METAS

# Rate of Change of Frequency

# Measurement Challenges and Potential Applications

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# Definition of ROCOF
## Signal model

Model of a **generic time-varying** power signal affected by disturbances [1]:

$$x(t) = A \cdot \left(1 + \varepsilon_A(t)\right) \cdot \cos\left(2\pi f t + \varphi_0 + \varepsilon_\varphi(t)\right) + \eta(t) + \rho(t)$$

where:

- $A, f, \varphi_0$ fundamental amplitude, frequency and initial phase
- $\varepsilon_A(t), \varepsilon_\varphi(t)$ amplitude and phase fluctuations (e.g. modulations)
- $\eta(t)$ DC, (inter-)harmonics, transient conditions
- $\rho(t)$ additive uncorrelated measurement noise

# Definition of ROCOF

## Fundamental parameters

Given a **reporting time instant $t_i$**, monitoring and control applications identify the **fundamental component** by means of three quantities:

| QUANTITY | FORMULA |
|---|---|
| Phasor | $\bar{X}_0(t_i) = A \cdot \left(1 + \varepsilon_A(t_i)\right) \cdot \exp\left[1j \cdot \left(2\pi f t_i + \varphi_0 + \varepsilon_\varphi(t_i)\right)\right]$ |
| Frequency | $f_0(t_i) = f + {}^{d\varepsilon_\varphi}/_{dt}\,(t_i)$ |
| **Rate Of Change Of Frequency (ROCOF)** | $\mathrm{ROCOF}_0(t_i) = {}^{d^2 \angle \bar{X}_0}/_{dt^2}\,(t_i) = {}^{d\, f_0}/_{dt}\,(t_i)$ |

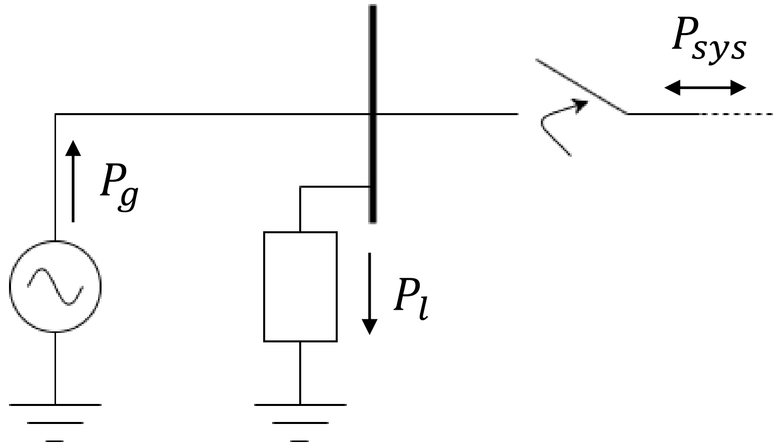
# Definition of ROCOF

## Imbalance detector

Let's consider a synchronous generator and a load.
At **steady-state**, the power balance is guaranteed:

$$P_g = P_l + P_{sys}$$

**Circuit breaker open ➔** **power imbalance $\Delta P$** and variation of generator rotor speed $\omega_g$ and angle $\delta_g$




$$\begin{cases} \dfrac{2H}{\omega_0} \cdot \dfrac{d\omega_g}{dt} = \Delta P = P_g - P_l \\ \dfrac{d\delta_g}{dt} = \omega_g - \omega_0 \end{cases}$$

➔

**$d\omega_g/dt$ (ROCOF)**
**PROPORTIONAL TO**
**POWER IMBALANCE**

$H$ inertia constant, $\omega_0$ nominal rotor speed

# Definition of ROCOF

## Properties and applications

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**ROCOF PROPERTIES:**

- is the **time-derivative of frequency** and thus allows for an **anticipative control** on frequency evolution;
- is **proportional to power imbalance** and thus allows for **promptly detecting and reacting** to potentially disruptive events.

**ROCOF applications:**

- Loss-of-Mains (LOM);
- islanding detection;
- load shedding.

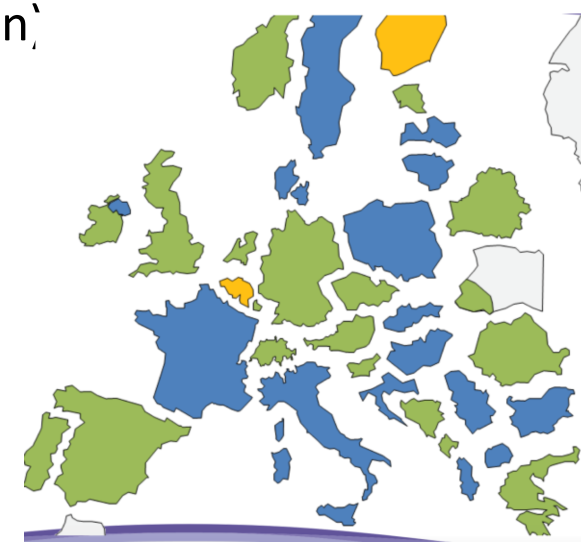
# Regulation framework

## TSOs organization

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

- ENTSO-E represents **42 transmission system operators (TSOs)** across Europe.

- **ENTSO-E main objectives** are:
  - to set up the **internal energy market** and ensure its optimal functioning;
  - to support the **European energy agenda** (e.g. renewables integration)
  - to maintain **security of supply** and support **regional cooperation**.



ENTSO-E reports at: https://www.entsoe.eu/publications/

European Network of Transmission System Operators for Electricity

entsoe

# Regulation framework

## Operating requirements

In April 2016, the EU Commission introduced a regulation on the **requirements for grid connection of power-generating facilities**.

- **FREQUENCY REQUIREMENT [2]**

| FREQUENCY RANGE | TIME PERIOD FOR OPERATION |
|---|---|
| [47.5, 48.5] Hz | To be specified by each TSO, but not less than 30 min |
| [48.5, 49.0] Hz | To be specified by each TSO, but not less than previous range (30 min) |
| [49.0, 51.0] Hz | Unlimited |
| [51.0, 51.5] Hz | 30 min |

# Regulation framework

## Operating requirements

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In April 2016, the EU Commission introduced a regulation on the **requirements for grid connection of power-generating facilities**.

- **ROCOF REQUIREMENT [2]**

*"[…] connected to the network and operating at **ROCOF** up to a **value specified by the TSO**, **unless** disconnection was triggered by ROCOF-based **LOM protection."***

- ROCOF values strongly depend on the specific network topology and composition
  ➔ more **difficult to define** a precise set of **operating requirements**;

- to the state of the art, there is not a reference method for ROCOF measurement
  ➔ more **difficult to compare** and aggregate **different meters' results**.

# Regulation framework

## Withstand capability

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In November 2017, ENTSO-E issued a guidance for the definition of **ROCOF withstand capability** and the implementation of EU regulations [3].

**Large ROCOF values** may occur after severe **system contingencies** but generating facilities shall remain connected to contribute to stabilize and restore the network.

➔ The facilities shall **not disconnect** from the network **up to a max ROCOF** defined by the TSO based on the system characteristics.

➔The **time window to measure ROCOF** has to be accordingly dimensioned, otherwise protection schemes are likely to trigger spuriously.

➔The resulting ROCOF withstand capability will be an important input to calculate the essential **minimum inertia** (inherent in synchronous generators or synthetic).

# Regulation framework

## Time window dependency

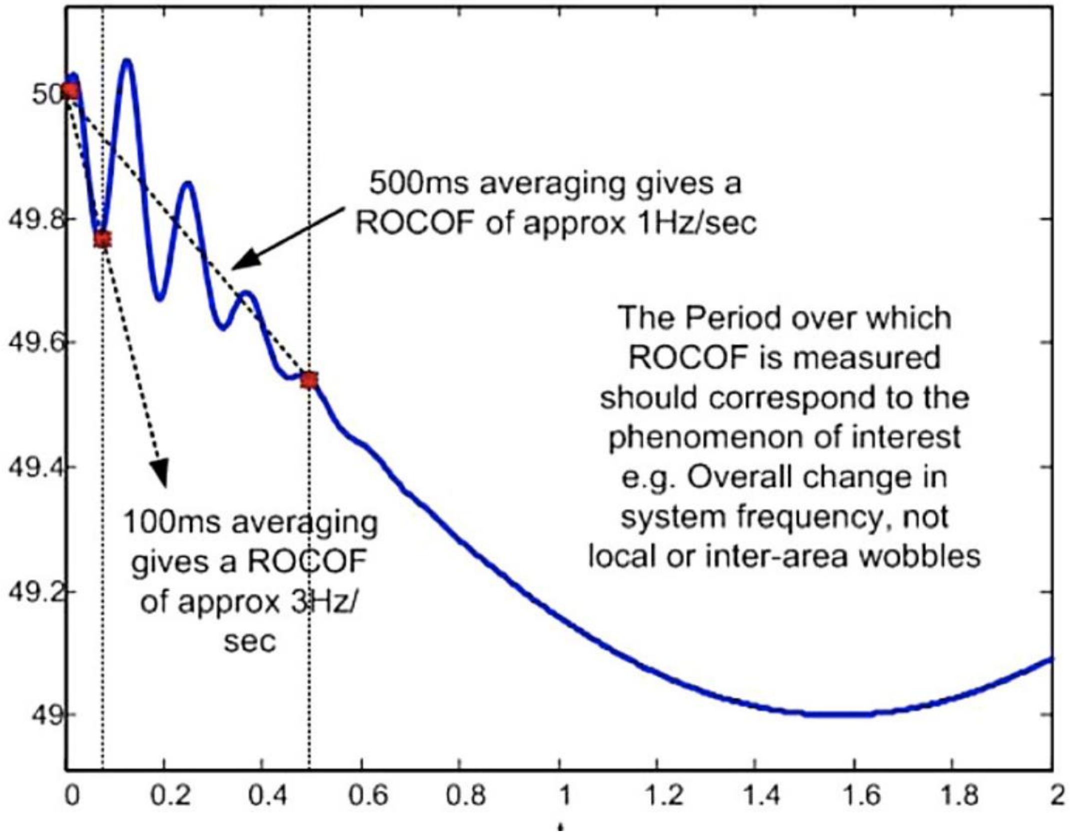
ROCOF measured values depend on the adopted time window [4].

**DIFFERENT TIME WINDOWS**

**=**

**DIFFERENT “AVERAGING” EFFECTS**

EirGrid (Irish TSO) proposed a **maximum ROCOF of 1Hz/s measured over a rolling 500 ms window**, since this aligns with the time for generators to return to a “coherent state” and for wind generation post-fault.

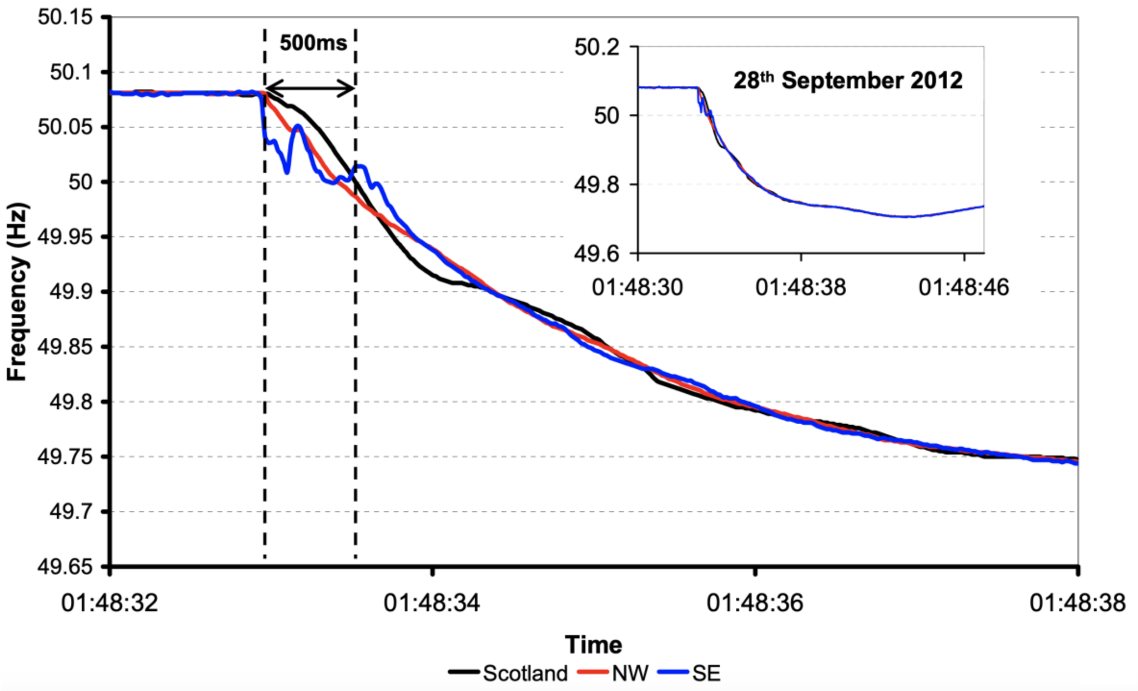


# Regulation framework

## Measurement comparability

Another issue to be considered is the possibility to **compare ROCOF measurements coming from different nodes**.

A window of **500 ms** seems a suitable time window as shown by **National Grid (UK TSO)** frequency measurements during a **1,000 MW instantaneous infeed loss** [5].

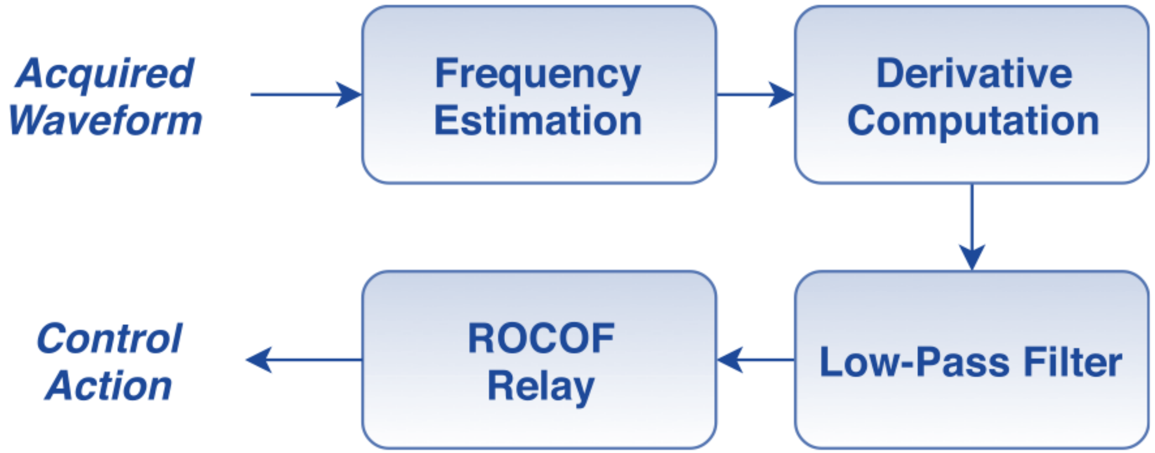


# Regulation framework

## ROCOF relay model

Typically, protection relays do not use instantaneous ROCOF measurements, but on a multi-stage processing technique [6].

1. Fundamental **frequency estimation** (time window: tens nominal cycles).
2. ROCOF computation as **weighted incremental ratio** of consecutive frequency estimates.
3. **Low-pass filtering stage** to remove fast ROCOF dynamics (e.g. moving average filter).
4. Comparison with **threshold levels** (based on inertia and network properties).



# Regulation framework

## Withstand capability

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However, **ROCOF withstand capabilities** of synchronous generators are **sensitive to the total duration of the ROCOF event** [7].

Most generators could achieve **compliance with a 1Hz/s over** a time window of **500 ms**, but their capability is significantly **reduced** when the **1Hz/s ROCOF** is sustained over **1 s** or if the **ROCOF peak** is increased up to **2 Hz/s**.

| Generator Type | Unit Size (MW) | Stable during ROCOF event? | | |
|---|---|---|---|---|
| | | 0.5 Hz/s | 1.0 Hz/s | 2.0 Hz/s |
| CCGT Single-shaft | 400 | Y | Y* | N |
| CCGT Dual-shaft | 260 | Y | Y* | N |
| CCGT Dual-shaft | 140 | Y | Y* | N |
| Steam Thermal (Reheat) | 300 | Y | Y* | N** |
| Steam Thermal (Once Through) | 150 | Y | Y* | N |
| Steam Thermal (Fluidised Bed peat) | 150 | Y | Y* | N |
| OCGT | 50 | Y | Y* | Y* |
| Salient-pole Hydro | 30 | Y | Y | Y |

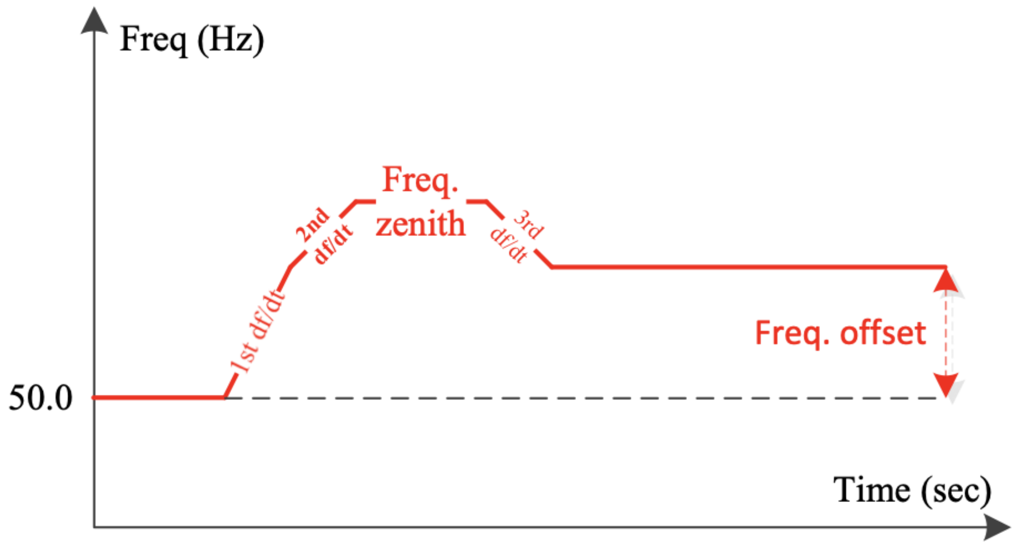
| | |
|---|---|
| Y | stable operation |
| Y* | pole slip only for 0.93 leading power factor |
| N | pole slip also for 1 leading power factor or 0.85 lag |
| N** | no pole slip, but negative power generation |

# Regulation framework

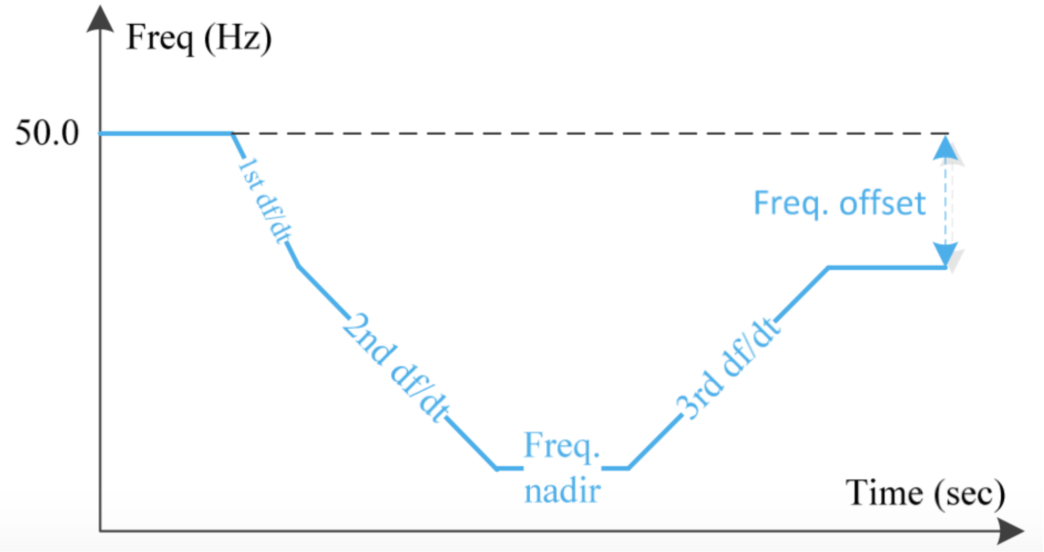
## Frequency-vs-Time profile

The TSO may define the withstand capability requirements as a set of **frequency versus time profiles**, with lower and upper limits for frequency deviation in the network **before, during and after the contingency.**

**Over-frequency**




**Under-frequency**



# Regulation framework

## ROCOF limit values

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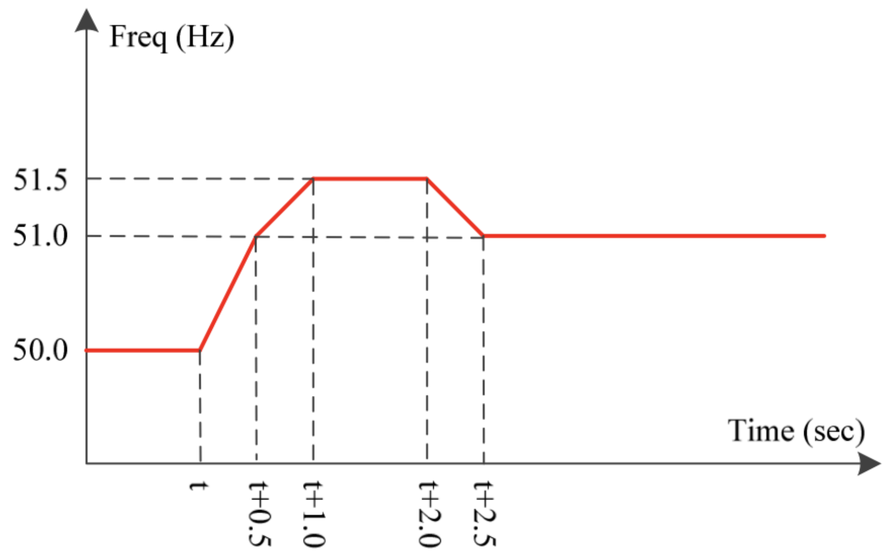


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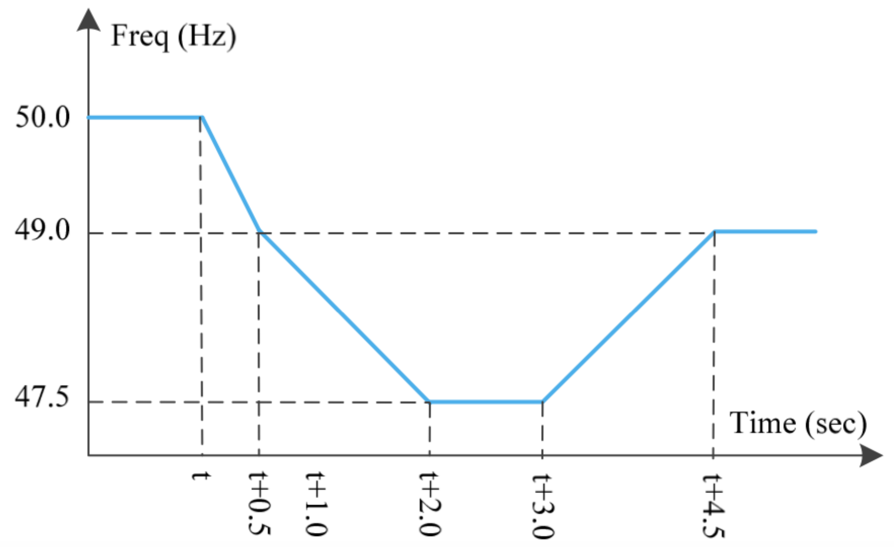


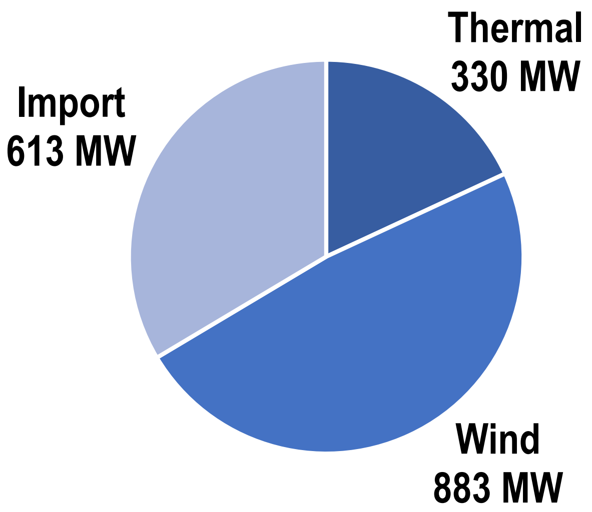

**max ROCOF = $\pm$2 Hz/s over 500 ms**

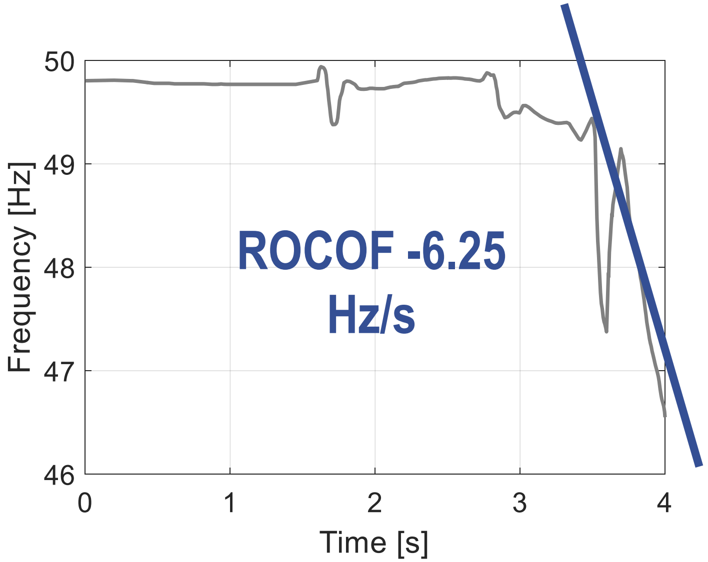
# Modern grid challenges

## South Australia black-out

South Australia Blackout, Sep 28, 2016, during extreme weather conditions [7].

- Pre-Event Generation Mix:




- 5 system faults in 87 seconds ➔ 3 transmission lines opened ➔ Loss of 456 MW of generation from 9 wind farms ➔ **Import increased up to 900 MW ➔ LOM.**
- Tripping of the interconnection ➔ Loss of imported 900 MW ➔ System frequency collapse.

# Modern grid challenges

## RES challenges

RES units (e.g. wind turbines and PVs) do not provide **any rotational inertia**.

High RES shares produce significant **measurement challenges**:

- faster frequency dynamics (quasi-stationary approximations no more valid);
- poorer power quality waveforms (e.g. harmonics from PEL-based controllers);
- transients and phase jumps (RES intermittent and volatile behaviour).

Being a second-order time derivative of phase, **ROCOF** is particularly sensitive to these kinds of disturbances and its estimation is typically associated to **uncertainty levels** comparable or even **larger than the protections' trip thresholds**.

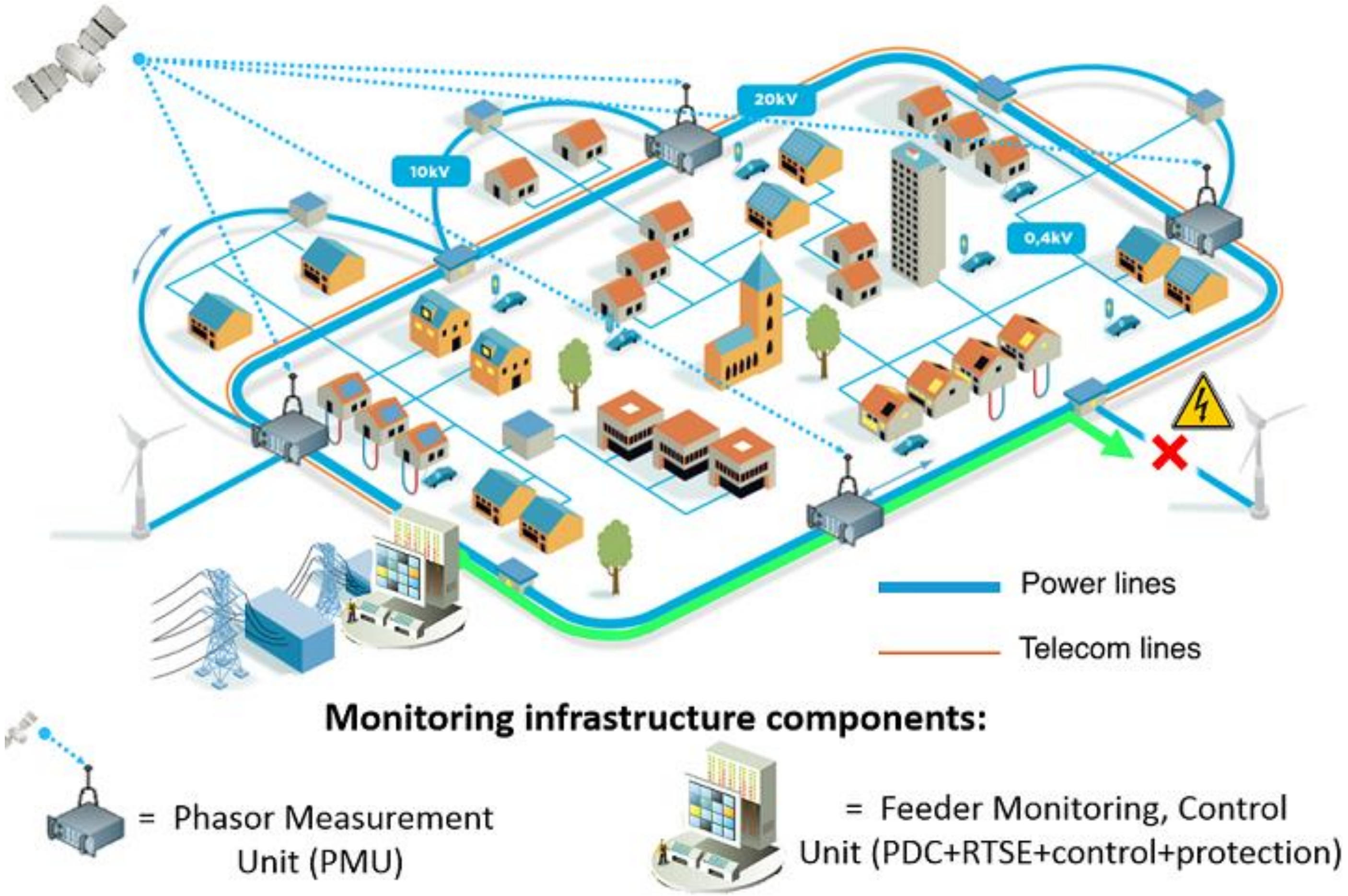
# PMU-based measurement

## Monitoring backbone

### Phasor Measurement Units (PMUs)

- synchronized to UTC
- noticeable accuracy
- easy to aggregate (PDC)

➔ promising solution for ROCOF measurements



# PMU-based measurement

## Typical parameters

Common PMUs employ **shorter time windows** in order to cope with latency and response time requirements:

- **P-class** → around 3-4 nominal cycles (e.g. 60 ms)
- **M-class** → 5 or more nominal cycles (e.g. 100 ms)

with reporting rates in the order of **tens frames per second**.

➔ On such short time windows the ROCOF estimation might be subject to **higher uncertainty** (fluctuations, inconsistent values) than traditional ROCOF relays.

➔ On the other hand, PMUs can guarantee a **much prompter response**, as well as **full comparability** among different nodes.

# New IEC Std and proposals

## Accuracy requirements

The recent IEC/IEEE 60255-118-1:2018 defines the PMU accuracy requirements in terms of **maximum ROCOF error (RFE)** in Hz/s (with reporting rate: 50 fps) [9].

| COMPLIANCE | TEST | P-CLASS | M-CLASS |
|---|---|---|---|
| Steady-state | Signal frequency | 0.4 | 0.1 |
| | Harmonic distortion | 0.4 | n.a. |
| | Out-of-band interference | n.a. | n.a. |
| Dynamic | Measurement bandwidth | 2.3 | 14 |
| | Frequency ramp | 0.4 | 0.2 |
| **LATENCY [ms]** | | **40** | **140** |

# New IEC Std and proposals

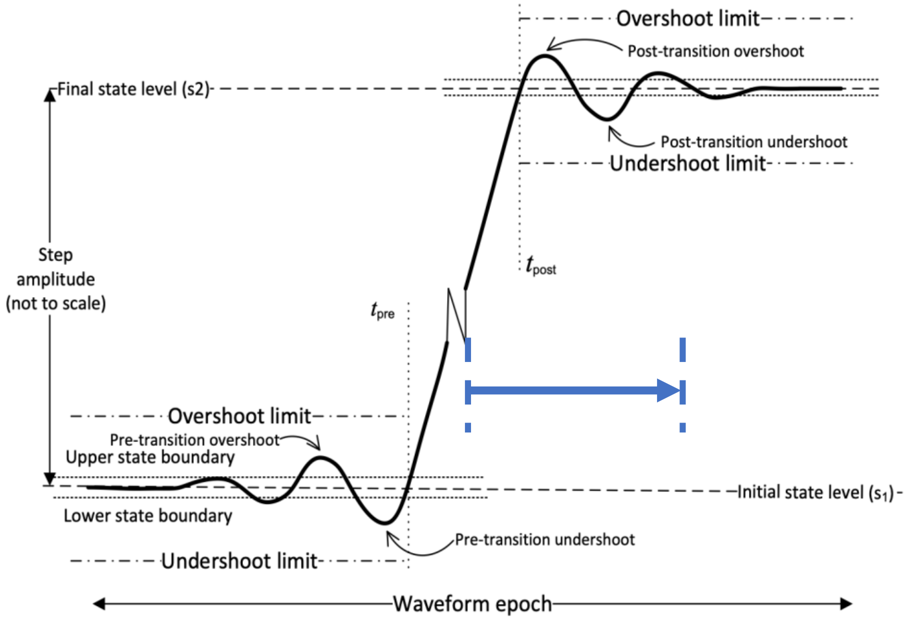
## Step response

In the **Input step change test**, the maximum susceptibility response time is assessed, here expressed in milliseconds.

As a summary, in terms of ROCOF estimation the IEC/IEEE Std requires:

- 0.x Hz/s uncertainty in steady-state
- (x)x Hz/s uncertainty in dynamics
- hundred ms response time in steps

➔ **is it compatible with ENTSO-E guidelines?**




| TEST | P-CLASS | M-CLASS |
|---|---|---|
| Amplitude step | 120 | 280 |
| Phase step | 120 | 280 |

# New IEC Std and proposals

## Significance issues

In order to better represent the real-world conditions, recent EMPIR project ROCOF proposes new test and accuracy limits depending on **USE CASES** [10]:

| TEST | UC 1 | UC 2 | UC 3 |
|---|---|---|---|
| Noise | 1.2 | 0.2 | 0.1 |
| Phase step + frequency ramp | 50 | 25 | 10 |
| Close-in interharmonics (flicker) | n.a. | 0.6 | 0.3 |

| USE CASE | LATENCY | STEADY-STATE RFE |
|---|---|---|
| UC 1 | 50 ms | 0.1 |
| UC 2 | 100 ms | 0.1 |
| UC 3 | 250 ms | 0.1 |

UC 1: active power control → window length: 100 ms

UC 2: more stable measurement → window length: 200 ms

UC 3: anti-islanding detection → window length: 500 ms

# Measurement uncertainty

## Simulated PMU models

Another approach for assessing the actual ROCOF measurement feasibility is to perform an analysis of two **PMU simulated models in real-world datasets** [6].

In particular, two algorithms from recent synchrophasor estimation literature:

- **Enhanced Interpolated-DFT** (eIpDFT) [11]
- **Compressive Sensing Taylor-Fourier Model** (csTFM) [12]

They both rely on a DFT-based approach (frequency domain), but aim at reducing the estimation uncertainty through different procedures.

# Measurement uncertainty

Static vs dynamic estimator

### Enhanced Interpolated-DFT

- static signal model
- interpolation to overcome DFT finite resolution
- compensation of long-range spectral leakage from negative image

### Compressive Sensing Taylor-Fourier Model

- dynamic signal model
- higher-order derivative terms to account for time-varying conditions
- model of signal support to mitigate injection from interfering tones

# Measurement uncertainty

## ROCOF computation

**STATIC (eIpDFT)**

- account only for *"$0^{th}$ order"* terms, i.e. amplitude, phase and frequency
- ROCOF  frequency incremental ratio:

$$ROCOF = \frac{f(t_2) - f(t_1)}{t_2 - t_1} \qquad (1)$$

- frequency dynamics approximated by the closest stationary trend

➔**delayed and LP-filtered estimation**

➔**affected by signal time-variations**

**DYNAMIC (csTFM)**

- accounts also for high-order derivative contributions
- ROCOF = signal state variable

$$ROCOF = \frac{\partial^2 \phi(t)}{\partial t^2} \qquad (2)$$

- higher sensitivity to noise and uncompensated disturbances

➔**instantaneous ROCOF estimation**

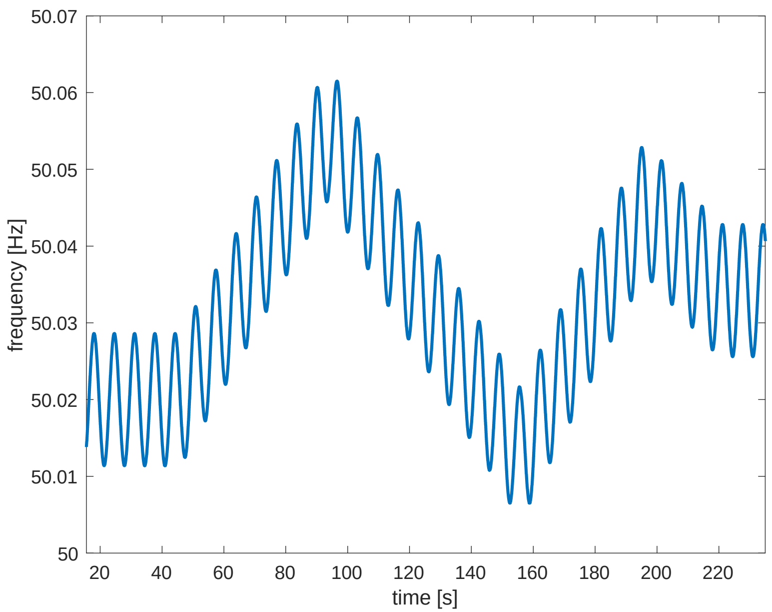
➔**lower robustness in noisy conditions**

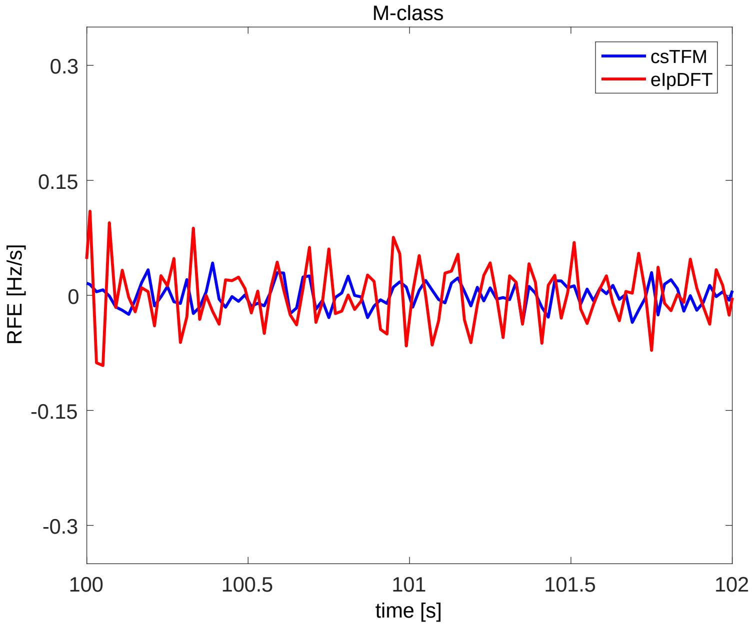
# Measurement uncertainty

## Inter-area oscillation

In December 2016, an unexpected opening of a line in the French TN caused an **inter-area oscillation** in the Continental Europe electricity system.

Based on the PMU estimates in Lausanne, we derive a test waveform and evaluate the **RFE** provided by the **two different PMU-algorithms (static vs dynamic)**.



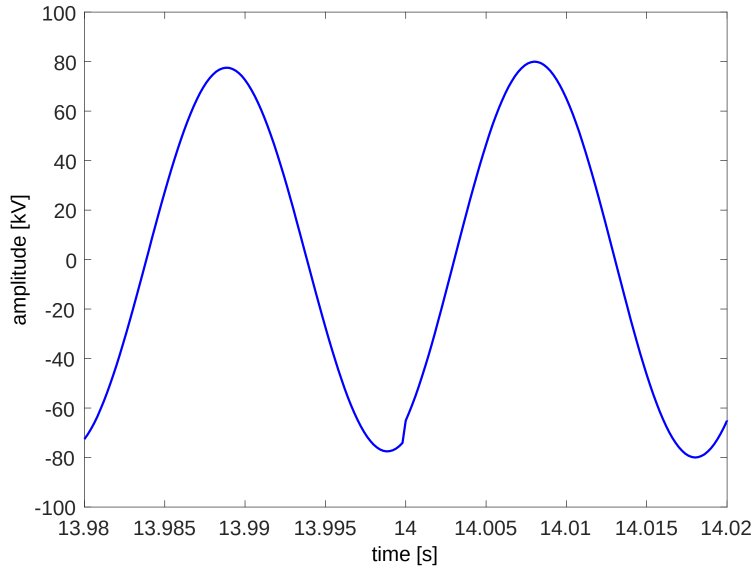
# Measurement uncertainty

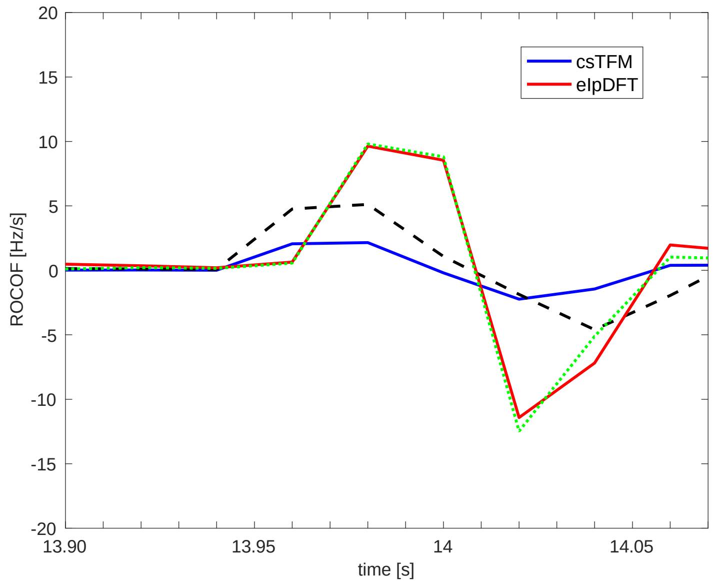
## Islanding test

Intentional **islanding maneuver** of MV urban area → **transient event (oscilloscope record** on Aug. 13rd, 2009) [13].

Since no reference values is retrievable, we simply compare the estimates:

- **elpDFT:** larger ROCOF values and sudden oscillations
- **csTFM:** smoother and more stable trend



# Measurement uncertainty
## Model inconsistence

By performing a spectrogram analysis

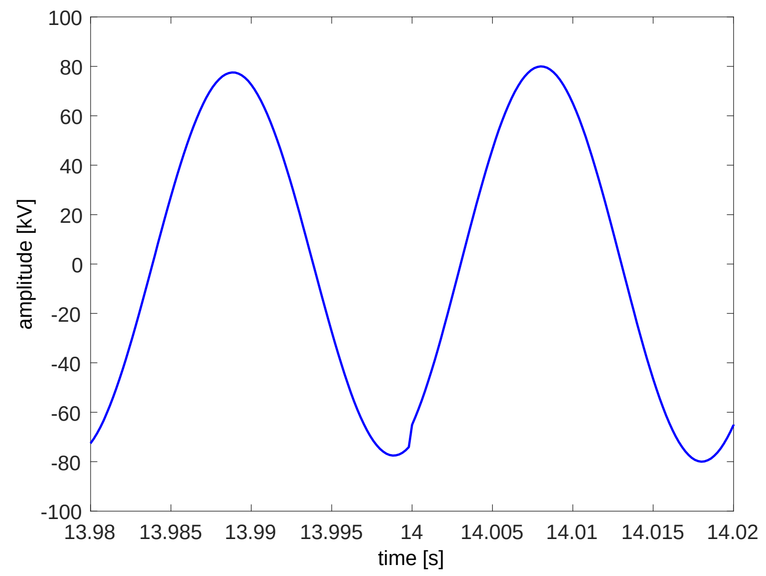
- $t < 14$ s : narrow-band single tone;
- $t \geq 14$ s : bandwidth over 500 Hz.

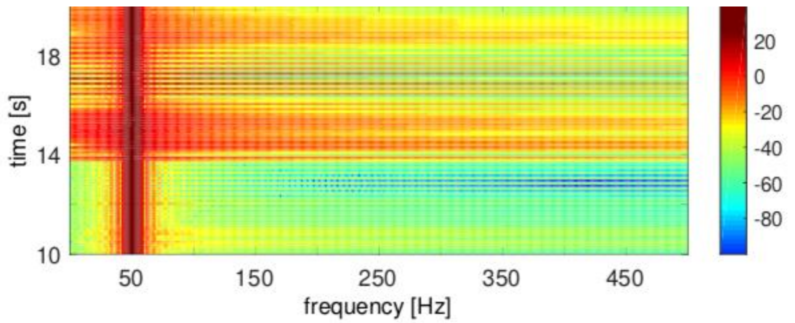
In the synchrophasor representation, signal DFT consists of one or few narrow-band components.

During transients, it can't account for the entire signal information content.

**➔unsuitable synchrophasor model**

**➔ROCOF estimate: reliable? significant?**



# Measurement uncertainty

## Definitional uncertainty

The dictionary of metrology (VIM) introduces the concept of:

***DEFINITIONAL UNCERTAINTY:*** *"component of measurement uncertainty resulting from the finite amount of detail in the definition of a measurand."*

In the specific case of PMU-based ROCOF estimation, this leads to:

- **introduction of reliability indices**

  normalized Root Mean Squared Error (nRMSE) [1]

  Goodness of Fit (GoF) [14]

- **modification of the signal model**

  $A \cdot \cos\big(\theta(t)\big) \rightarrow A \cdot \cos\big(\theta(t) + \psi(t)\big)$

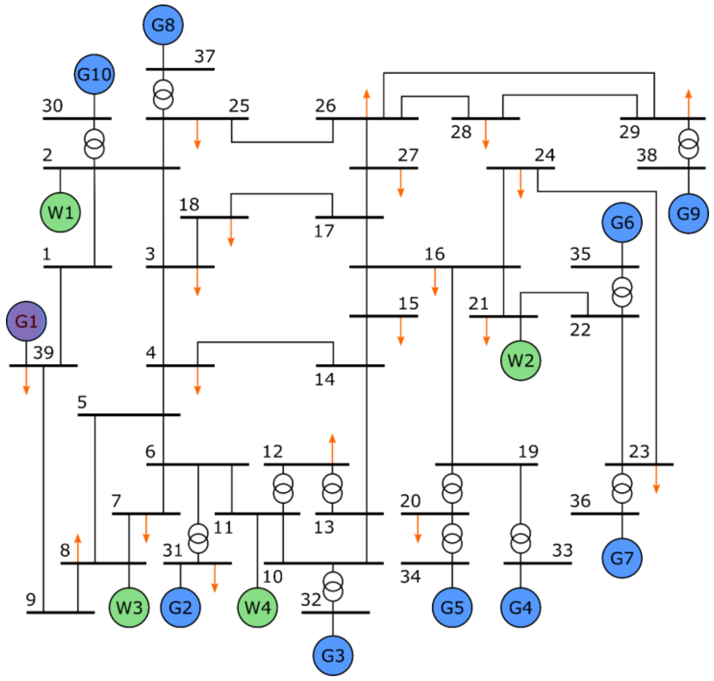
  where $\psi(t)$ accounts for phase steps [15]

# UFLS application example

## Low-inertia scenario

In order to study the behavior of PMU-based measurements of frequency and ROCOF in a reduced-inertia scenario, we modified the **IEEE 39-Bus** standard test system by adding **4 wind farms and dynamic load profiles** [16].

A **PMU** is placed **in each node** in order to measure frequency and ROCOF.




**Opal-RT PMU and network models available at:**
**https://github.com/DESL-EPFL**

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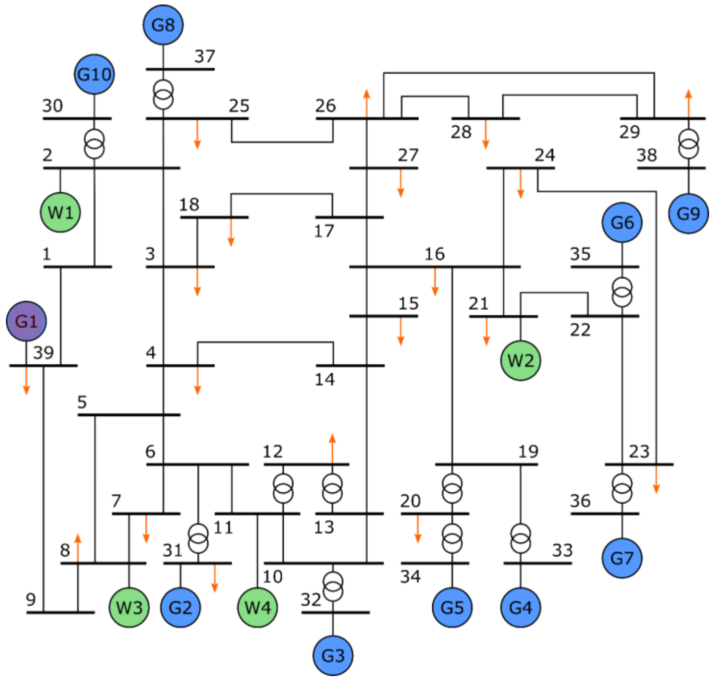


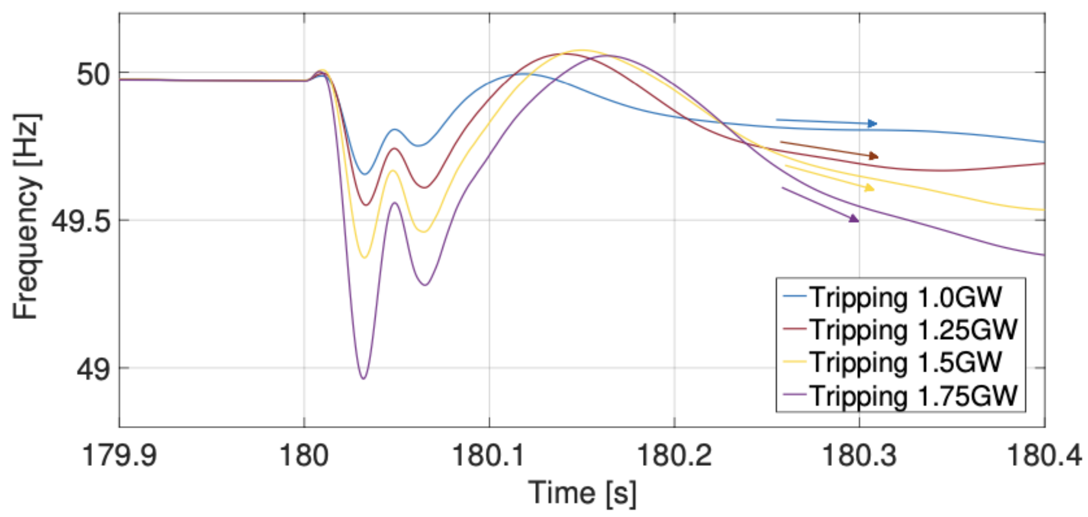

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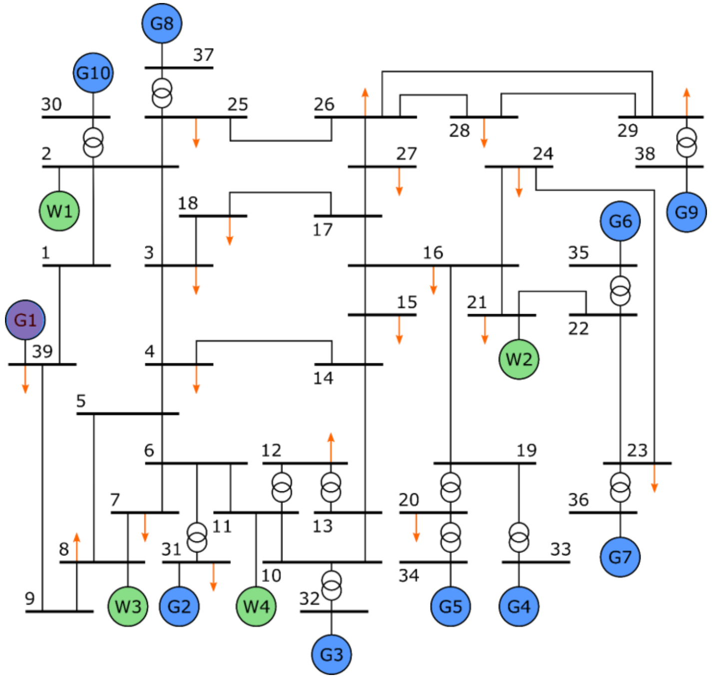
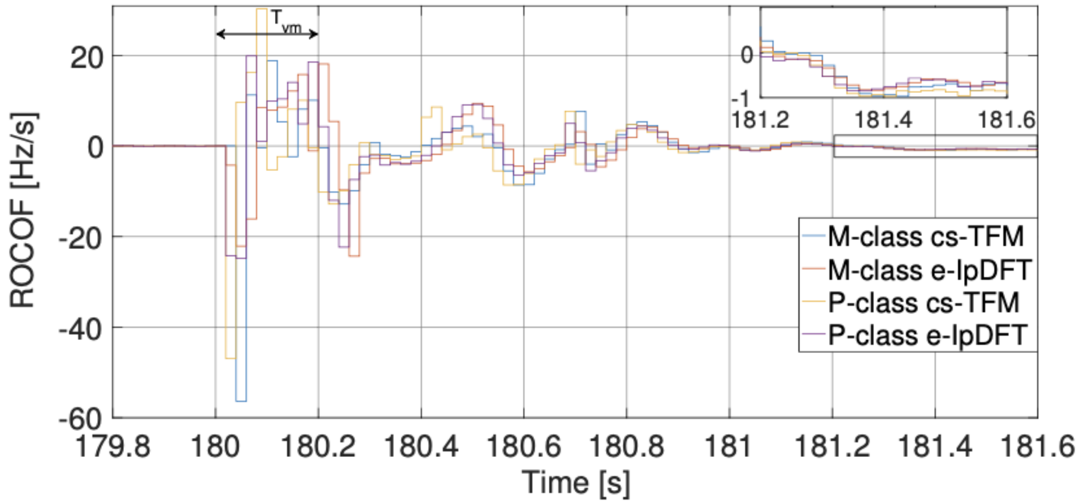


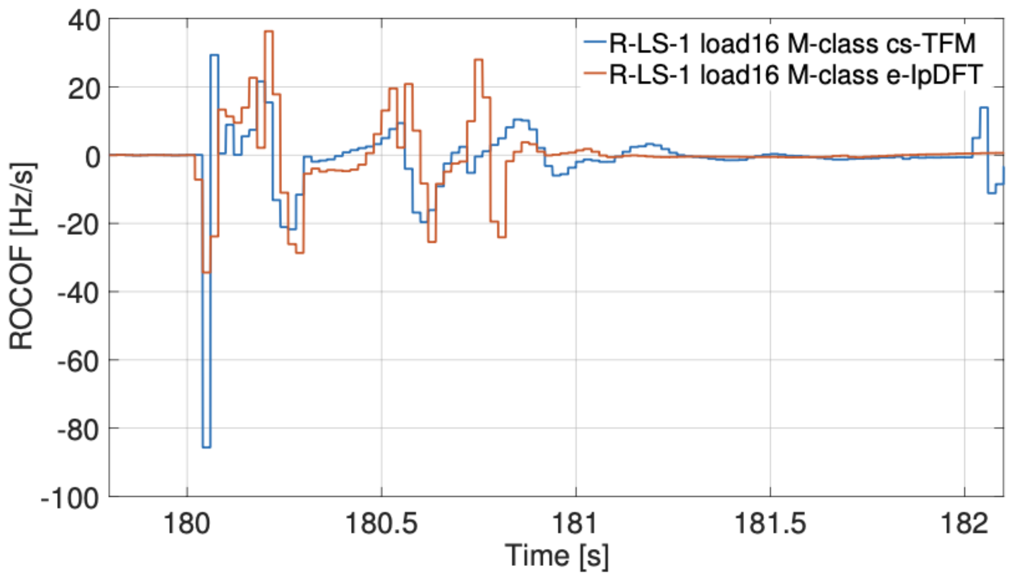
# UFLS application example

## Low-inertia scenario

**Under-frequency load-shedding (UFLS)** scheme relying on PMU measurements.

We consider ROCOF estimates $R$ over an interval of **500 ms**, 25 estimates at 50 fps. The load share is shed if **at least $p$ estimates** exceed the corresponding threshold.

| Load Share [%] | 95 | 90 | 85 | 75 | 60 |
|---|---|---|---|---|---|
| ROCOF [Hz/s] | 0.3 | 0.4 | 0.6 | 0.7 | 1 |
| $p$ [%] | 88 | 84 | 72 | 68 | 64 |



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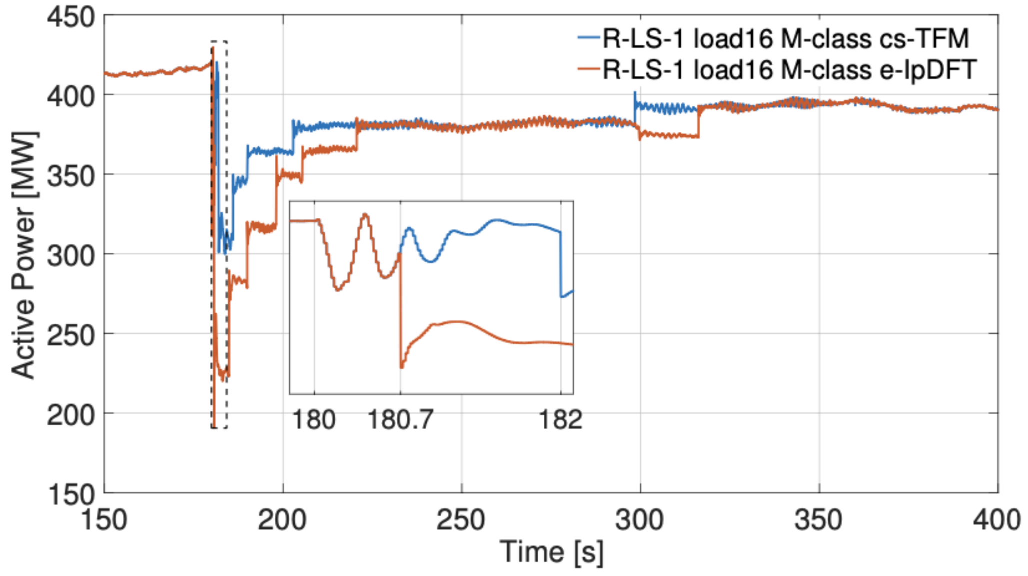

# Conclusions

**ROCOF measurements** prove to be **dependent on the time window and location**.

- typically, rolling windows of 500 ms

**ENTSO-E guidance**:

- frequency-vs-time profiles
- max withstand capability of $\pm 2$ Hz/s over 500 ms

**PMU-based measurements**:

- shorter windows → higher uncertainty
- different estimation techniques
- positive results in inter-area oscillations and under-frequency load shedding

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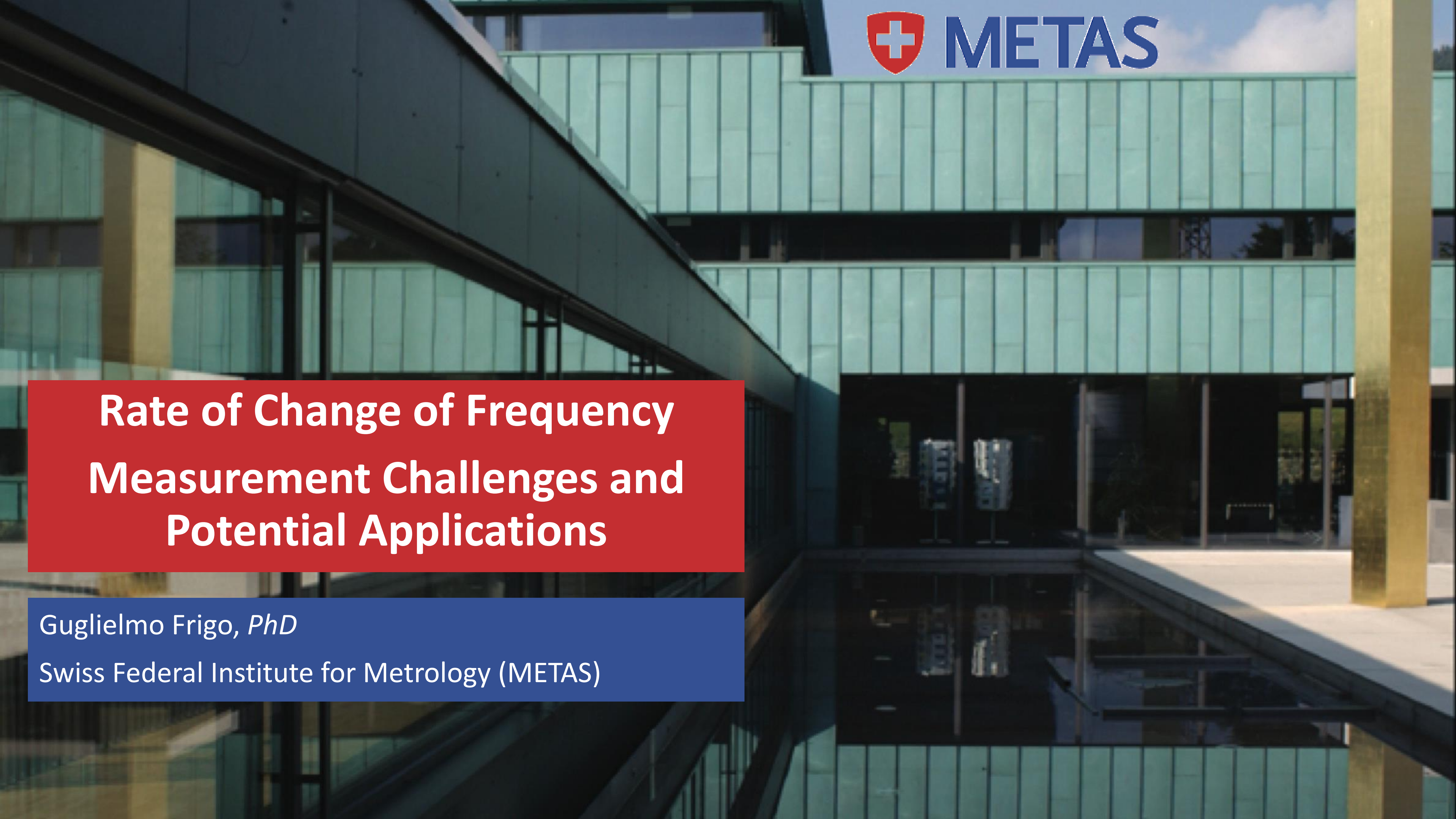

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# Rate of Change of Frequency Measurement Challenges and Potential Applications


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