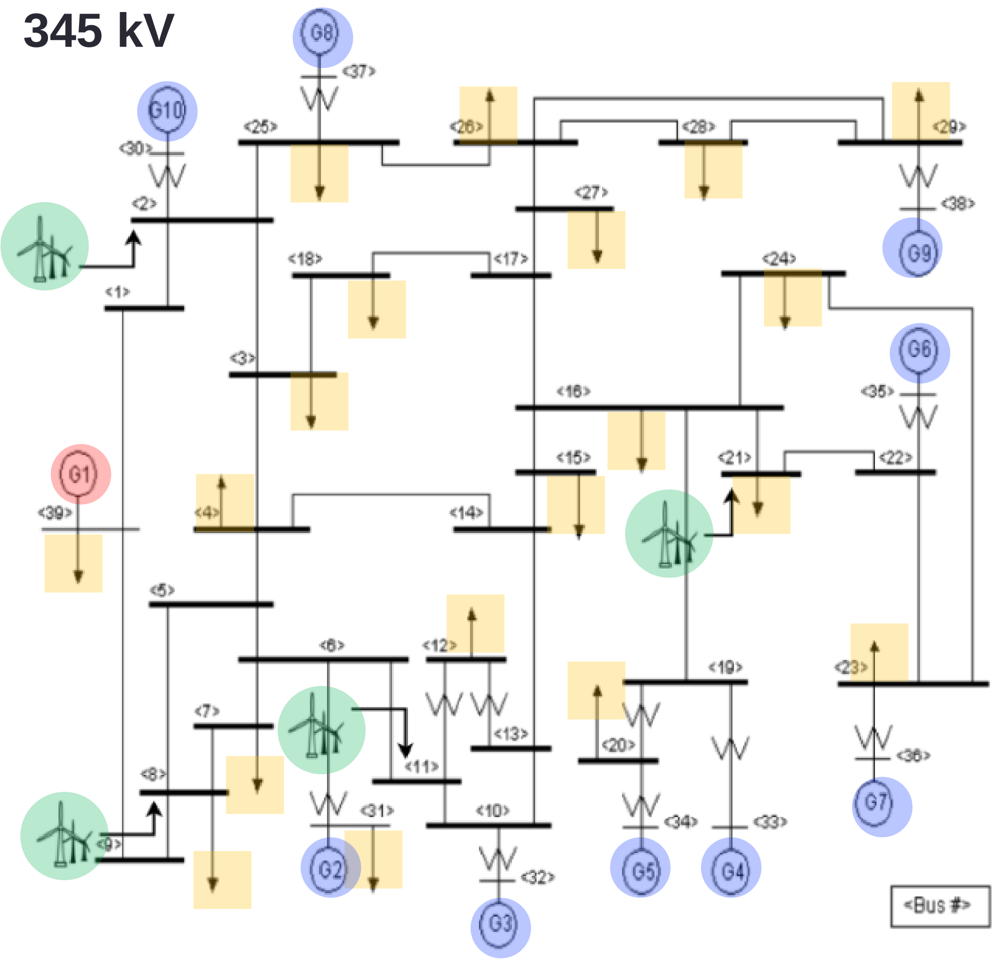


Synchronous generators

- **Thermal** (3 GVA)
- **Hydro** (1 GVA or 520 MVA)
- Dynamic model of prime mover
- Synchronous genrator
- Speed governor
- Exciter + AVR
- Sixth-order state-space model available (SimPowerSystem Simulink toolbox)
- **Only primary frequency** control with regulation coefficient of 0.05

The Simulation Model

IEEE 39-bus power system integrating renewables



Wind Farms

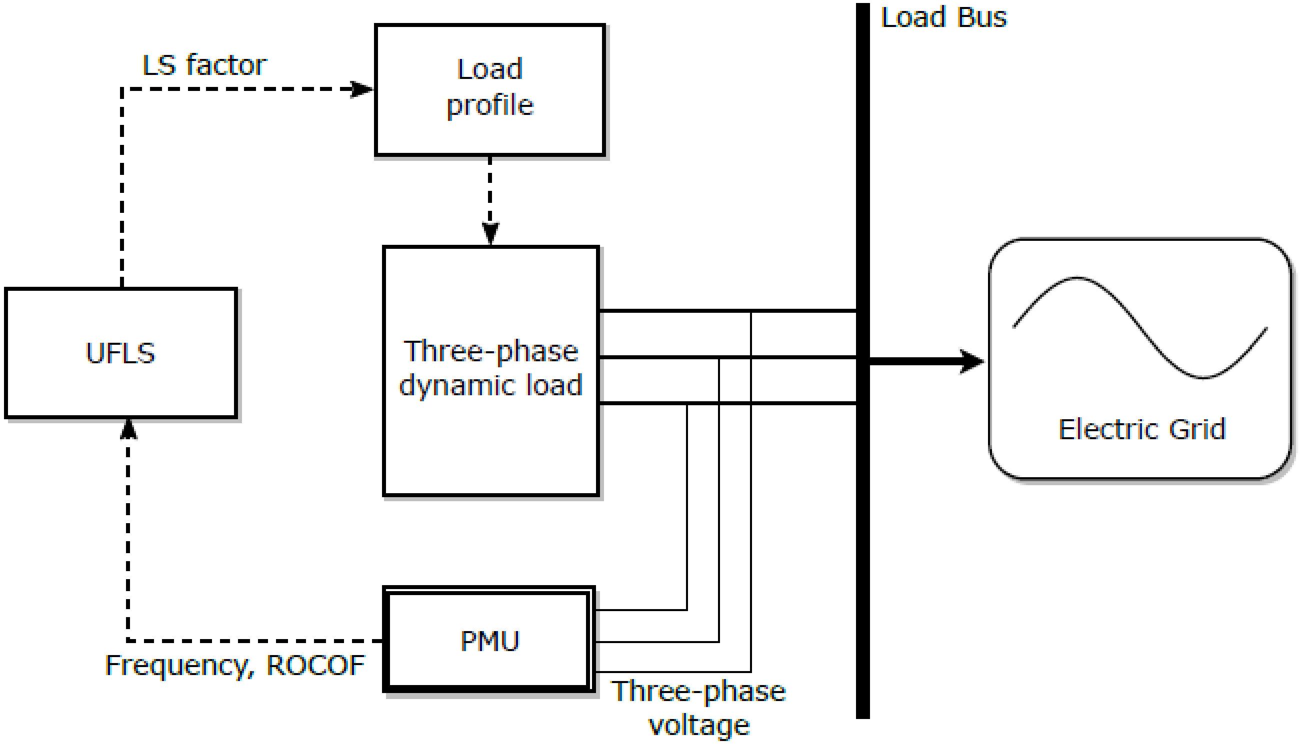
- Total nominal capacity of 1.35 GW
- Type-3 double-fed induction generator
- Asynchronous machine
- Back-to-back voltage source converter
- Power profile based on real measurements

Load Profiles

- Power profile based on experimental measurements of a real PMU installation

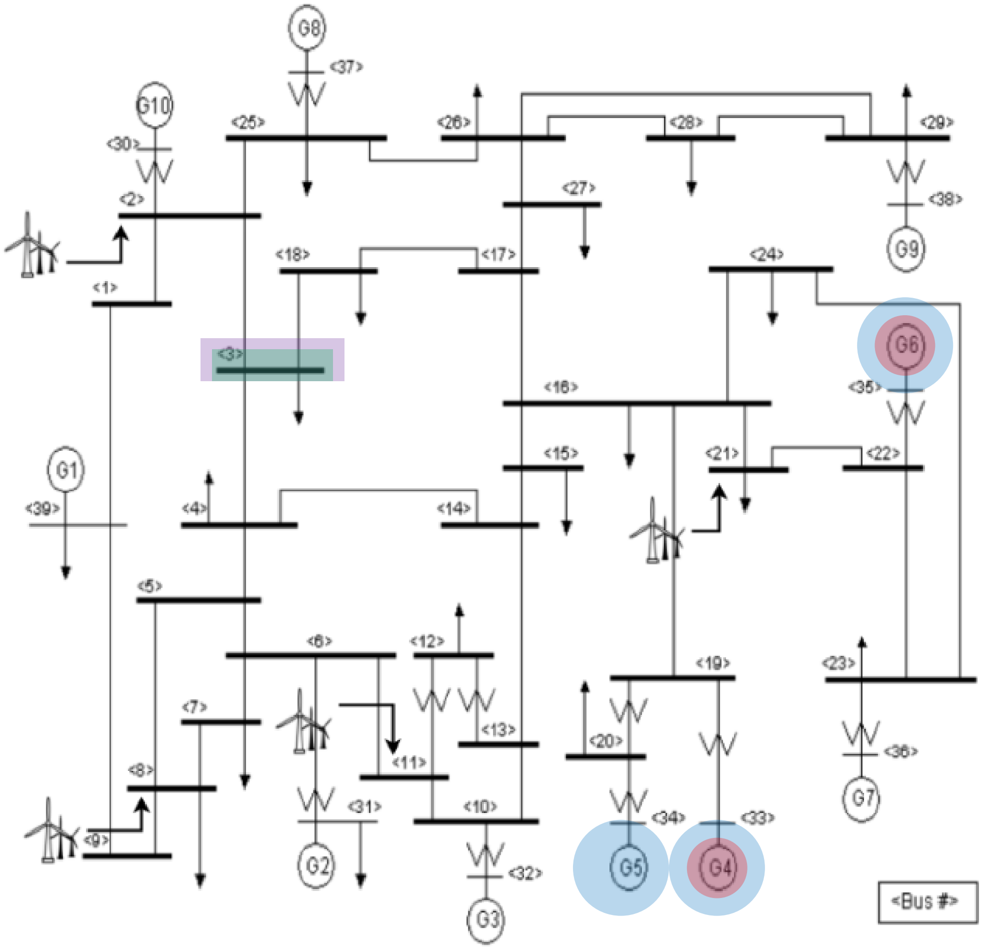
The Simulation Model

Proposed local UFLS scheme



Results

2 simulated scenarios



S1 ➔ non-severe contingency
- G4 and G6 outage
- **1 GW** tripped power

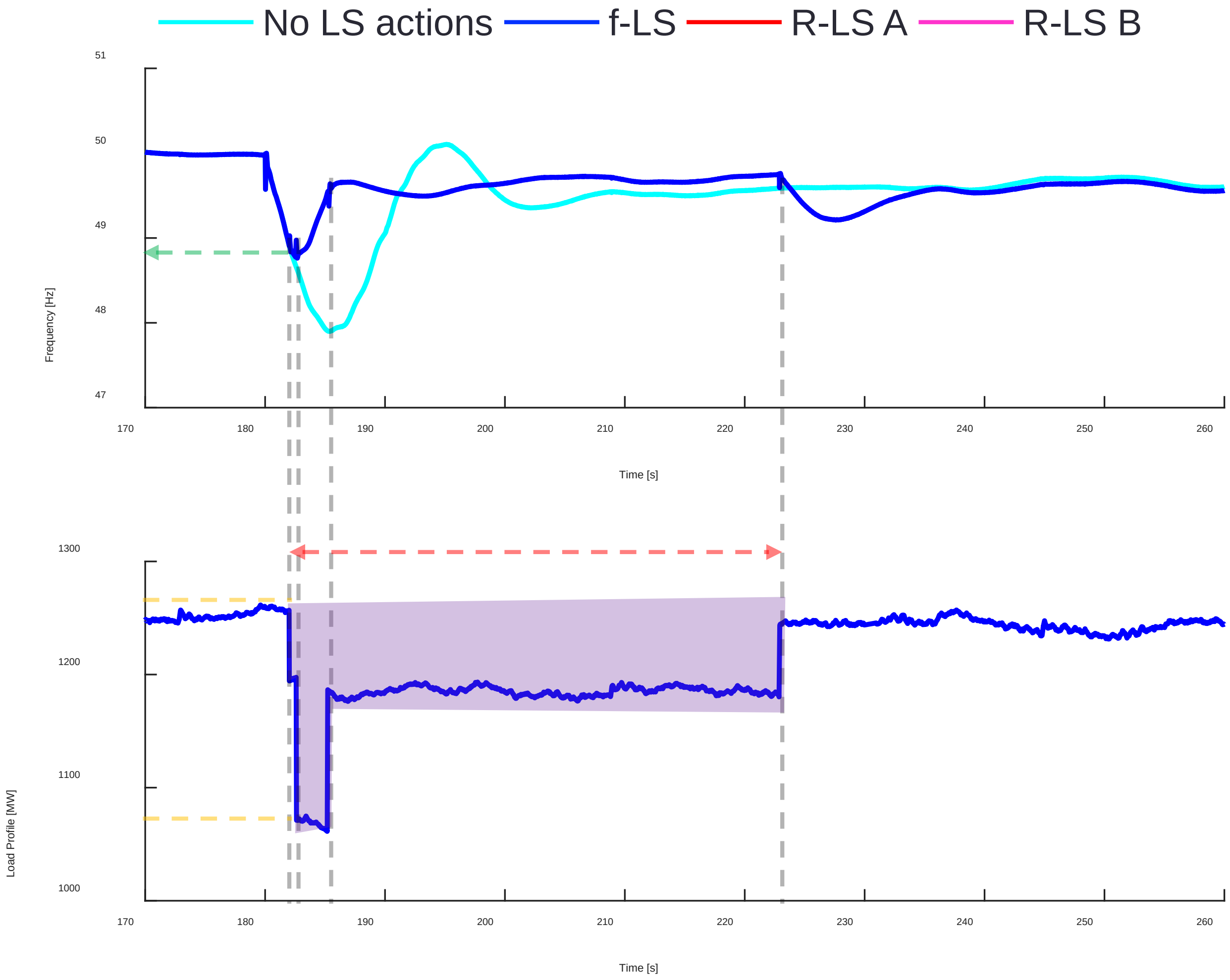
S2 ➔ severe contingency
- G4, G5 and G6 outage
- **1.5 GW** tripped power

Frequency-LS ➔ **f-LS**
ROCOF-LS case A ➔ **R-LS A**
ROCOF-LS case B ➔ **R-LS B**

bus #3

Results

Presentation of the results, bus #3



Load Shedding

↓

LS

Load Restoration

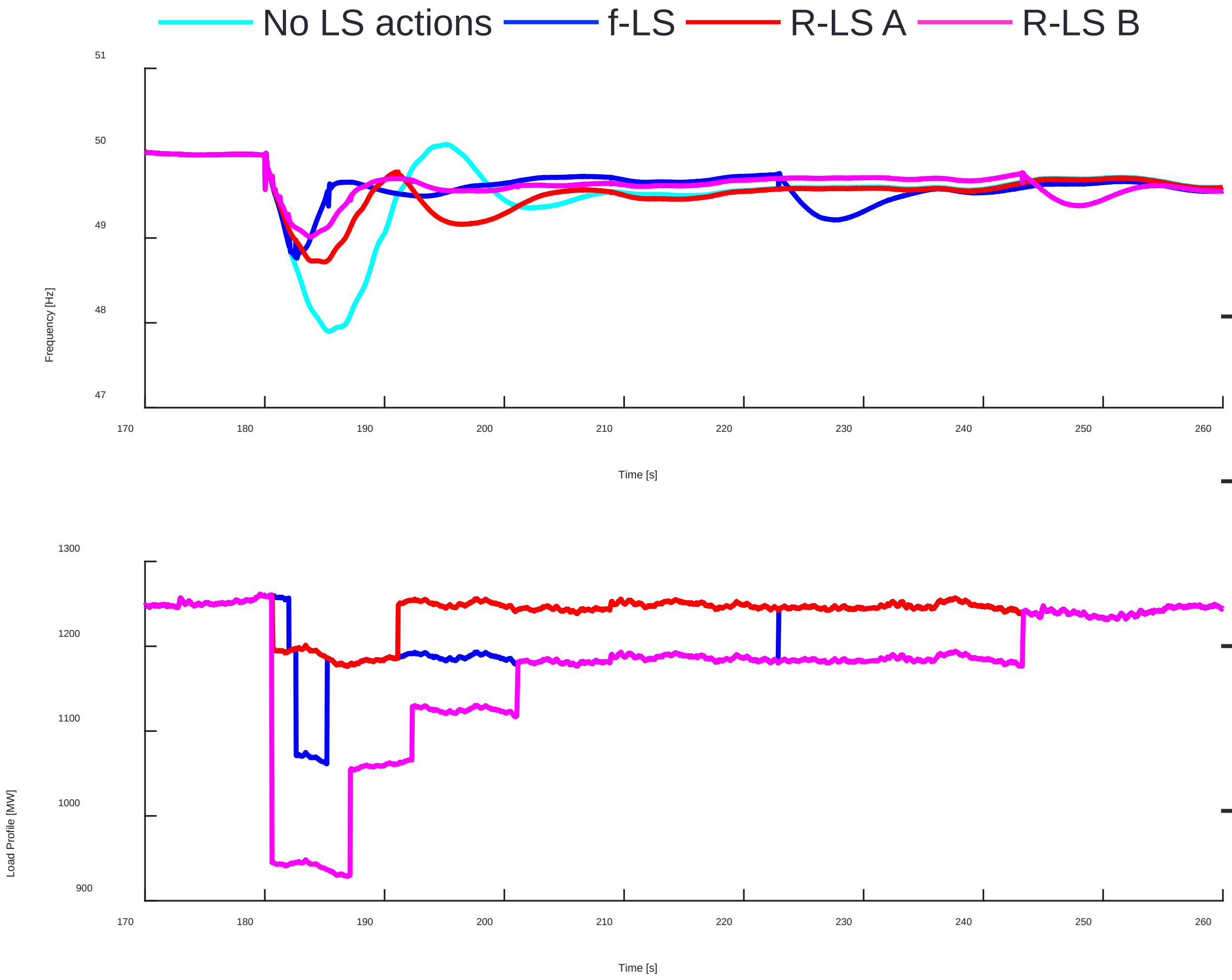
↓

LR

- Nadir frequency
- Maximum LS
- LS Duration
- Curtailed Energy

Results

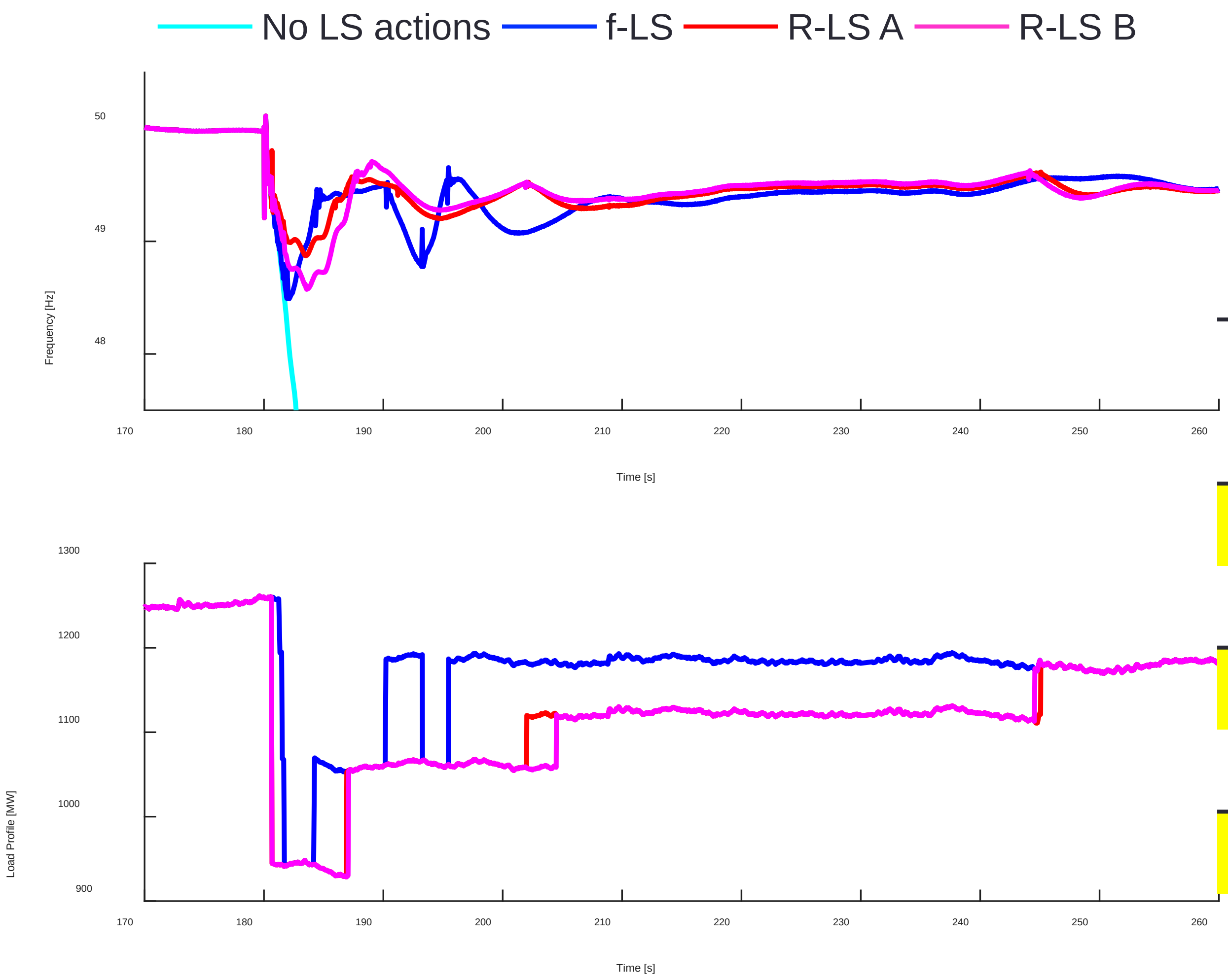
Scenario 1 ➔ 1 GW tripped power



f-LS	**R-LS A**	**R-LS B**
Nadir frequency [Hz]		
48.8	48.7	49.0
Max LS [%]		
15	5	25
Duration [s]		
41	11	63
Energy [MWh]		
4.0	0.9	4.8

Results

Scenario 2 ➔ 1.5 GW tripped power



	f-LS	**R-LS A**	**R-LS B**
Nadir frequency [Hz]	48.5	48.8	48.6
Max LS [%]	25	35	25
Duration [s]	14	65	63
Energy [MWh]	13.7	14.8	15.5

Conclusions & Future works

- Description of a local UFLS and LR scheme, relying on PMU-based measurements of frequency and ROCOF
  - ROCOF estimates ➔ LS
  - Frequency estimates ➔ LR
- Performance assessed within a RTS integrating IEEE 39-bus
- **Under non-severe system contingencies (Scenario 1) ➔ ROCOF-LS 75% less total curtailed energy 75% shorter**
- Under severe system contingencies (Scenario 2) ➔ The performance of ROCOF-LS and f-LS is comparable
- Future works:
  - Impact of different synchrophasor estimation algorithms
  - Effects of measurement noise

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References

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