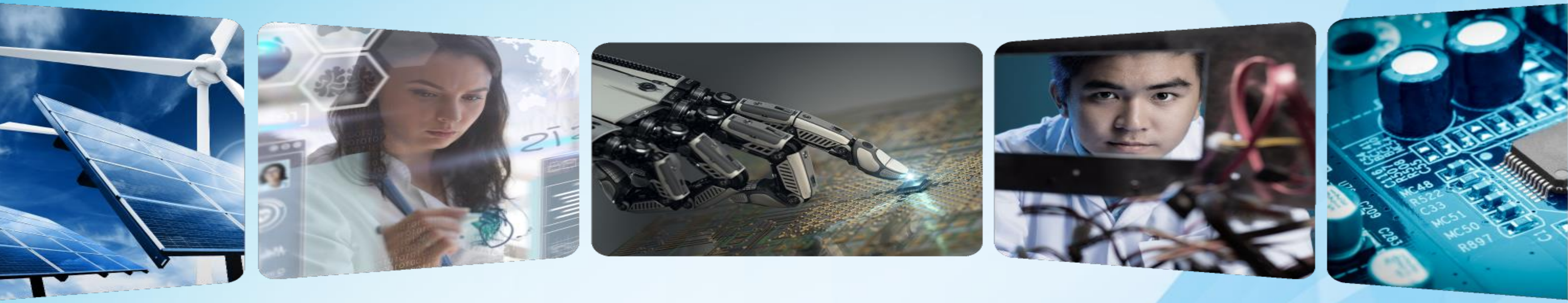

Wide Area Control of Distributed Resources through 5G Communication to Provide Frequency Support

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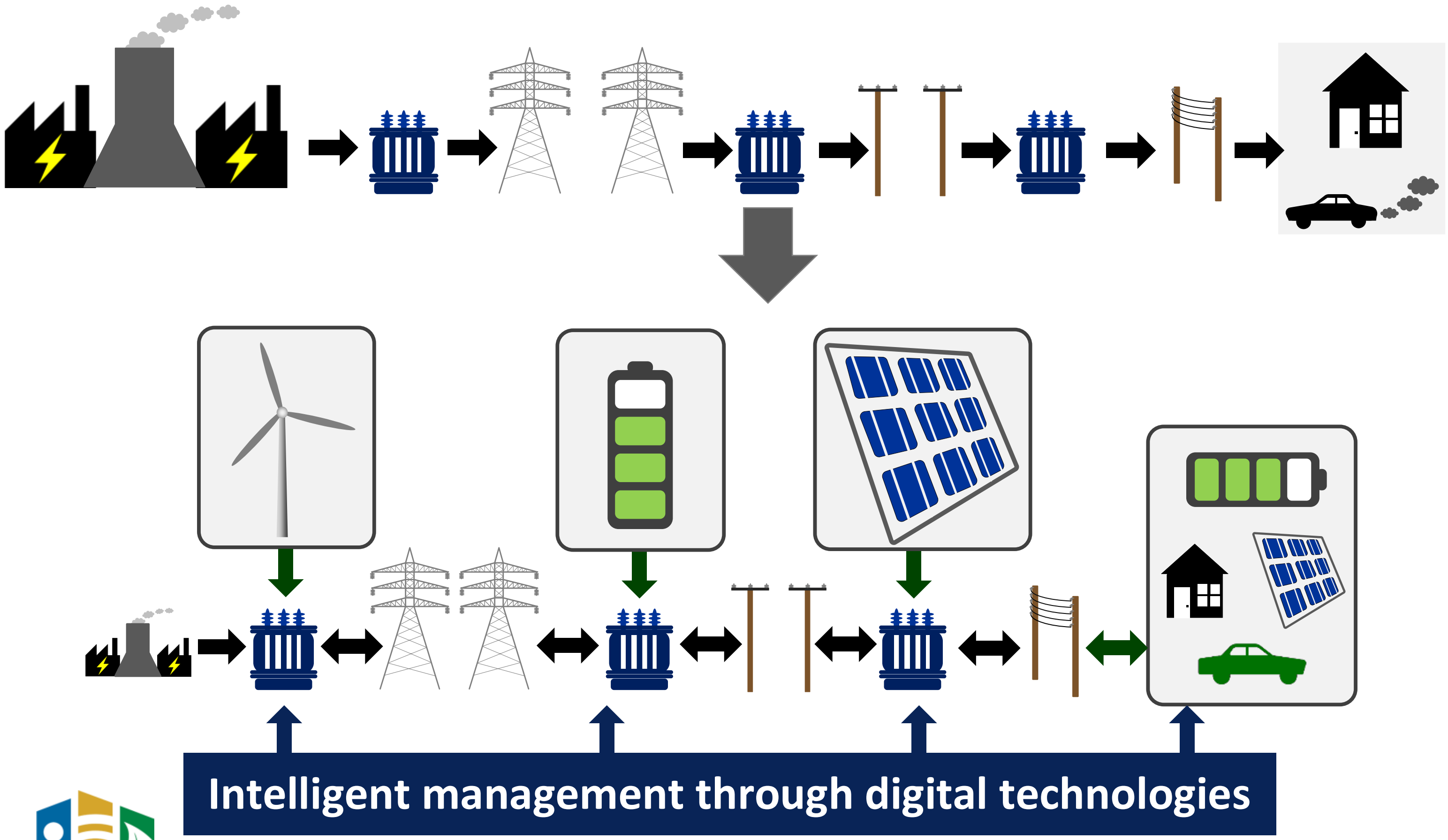
Outline

- Introduction
- Frequency response in power system
- Local frequency support schemes
- Proposed wide area control for fast frequency support through 5G
- Demonstration of use cases
- Conclusions

Introduction

Introduction

- Green, digital and intelligent evolution of electricity grids is a key priority



Introduction

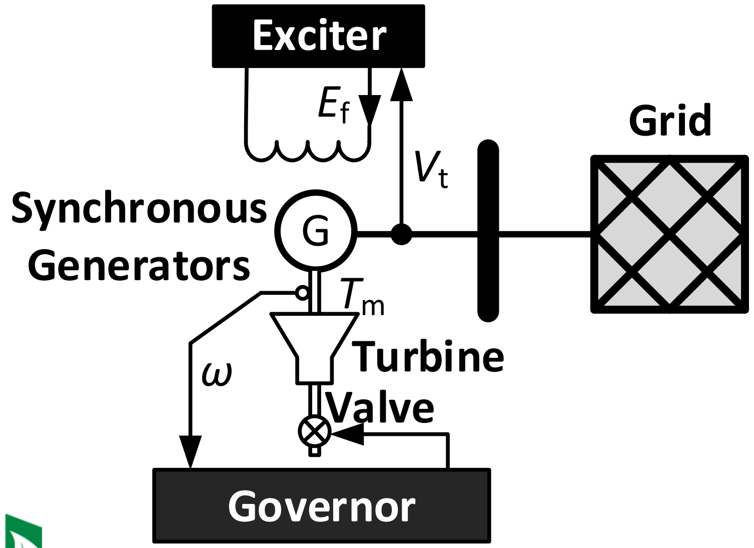
- **Challenges by the massive deployment of Distributed Energy Resources (DERs):**
  - Unpredicted nature of renewable energy resources → intense power imbalances
  - Inverter-based DERs are replacing the conventional generators → reduced inertia

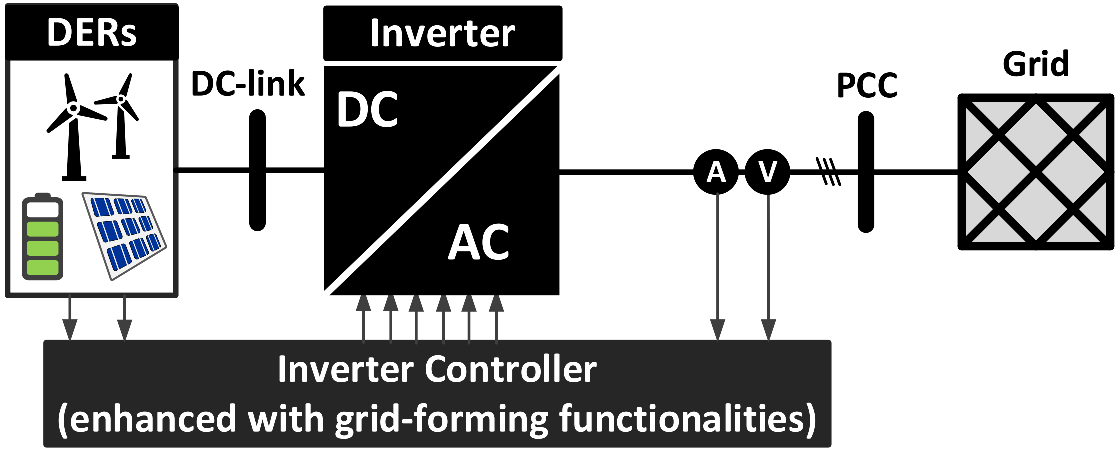
- **Inertia:** a key factor resisting against frequency deviations under a power imbalance

The frequency stability is threatened in modern power systems with low-inertia due to the high penetration of DERs

Introduction

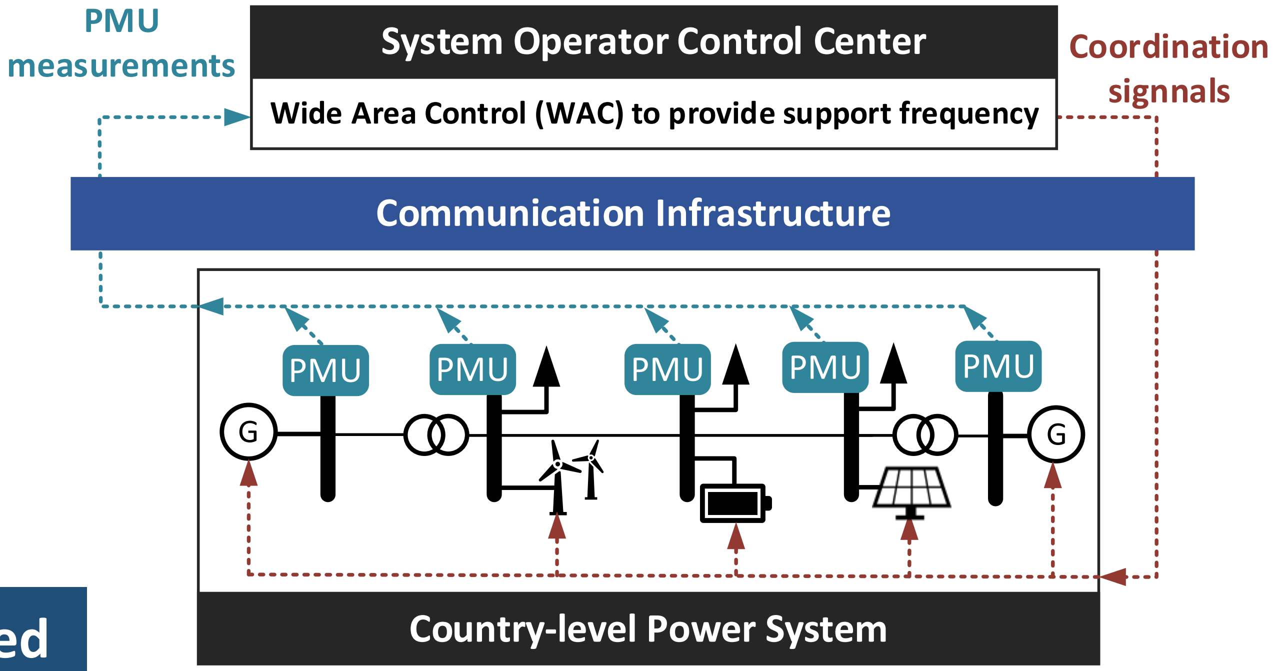
- **How to support the frequency stability?**
- **Local control schemes (no communication is needed)**
  - **Synchronous generators:** equipped with governor and automatic generation controllers
  - **Inverter-based DERs:** enhanced with grid forming functionalities (virtual inertia, droop)





Introduction

- **How to support the frequency stability?**
- **Wide Area Control (WAC) schemes (centralized controller at a country level)**
  - **Acquire measurements:** from Phasor Measurements Units (PMUs)
  - **WAC:** Process the measurements and generate control signals for support
  - **Control the flexible resources** (e.g., generators, DERs)



Fast and reliable wired communication is needed

Introduction

- **Contribution of this work:**
  - **Development of a Wide Area Control (WAC) scheme able to coordinate DERs over the 5G communication to support the frequency stability of the power system**
    - PMU data process to identify power imbalances and control DERs to support frequency
    - Data exchange over wireless communication (5G) allowing the wide deployment of WAC
  - **Development of an experimental Hardware In the Loop (HIL) setup to:**
    - Validate the effectiveness of the proposed WAC scheme under realistic environment
    - Performance investigation considering different controller (e.g., governor controller, DER local controller, WAC schemes) and different communication infrastructure (e.g., 5G, 4G, 3G)

Frequency Response in Power Systems

Frequency Response in Power Systems

Swing Equation

- The frequency response (*f*) of a power system is defined by its rotational speed (ω=2π*f*) which is determined by the swing equation:

$$\frac{2H}{\omega_s}\frac{d\omega}{dt} = P_m - P_e$$

where:

- H: is the normalized inertia constant of the rotational mass (generators) (in s)
- ω_s: is the synchronous speed of the system (in rad/s),
- P_m: is the mechanical power provided by the turbine (in pu),
- P_e: corresponds to the electrical load demand served by the generator (in pu).

Frequency Response in Power Systems

How a frequency event is initiate?

$$\frac{2H}{\omega_s}\frac{d\omega}{dt} = P_m - P_e$$

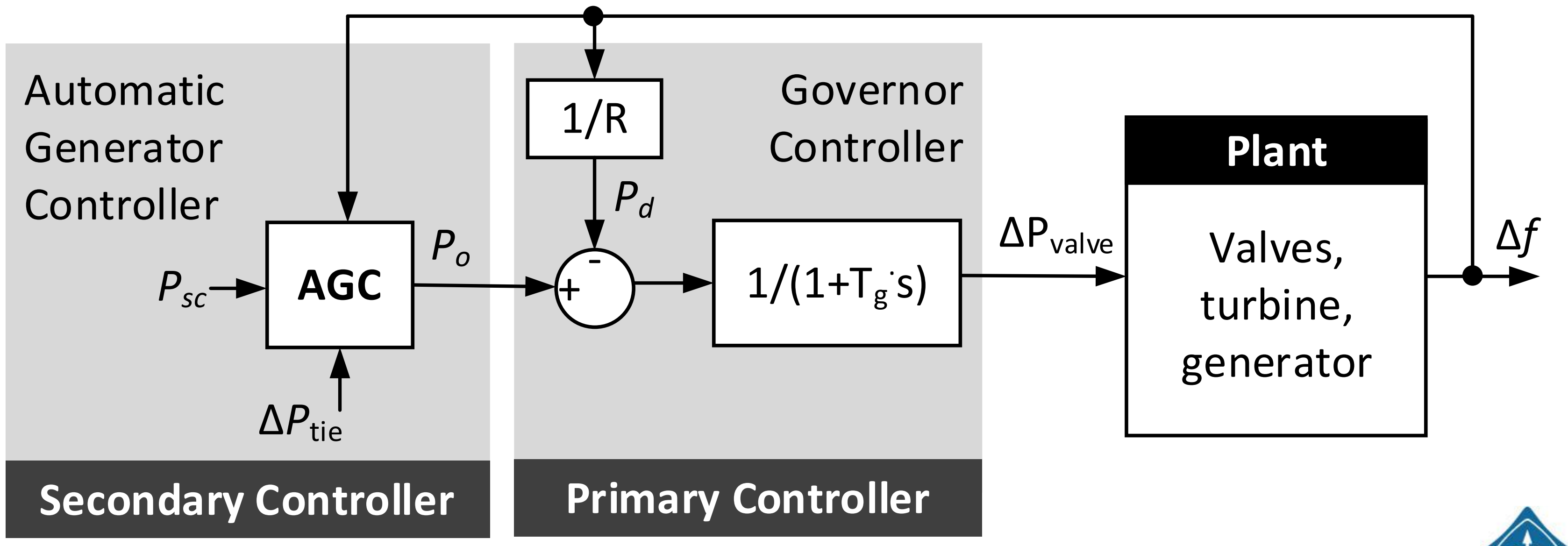
- **During steady state conditions:**
  - Power balance $(P_m = P_e) \rightarrow \frac{d\omega}{dt} = 0$ → frequency is constant at nominal value (50 Hz)
- **An under-frequency event can occur after an intense power imbalance:**
  - A loss of generator lead to power imbalance $(P_m < P_e) \rightarrow \frac{d\omega}{dt} < 0 \rightarrow$ frequency droop
- **Inertia (*H*) is a dominant factor that resists against frequency deviations** in the initial stage of an event (e.g., first 200 ms), since $\frac{d\omega}{dt} = \frac{\omega_s(P_m - P_e)}{2H}$

Local Frequency Support by Conventional Generators

Local Frequency Support Schemes

Frequency support by conventional generators

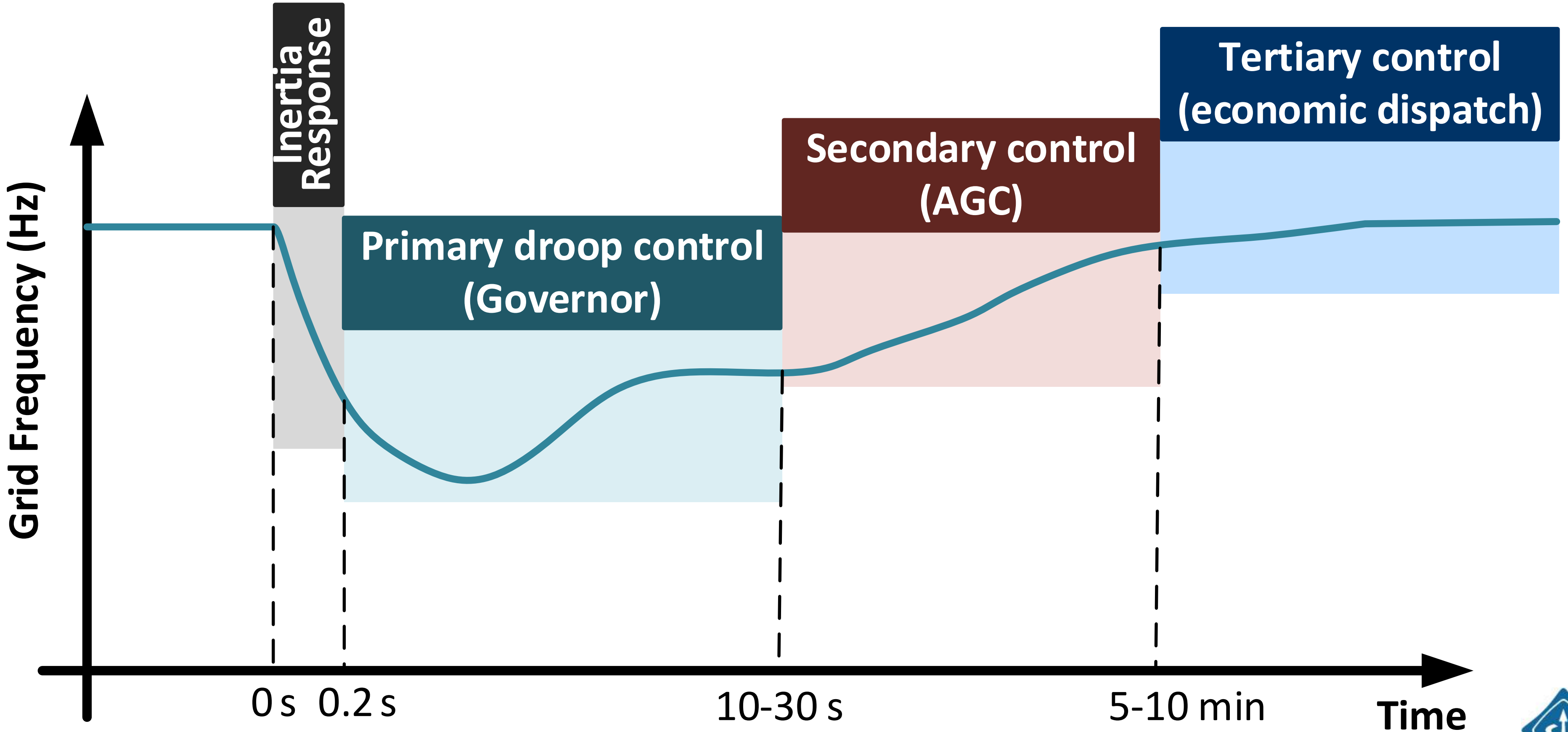
- In traditional power system, the frequency stability is maintained by the generators
  - **Primary control - Governor:** droop $\left(\frac{1}{R}\right)$ control approach (first-order transfer function)
  - **Secondary control - Automatic Generation Control (AGC):** based on integral controller



Local Frequency Support Schemes

Frequency support by conventional generators

- Inertia response and primary – secondary - tertiary control response



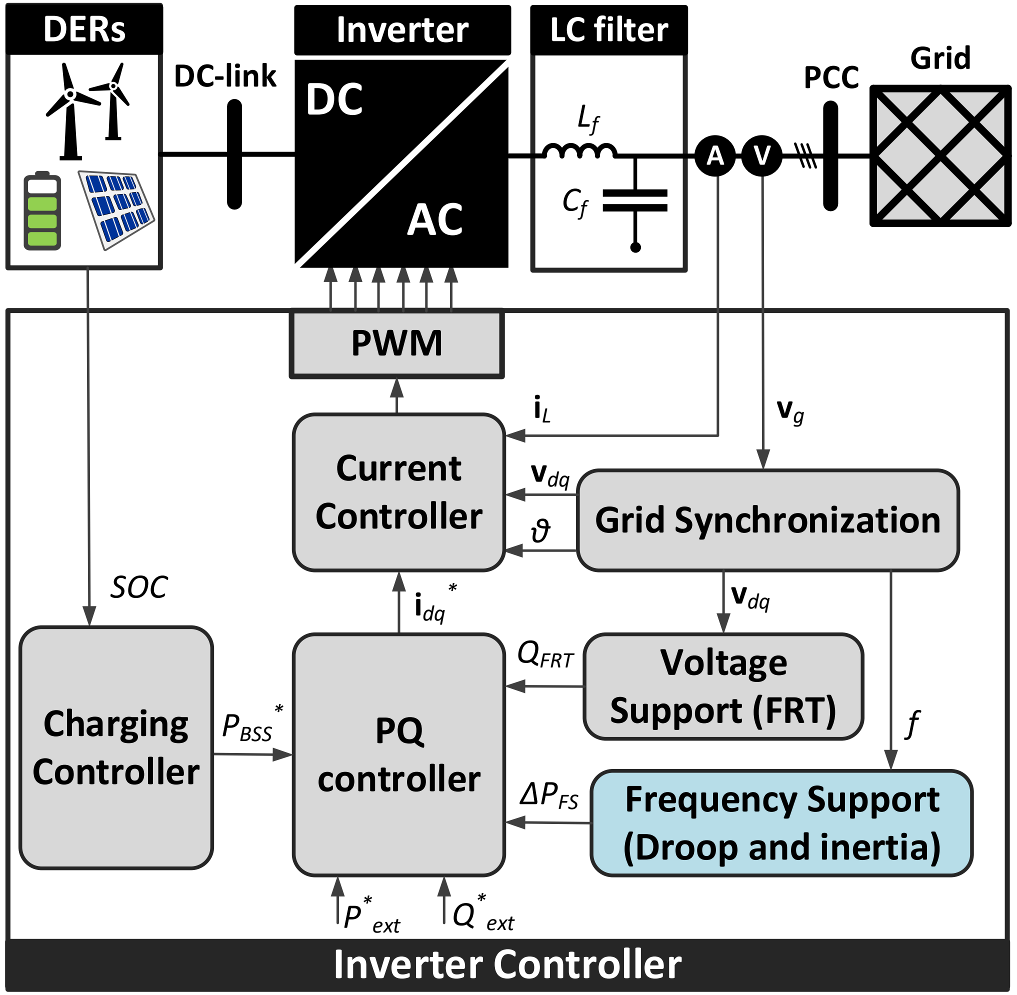
Local Frequency Support by Modern Distributed Resources

Local Frequency Support Schemes

Frequency support by inverter-based DERs

- DERs are replacing conventional generators
- Inverter-based DER should support frequency
- Grid-following → Grid-forming inverters
- Droop support and virtual inertia
  - $\Delta P_{FS} = k_f \cdot \Delta f + k_{vi} \cdot \frac{df}{dt}$

Droop | Virtual Inertia

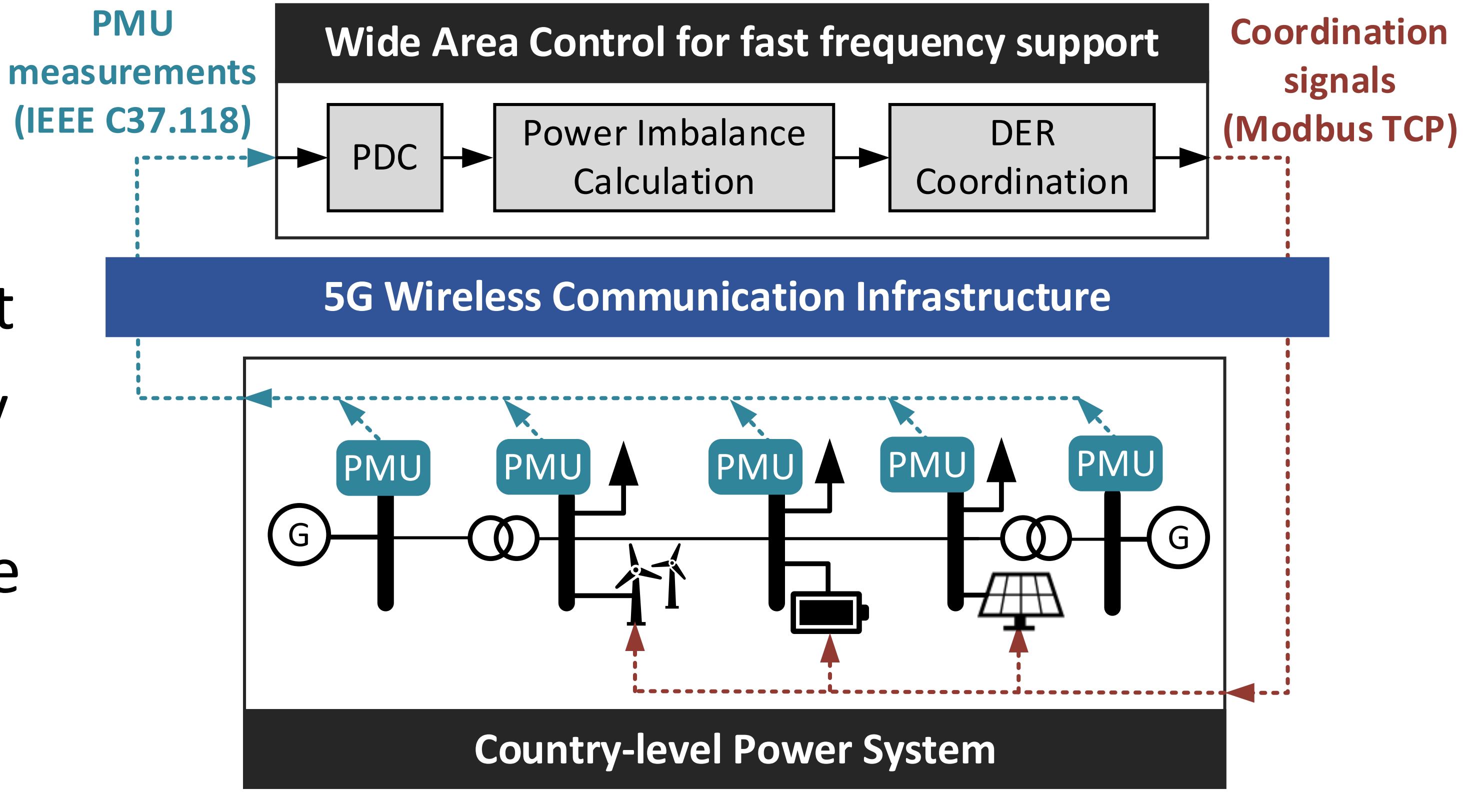


Wide Area Control for Fast Frequency Support

Proposed WAC for fast frequency support through 5G

Requirements

- PMUs in substations to report power injection measurements
- Flexible DERs able to provide fast upward and downward flexibility
- 5G communication infrastructure

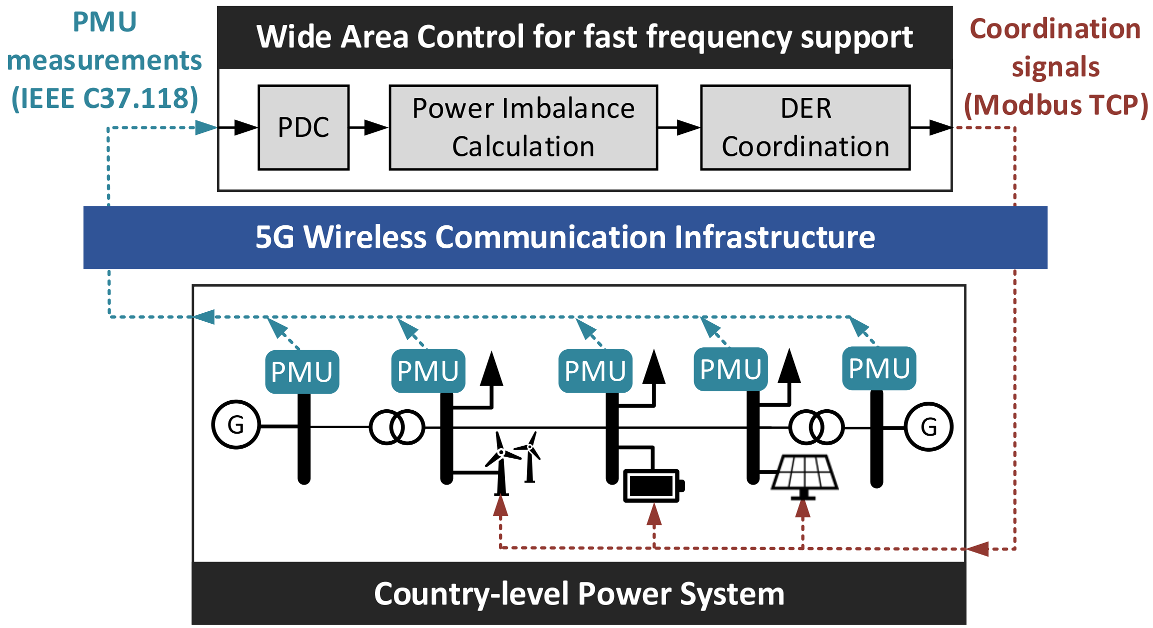


Proposed WAC for fast frequency support through 5G

WAC controller

- **Step 1: Phasor Data Concentrator (PDC)**

- Received and time-aligned PMU measurements for the power injection at each bus (substation)



Proposed WAC for fast frequency support through 5G

WAC controller

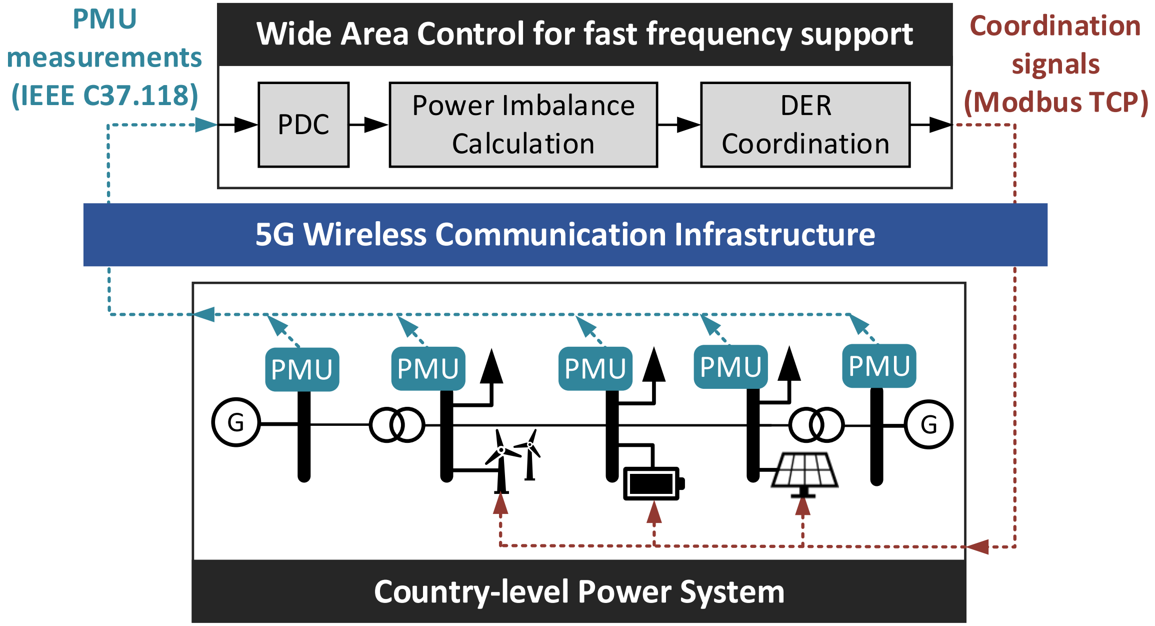
- **Step 2: WAC activation and power imbalance calculation**

A. Net power calculation at time *t*

$$P_{net}^{t} = \sum_{i \in \mathcal{B}^G} P_i^t - \sum_{j \in \mathcal{B}^L} P_j^t - \sum_{k \in DERs} P_k^t$$

Gene-ration | **Demand** | **DERs**

Power injection PMU measurements



B. Power imbalance identified at *time t*

$$\Delta P_i^t = P_{net}^t - P_{net}^{t-1}$$

Proposed WAC for fast frequency support through 5G

WAC controller

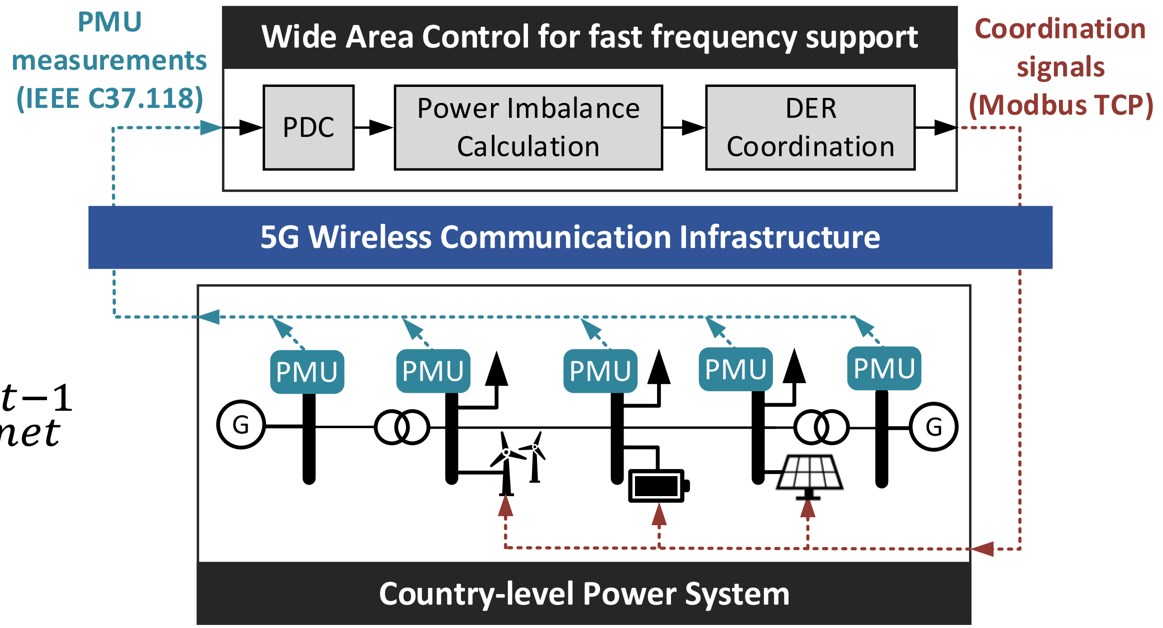
- **Step 2: WAC activation and power imbalance calculation**

C. WAC activation

If $\Delta P_i^t > \Delta P_{threshold}$ then

WAC is activated

Store before the fault net power: $P_{bf} = P_{net}^{t-1}$



D. Total power imbalance for the event

$$\Delta P_i = max\left(\left|P_{net}^t - P_{bf}\right|, |\Delta P_i|\right)$$

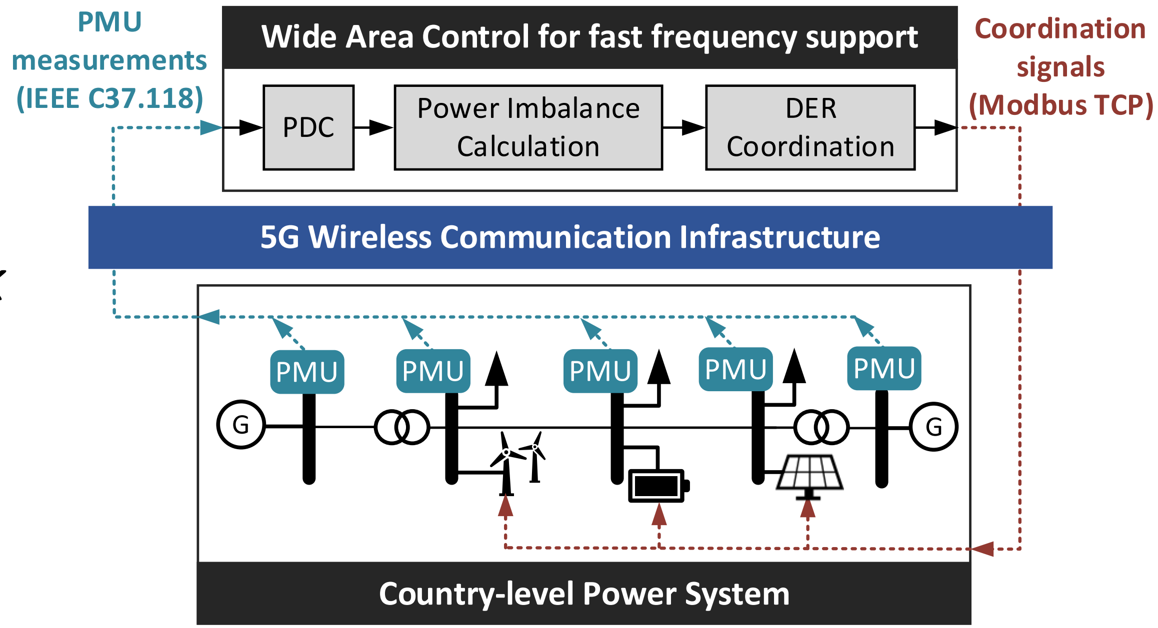
Proposed WAC for fast frequency support through 5G

WAC controller

- **Step 3: DERs coordination**
- ΔP_i should be proactively compensated by DERs to prevent an intense frequency event
- Allocation of coordination signals to each DER *k*

$$\Delta P_k^{t*} = \frac{\bar{P}_k^t}{\sum_{k \in DERs} \bar{P}_k^t} \Delta P_i$$

where $\bar{P}_k^t$ is the upward availability of DER *k*

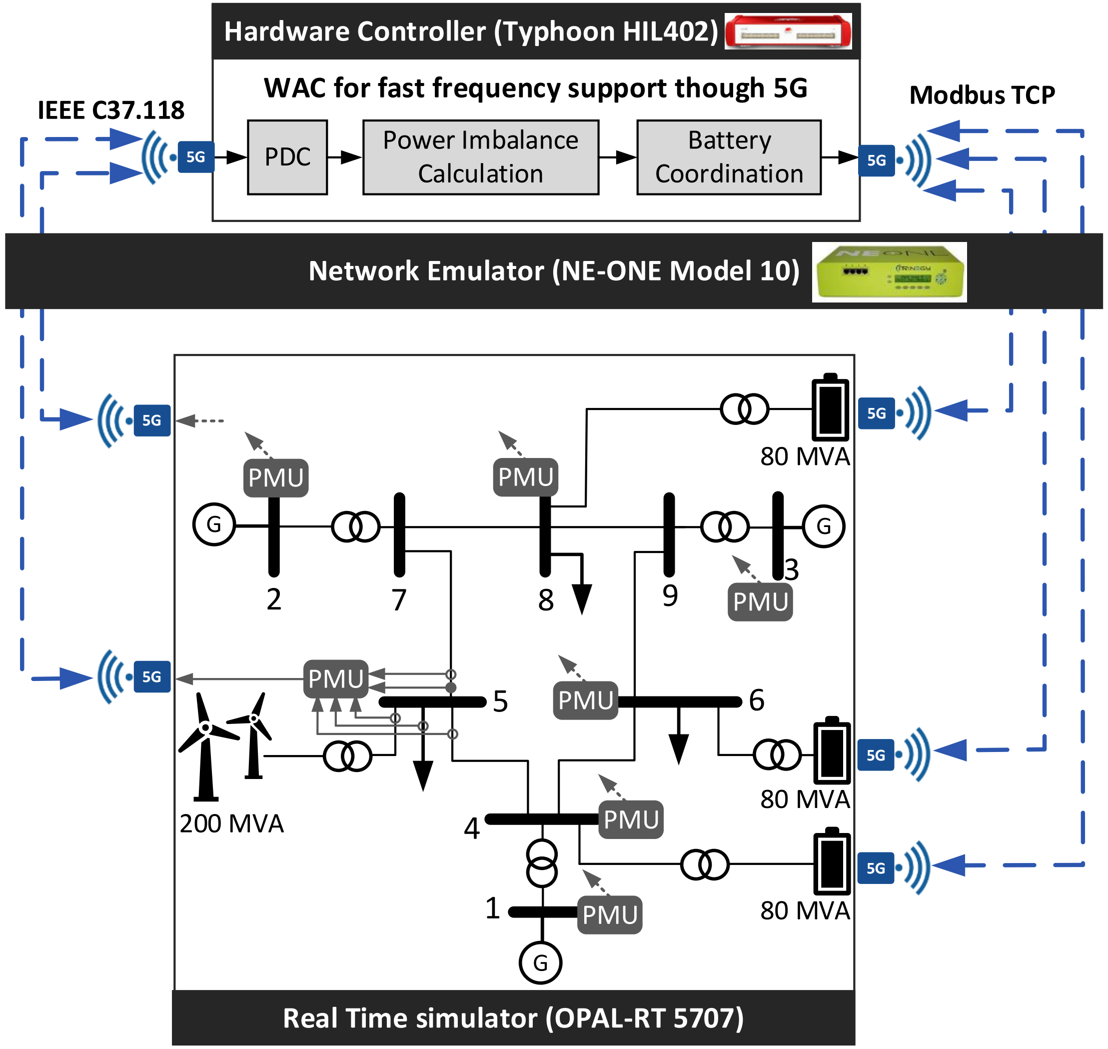


Demonstration of Use Cases

Demonstration of Use Cases

Hardware In the Loop (HIL) experimental setup

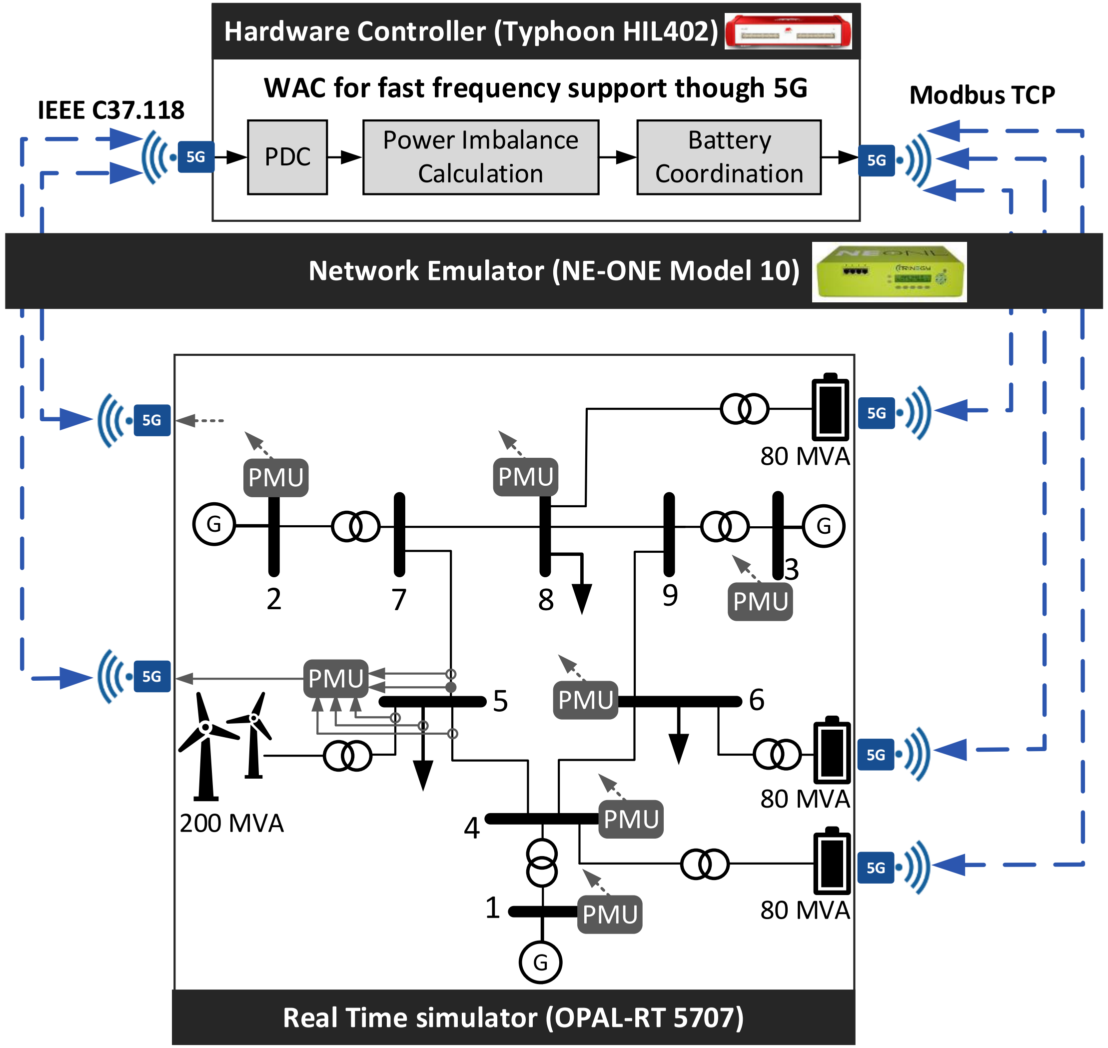
- **Power system real-time digital twin**
  - Simulink model in a real time simulator
  - Dynamic and discrete-time IEEE 9-bus model
  - 640 MVA synchronous generators
  - 240 MVA flexible DERs (battery storage)



Demonstration of Use Cases

Hardware In the Loop (HIL) experimental setup

- **Proposed Wide Area Controller (WAC)**
  - Digitally implemented in a Typhoon hardware controller due to hard real time constrains
  - PMU measurements using IEEE C37.118
  - Coordination signals using Modbus TCP
- **Network Emulation**
  - A hardware network emulator is used to replicate the performance of different communication infrastructure (e.g., 5G, 4G, 3G)



Demonstration of Use Cases

Scenarios

1. No support by DER (baseline)
2. DER with droop and virtual inertia
3. WAC-FFR with 3G (100ms)
4. WAC-FFR with 4G (20<delay<50ms)
5. WAC-FFR with 5G (3ms<delay<10ms)
6. WAC-FFR with ideal communication

Key Performance Indicators (KPIs)

- Minimum frequency or frequency nadir (f_{nadir})
- Average Rate of Change of Frequency for the first 0.5 s ($ROCOF_{0.5s}$)

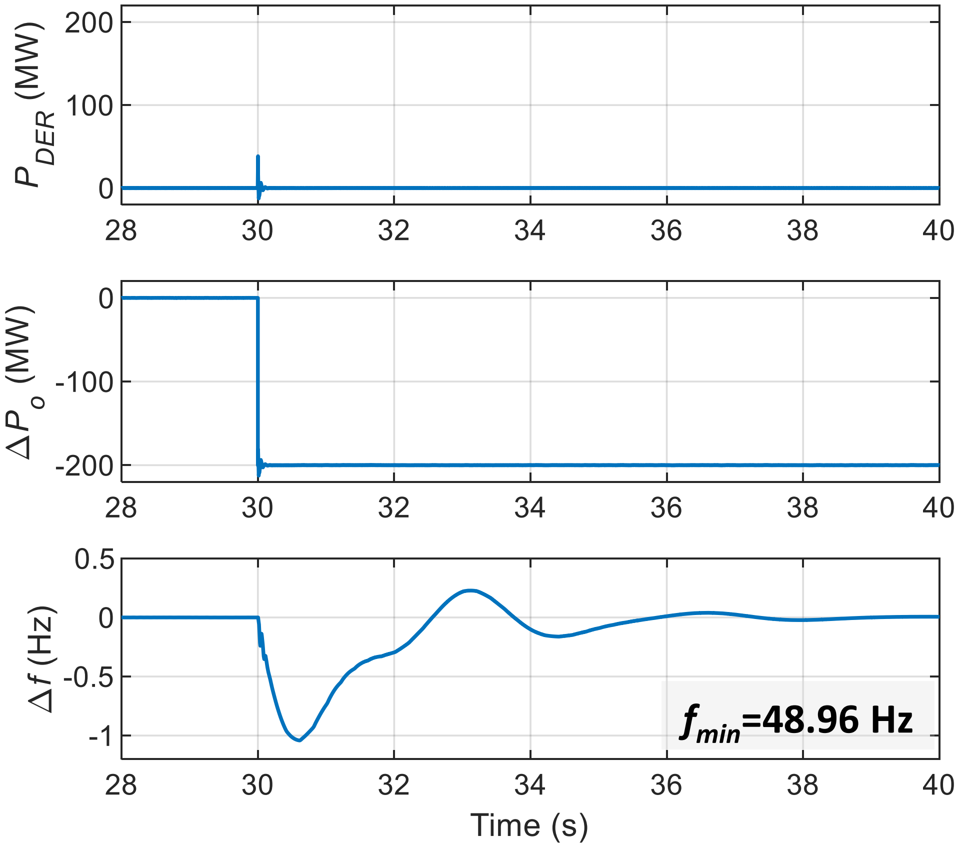
Power Disturbance

- Loss of 200 MW at *t*=30 s in all the scenarios

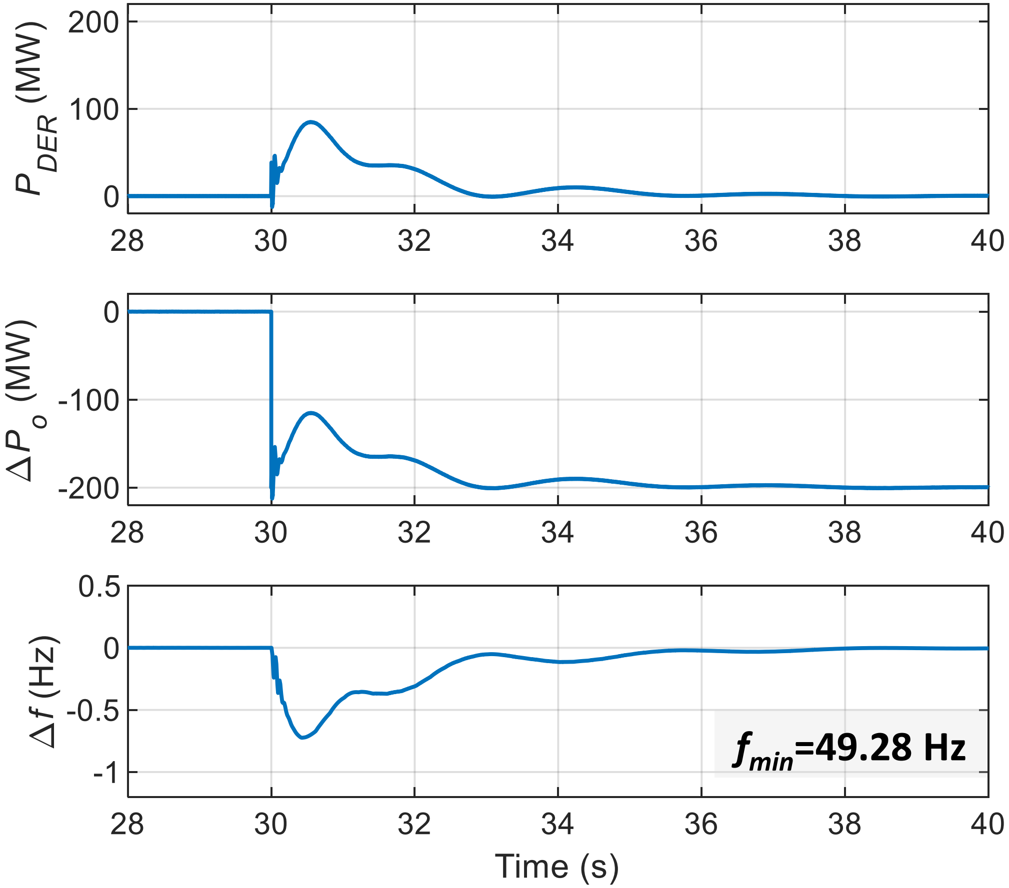
Demonstration of Use Cases

Results with local control schemes

1. No support by DERs



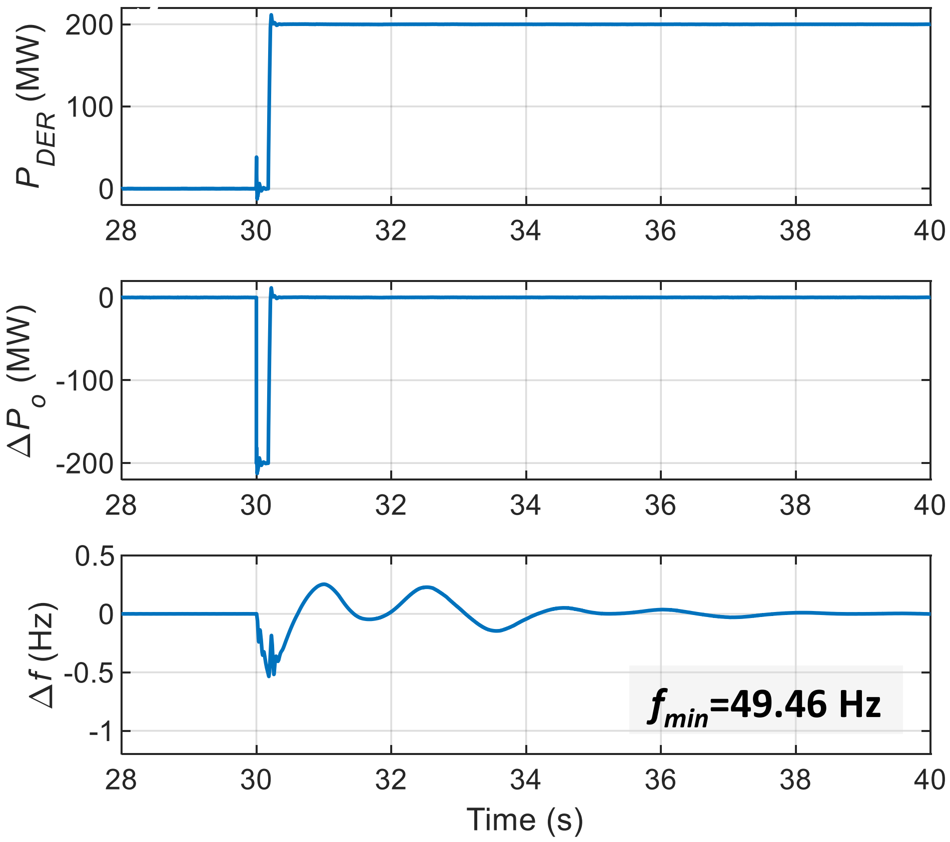
2. DERs with droop and inertia



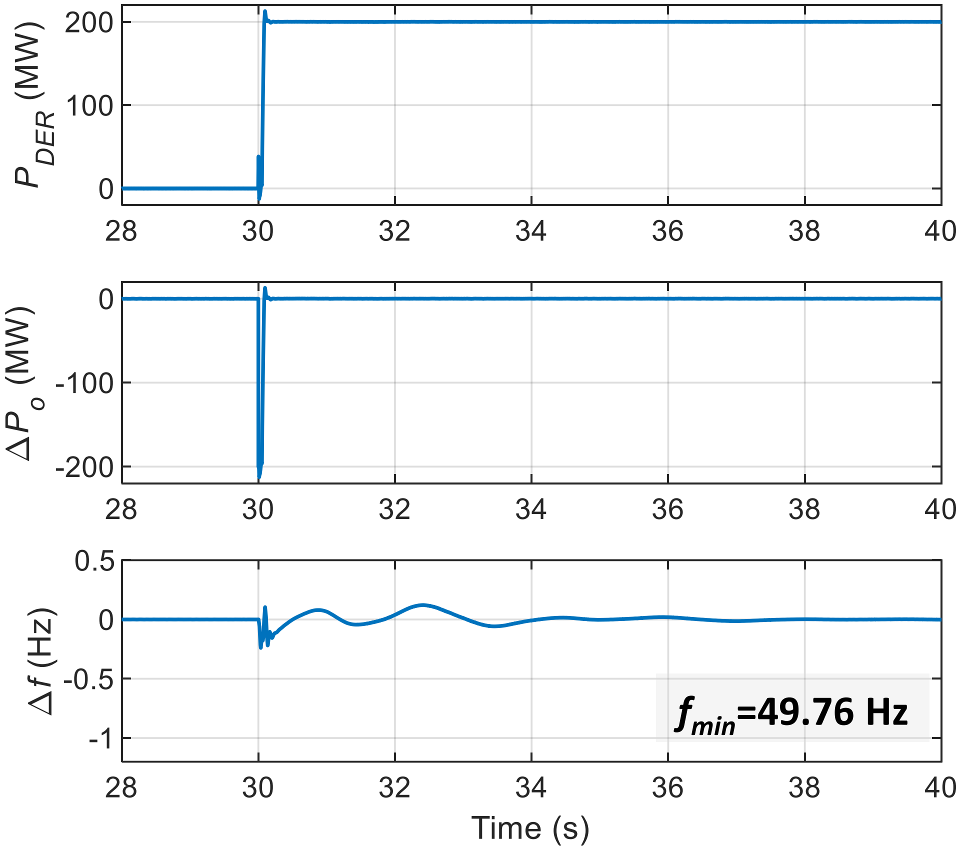
Demonstration of Use Cases

Results with WAC scheme

4. WAC with 4G communication



5. WAC with 5G communication

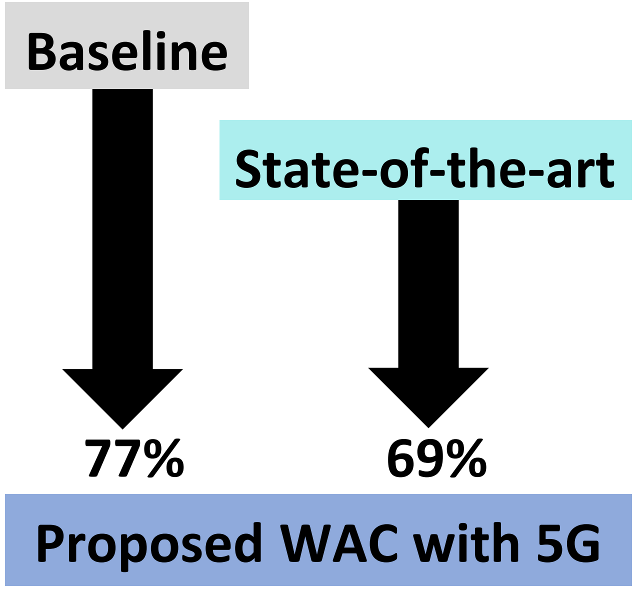


Demonstration of Use Cases

Benchmarking

Scenario	f_{nadir} (Hz)	$ROCOF_{0.5s}$ (Hz/s)
No support by DER (baseline)	48.96	2.01
DERs with droop and virtual inertia	49.28	1.43
WAC for frequency support with 3G (100 ms)	49.22	0.75
WAC for frequency support with 4G (50 ms)	49.46	0.28
WAC for frequency support with 5G (10 ms)	49.76	0.03
WAC for frequency support with ideal comm.	49.80	0.08

Frequency stability improvement



Conclusions

Conclusions

- **The proposed WAC for coordinating the fast frequency support by DERs through 5G communication can significantly enhance the system frequency stability**
- **WAC with fast and reliable communication can improve the system stability compared to local control schemes applied in synchronous generators and/or DERs**
- **Benchmarking of the system stability considering different communication response:**
  - 3G is inadequate for such WAC schemes and 4G can only provide marginal improvement
  - Significant improvement can be achieved when 5G communication is used
- **Advanced feature of 5G technology can initiate novel applications for smart grids**

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