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Field Deployment and Demonstration of an Adaptive Wide-Area Oscillation Damping Controller at the Italian Power Grid

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Team:
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3. Terna: Guido Coletta, Silverio Casulli, Salvatore Tessitore, Cosimo Pisani, Giorgio Giannuzzi
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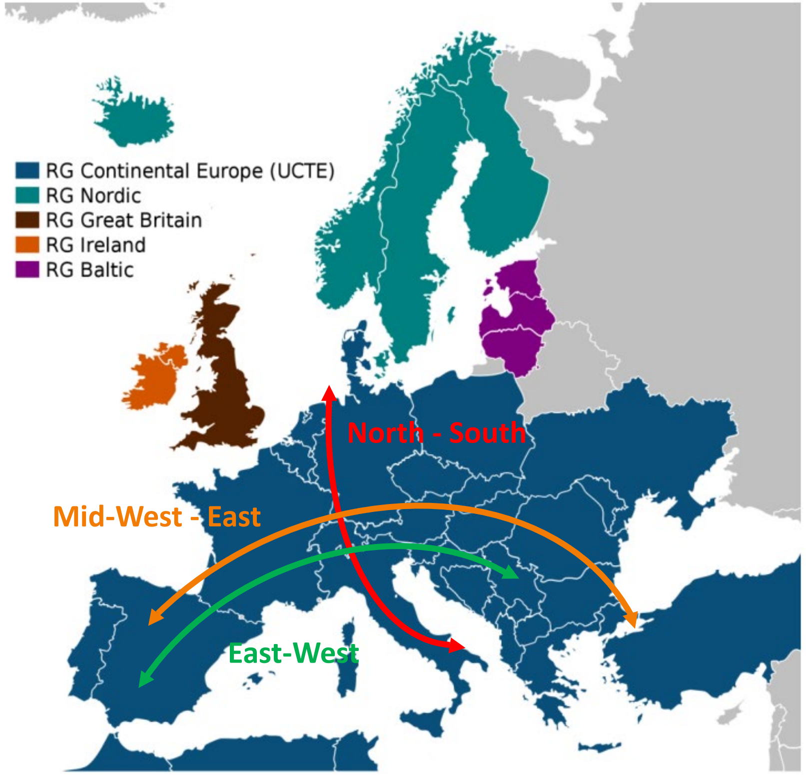
NASPI Work Group Meeting
Apr 15, 2025 - Apr 16, 2025
Minneapolis, Minnesota

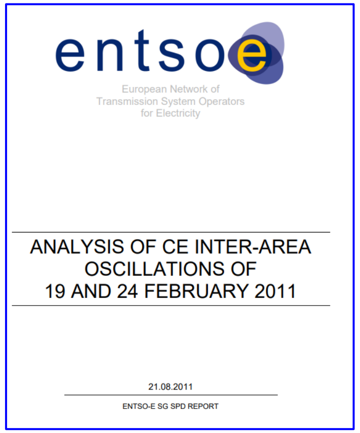
Background and Motivations

- The European power grid experiences **oscillations in generator speed**, leading to **frequency fluctuations**.
- Dominant modes in Continental Europe system
  - North – South Mode: 0.25 Hz - 0.30 Hz
  - East – West Mode: 0.15 Hz - 0.21 Hz
    - Mid-West-East Mode: Sub-mode of the East-West mode
- The **largest frequency oscillations** occur at the **edges of the system**, while **power variations** are strongest at the **center** of the grid.
- The **expansion of electrical grids** increases the distance between system edges, amplifying oscillations.
- These oscillations are constantly excited by **small fluctuations in demand and generation**, which disrupt the balance between supply and consumption.

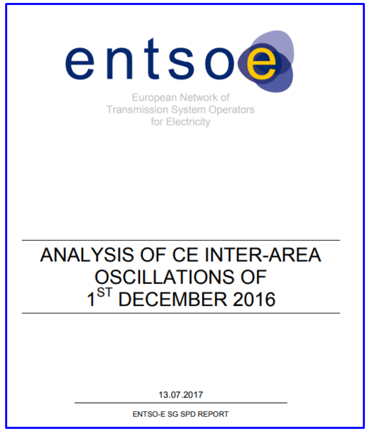


Background and Motivations

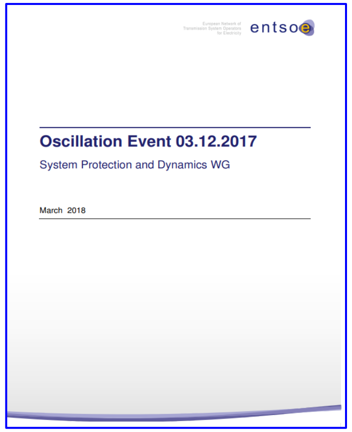
- The **reduction in system inertia** due to the growth of **inverter-based generation** weakens the grid, deteriorates voltage control, and reduces the stabilizing effect of synchronous generators.
- PSS optimization itself cannot be sufficient in case of large angle displacements
  - Losing PSS when retiring conventional synchronous generators
  - Critical PSSs may be offline when synchronous generators are not in service in light-loading condition
- In recent years, **oscillatory events have increased** across Europe and worldwide due to **the rapid transformation of power systems**.


entsoe
European Network of Transmission System Operators for Electricity
ANALYSIS OF CE INTER-AREA OSCILLATIONS OF 19 AND 24 FEBRUARY 2011
21.08.2011
ENTSO-E SG SPD REPORT

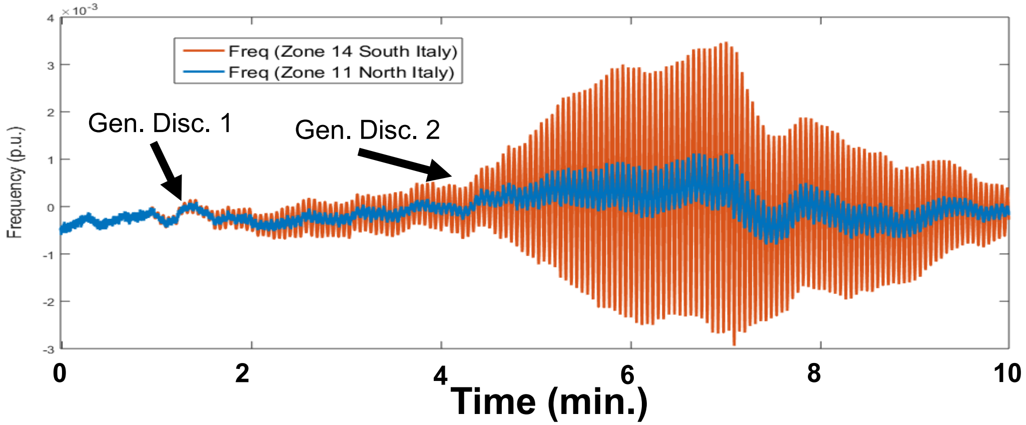
Feb. 19 and 24, 2011: 0.25 Hz + 0.18 Hz


entsoe
European Network of Transmission System Operators for Electricity
ANALYSIS OF CE INTER-AREA OSCILLATIONS OF 1ST DECEMBER 2016
13.07.2017
ENTSO-E SG SPD REPORT

Dec. 1, 2016: 0.15 Hz


entsoe
Oscillation Event 03.12.2017
System Protection and Dynamics WG
March 2018

Dec. 3, 2017: 0.29 Hz



Dec. 3, 2017 Continental Europe Oscillation Event
(Triggered by two consecutive generation disconnections due to regular market operation)

EPRI

Project Overview and Timeline

June 2017: Phase I (Offline simulations) started

Phase I

- Replicated December 3, 2017 oscillation event
- WADC performance verification under the replicated December 3, 2017 oscillation by offline simulation

September 2019: Phase II (Hardware-in-the-loop implementation and testing) started

Phase II

- Implemented WADC as an openHistorian adaptor and Graphical User Interface (GUI)
- Tested the WADC with enhanced PMU in Hardware-In-the-Loop (HIL)

- Converted Terna grid model into OPAL-RT ePHASORSIM format for real-time simulation
- Implemented WADC on a generic purpose hardware platform (NI's CompactRIO)
- Tested the WADC under communication uncertainties

January 2022: Phase III (Field deployment and testing) started

Phase III

April 2022:
- WADC field deployment
- Field testing with synchronous condenser at one substation

October 2022:
- Technology transferred to GPA for production grade tool development

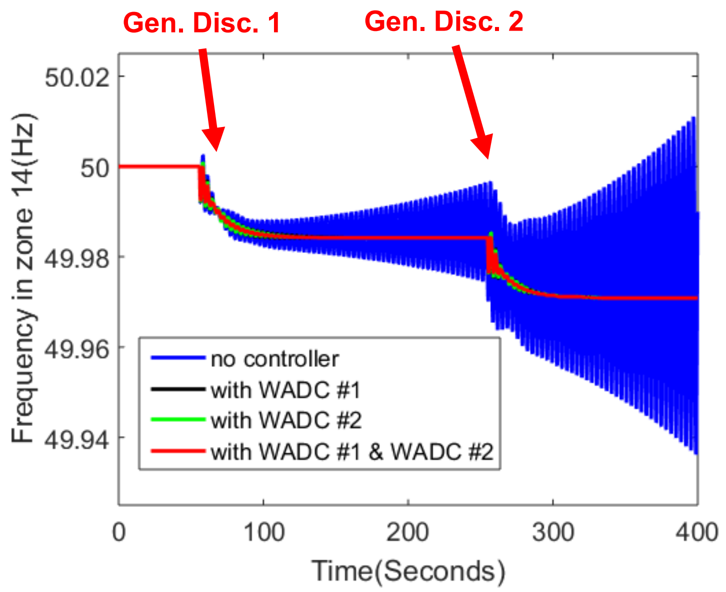
June 2023:
- Field testing with synchronous condenser at the second substation

March 2024:
- Significant update to meet Terna's requirements on WAMPAC tool
- Online closed-loop operation in routine grid operation: Trial

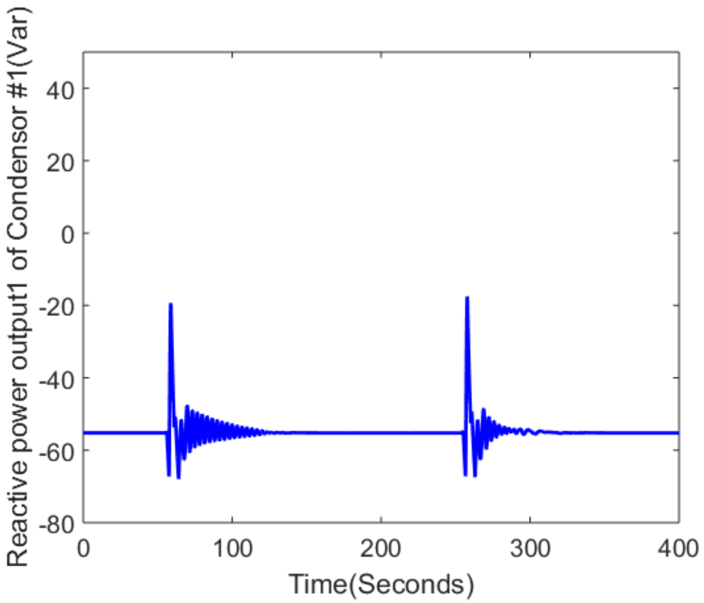
February 2025:
- WADC upgrade to handle multiple actuators and add system identification function
- Field testing with multiple actuators and adaptive capability

Phase I: WADC Performance Demonstration by Simulations

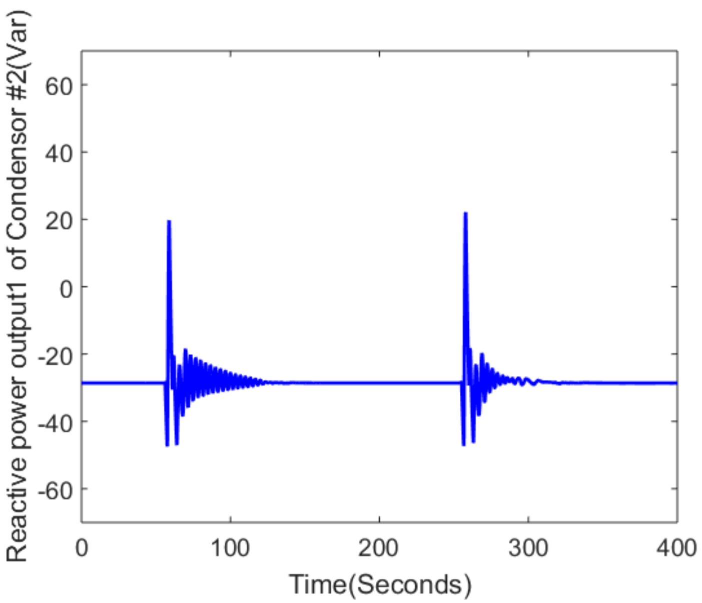
- 2k+ bus Italian grid model in PSS/e (Converted from PowerFactory)
- Replicated December 3, 2017 oscillation event (0.293 Hz)
- Observation signal: Bus frequency in South Italy
- WADC @ synchronous condenser #1 & #2 in South Italy



Frequency response in South Italy



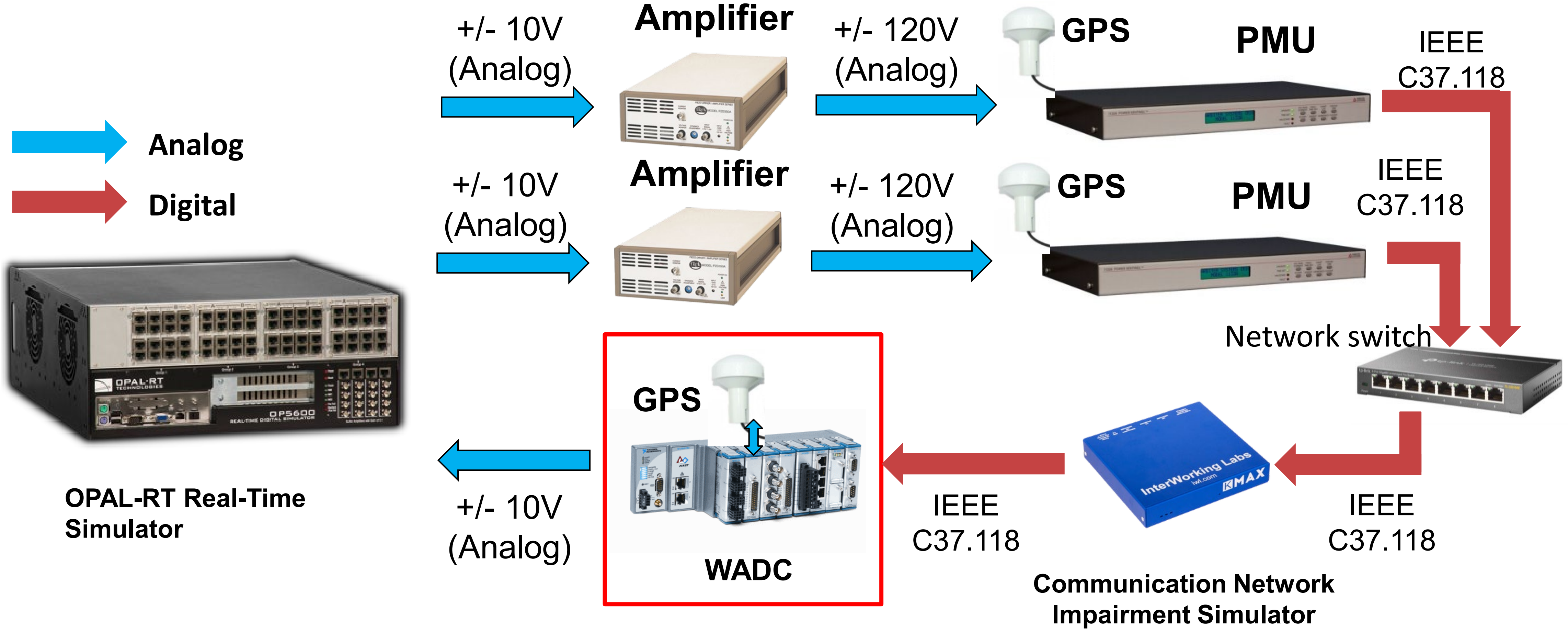
Condenser #1 reactive power output



Condenser #2 reactive power output

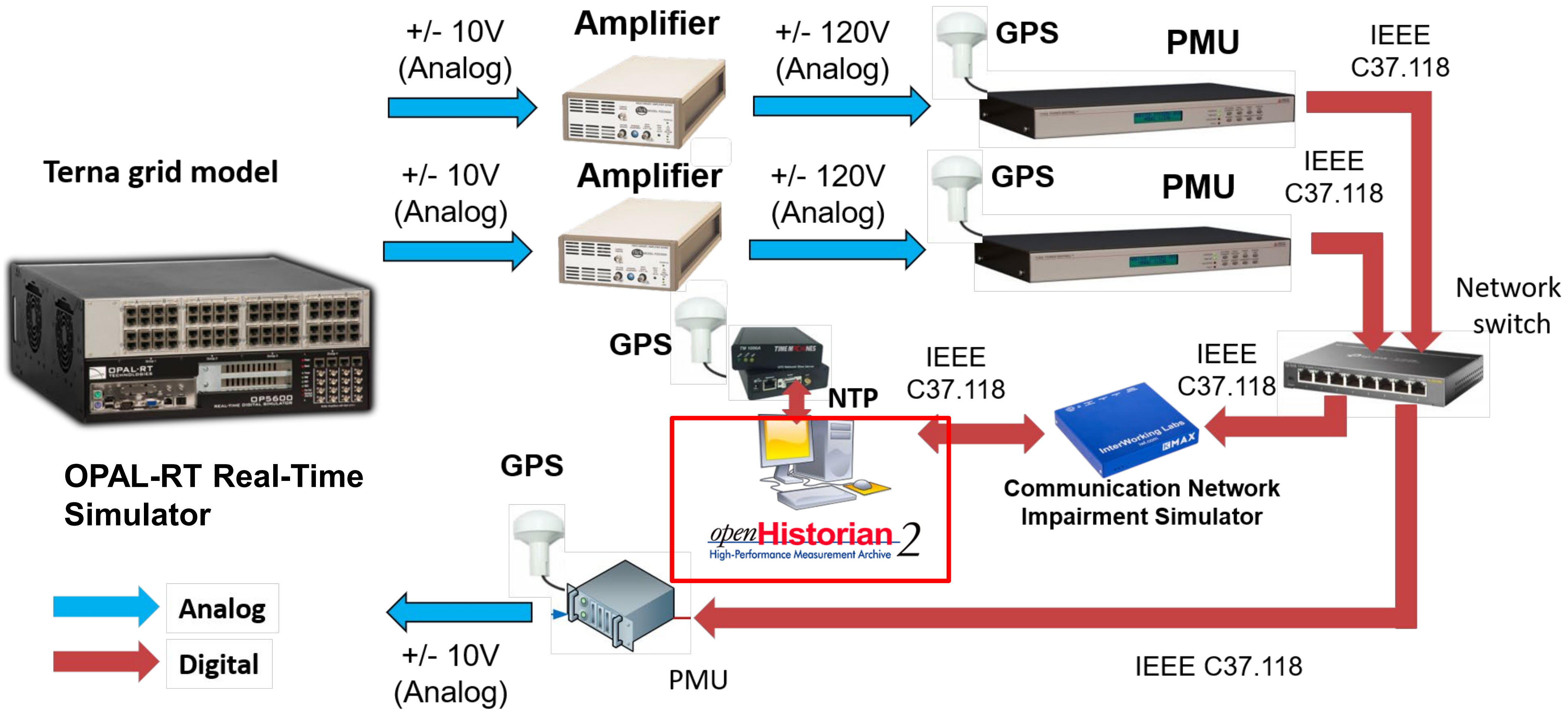
Phase II: HIL Implementation and Testing (Hardware Controller)

- TERNA grid modeled in OPAL-RT ePHASORSIM
- WADC implemented on generic purpose hardware platform – National Instruments' CompactRIO



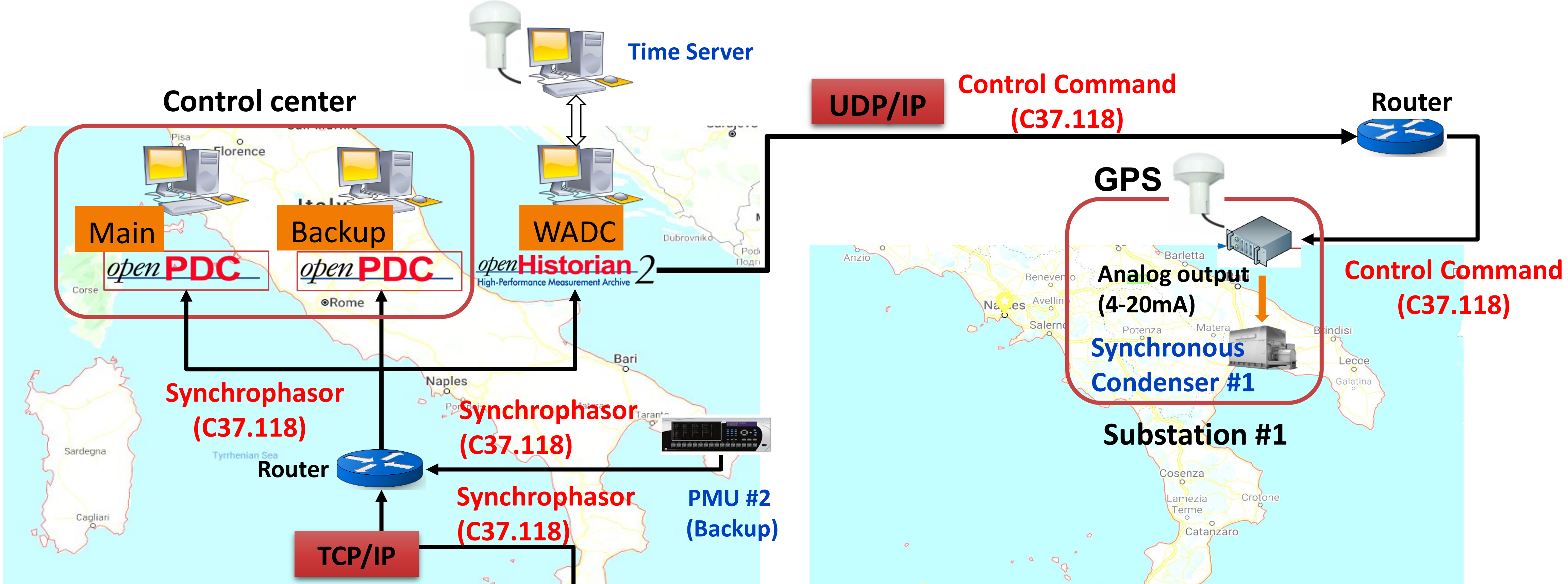
Phase II: HIL Implementation and Testing (Software Controller)

- WADC implemented as openHistorian adaptors and GUI for field deployment
- Replicated field setup in the lab with OPAL-RT and enhanced PMU in HIL



Phase III: Field Deployment and Testing

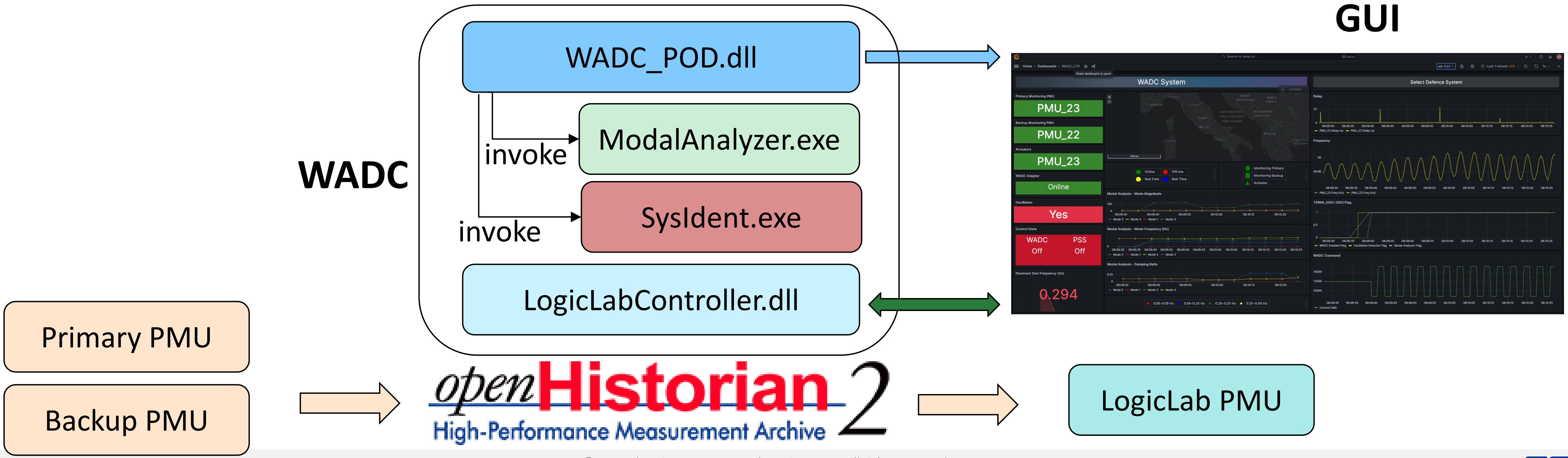
- WADC field deployed at Terna control center and substation



- Input: Frequency of two selected PMUs
- WADC: openHistorian adaptors and Grafana GUI
- Actuator: Synchronous condenser(s)
- Communication: IEEE C37.118

WADC System Architecture

- WADC_POD.dll: WADC control functions
  - ModalAnalyzer.exe: Perform modal analysis and identify dominant oscillation mode using ambient data, invoked by WADCAdaptor.dll every ~25 seconds
  - SysIdent.exe: Periodically inject a probing signal to voltage set point (within +/- 0.04 p.u.), and use the probing signal and frequency response to develop a transfer function and evaluate the need to update WADC parameters
- LogicLabController.dll: Communication functions with enhanced PMU in substation
- Grafana GUI: For visualization



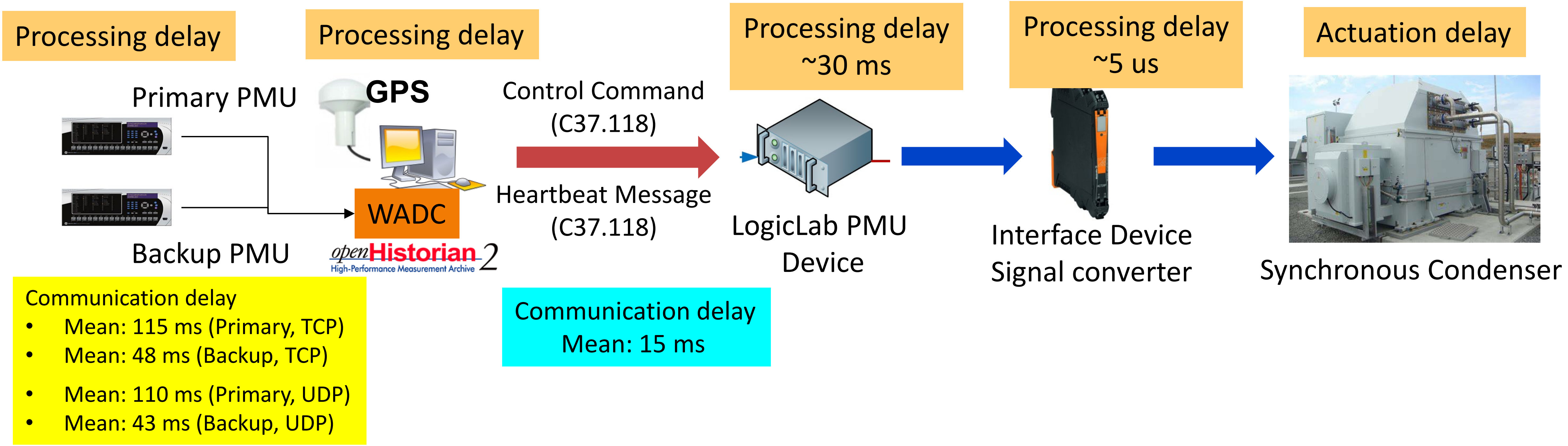
Phase III: Field Deployment and Testing

- Field testing with synchronous condenser at one substation
- Multiple test scenarios

	Test Scenario	Test Objective
1	Communication	• Verify if communication channels are available and functional
2	Control Loop Software, Hardware and Communication Test	• Check functionality of software/hardware • Measure delay and data loss of communication channels
3	Exciter Response Test and Logic	• Check if condenser can follow WADC commands • Test condenser's response if loss of WADC control command
4	WADC Parameter Tuning and Verification	• Open-loop test for WADC parameters tuning • Open-loop and closed-loop tests for WADC parameters verification
5	Test WADC under Large Disturbances in Closed-loop	• Test damping performance of WADC under large disturbances
6	WADC Long-Term Operation in Open-Loop	• Test continuous operation of WADC

Communication Delay and Data Loss

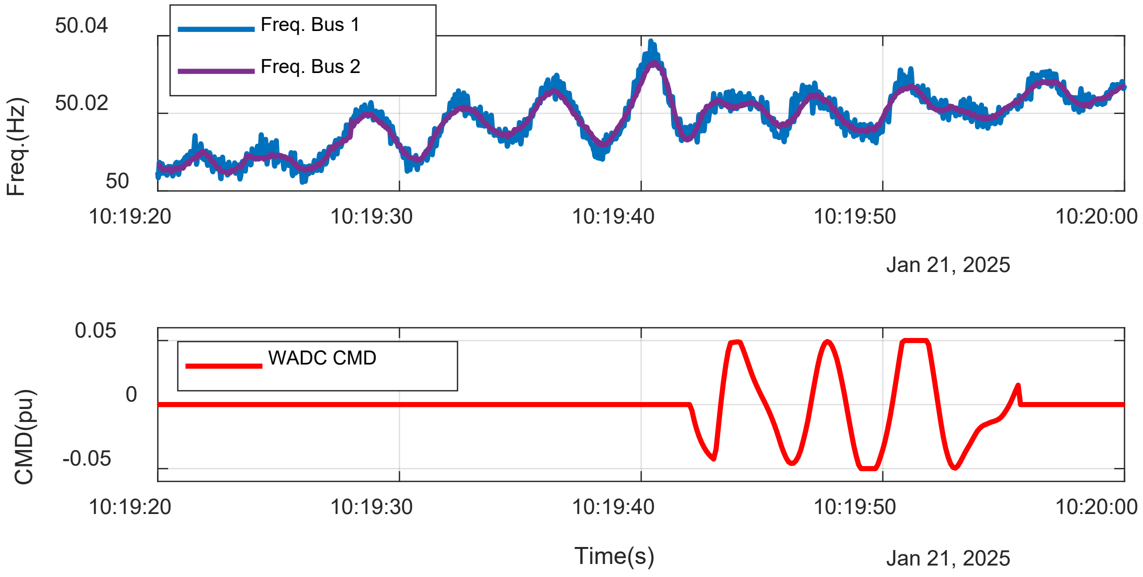
- Entire control loop delay: ~250 ms mean (Primary) / ~192 ms mean (Backup)
  - Communication delay (PMUs to openHistorian): 115 ms/48 ms mean (TCP), 110 ms/43 ms mean (UDP)
  - Communication delay (openHistorian to LogicLAB PMU): 15 ms mean
  - Processing/Actuation delay: ~130 ms mean
- TCP/IP has way much less data loss than UDP/IP

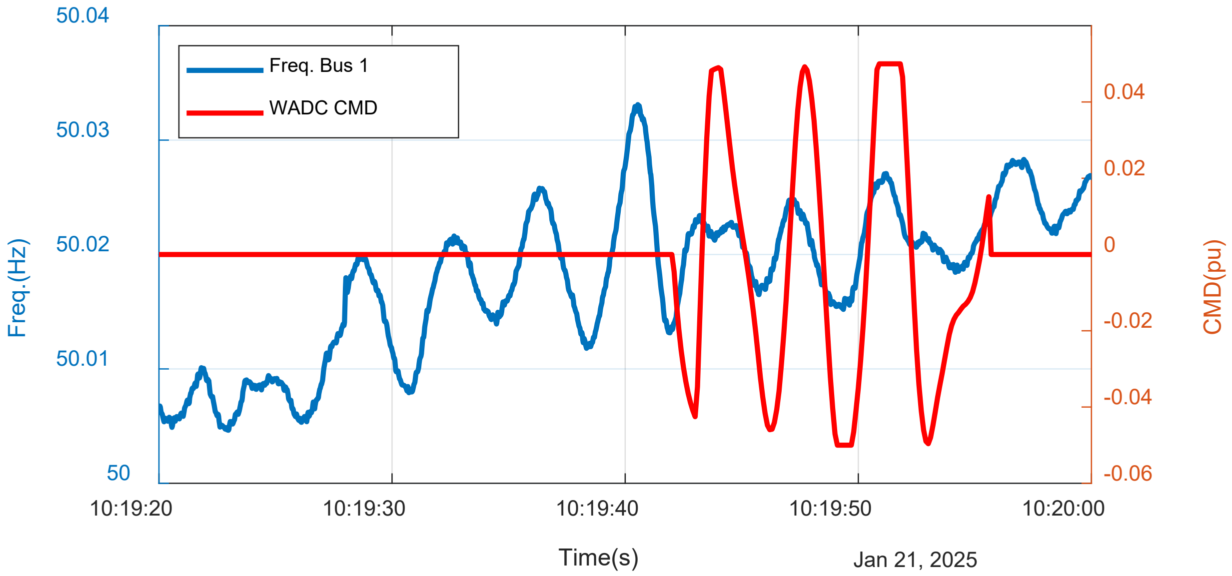


Real Intervention of WADC System

- WADC's control commands were as expected;
- Oscillation was detected after a few cycles as expected.

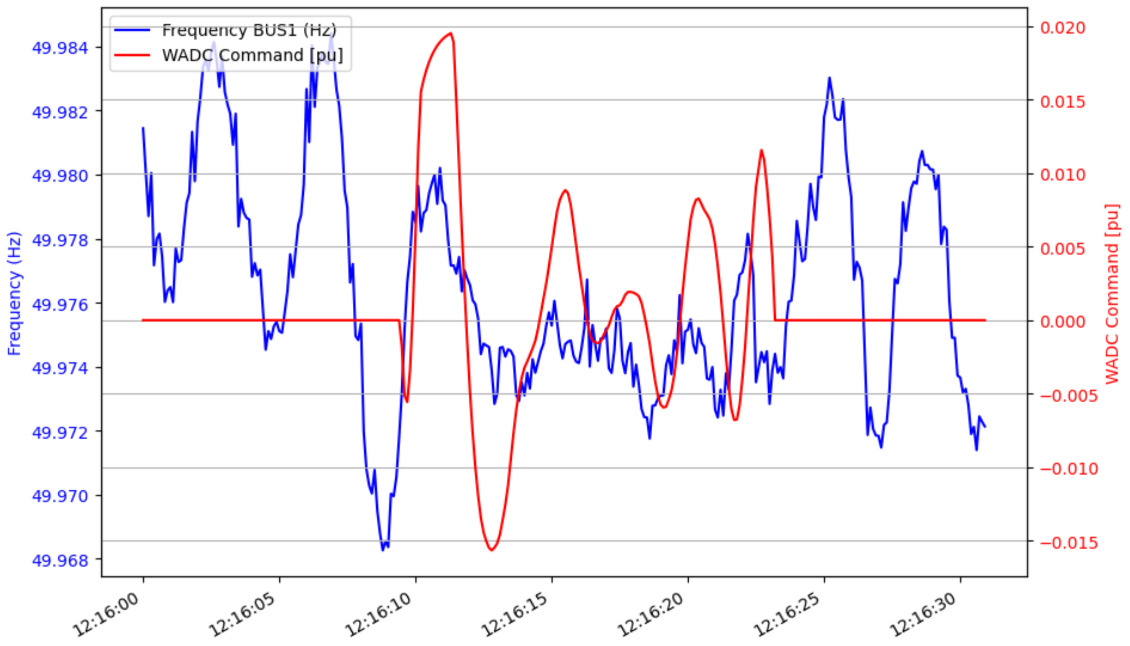
- **<u>Event 1:</u>** <u>Jan. 21, 2025 10:19:20 to 10:20:00</u>



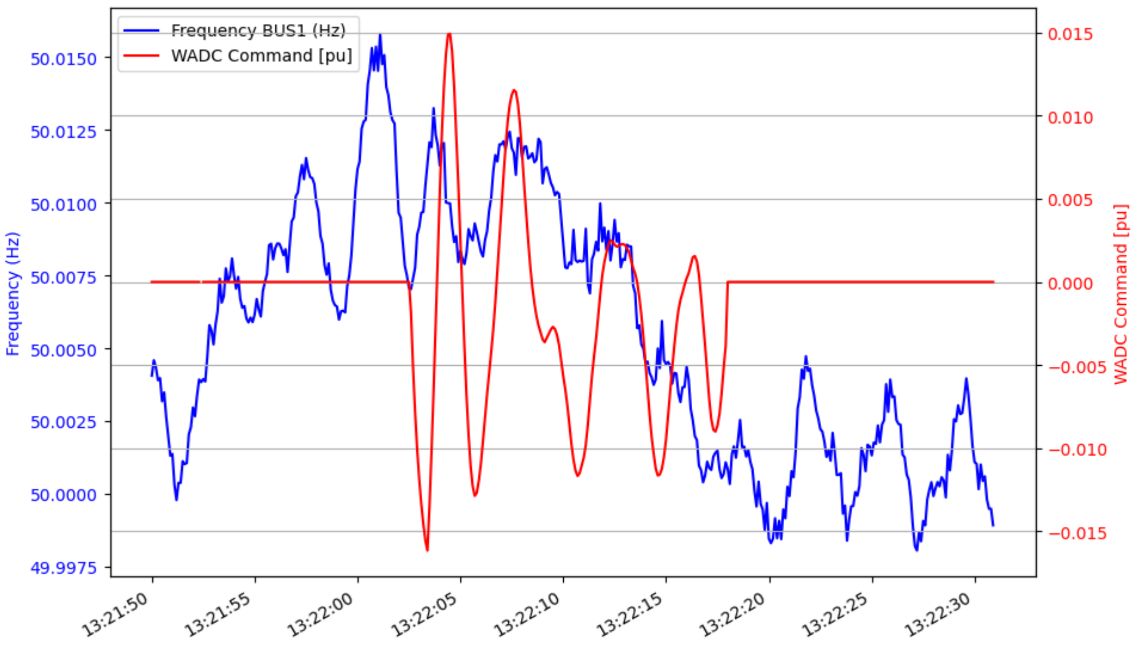


Real Intervention of WADC System

- From the WADC system recordings, its proper functioning is observed.
- At the onset of the oscillation, the system injects a stabilizing signal with a frequency equal to that of the oscillation itself.
- This behavior helps ensure greater damping of the oscillation, thereby improving the overall stability of the electrical system.



Event 2: Jan. 21, 2025 12:16:00 to 12:16:30



Event 3: Jan. 21, 2025 13:21:50 to 13:22:30

Closed-Loop Testing Under Large Disturbance

- Verified WADC damping control performance under large disturbance
  - ~300 MW load rejection in south Italy
  - WADC can generate proper control command based on input frequency during the disturbance
  - WADC can improve damping ratio of both the 0.27 Hz and 0.20 Hz oscillation modes
- The performance of WADC is as expected

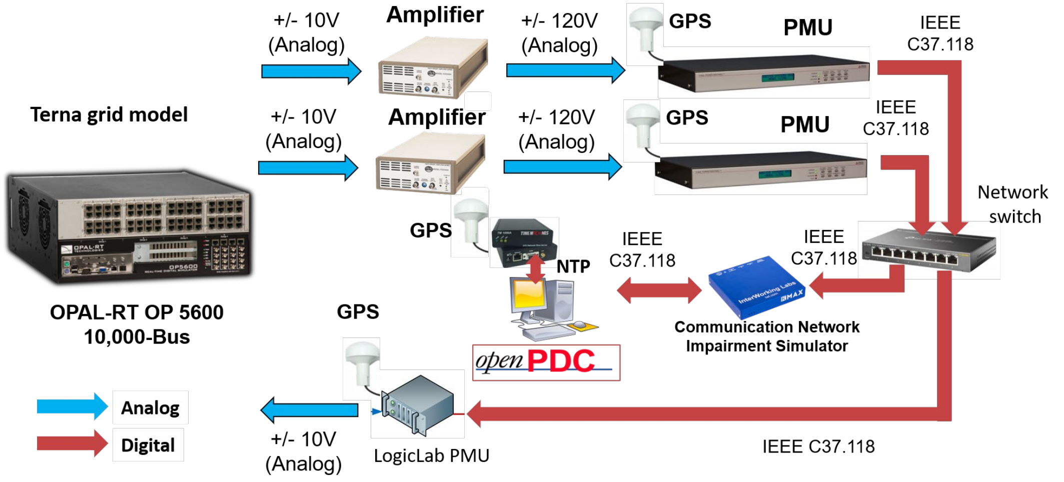
Ambient data: **WADC ON**	Event data: **WADC ON**	Ambient data: **WADC OFF**	Ambient data: **WADC OFF**
• 0.212 Hz, 19.42%	• NA	• NA	• 0.200 Hz, 12.23%
• **0.261 Hz, 17.02%**	• **0.262 Hz, 20.46%**	• **0.283 Hz, 13.05%**	• **0.286 Hz, 11.67%**
~20 minutes		~11 minutes	~20 minutes

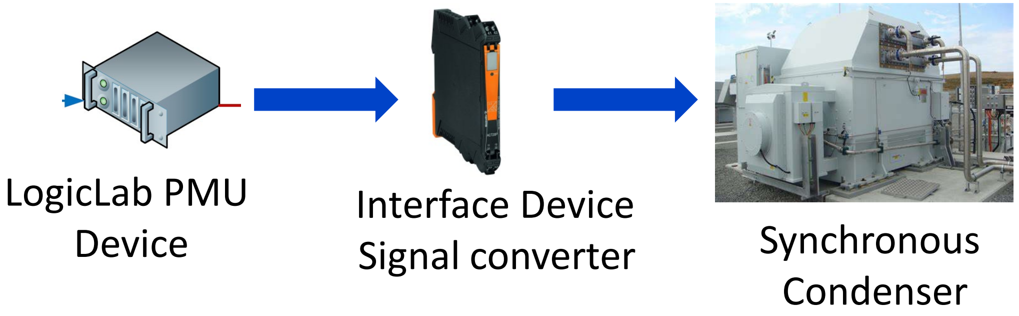
Summary and Future Work

- Development, field deployment, and field testing of an adaptive wide-area oscillations damping controller (WADC) to mitigate continental Europe N-S oscillations
- Successful application of synchrophasor technology in closed-loop wide-area control
- Demonstrated satisfactory damping control performance under various field test scenarios
- Operating as a novel automated wide-area monitoring protection and control (WAMPAC) tool in Terna's routine grid operation
- Future Work
  - Field testing with multiple actuators
  - Field testing with adaptive capability to accommodate grid operating condition variations
  - Other types of actuators, e.g., STATCOMs

Lessons Learned

- HIL is valuable to accelerate field deployment and adoption of new technologies
  - Revealed a lot of practical issues: Random delay, occasional/consecutive data loss, time error, etc.
  - Tests on HIL with replicated field setup saved a lot of efforts in field deployment
- A long way from field deployment/testing to field adoption as an online application in grid routine operation
  - Offline simulation: ~10% of total effort
  - HIL implementation and testing: ~40% of total effort
  - Field deployment and testing: ~20% of total effort
  - Field adoption in grid routine operation: ~30% of total effort
- During new equipment (e.g., synchronous condenser) commissioning is a good opportunity to perform field testing for OEM's support in physical interface

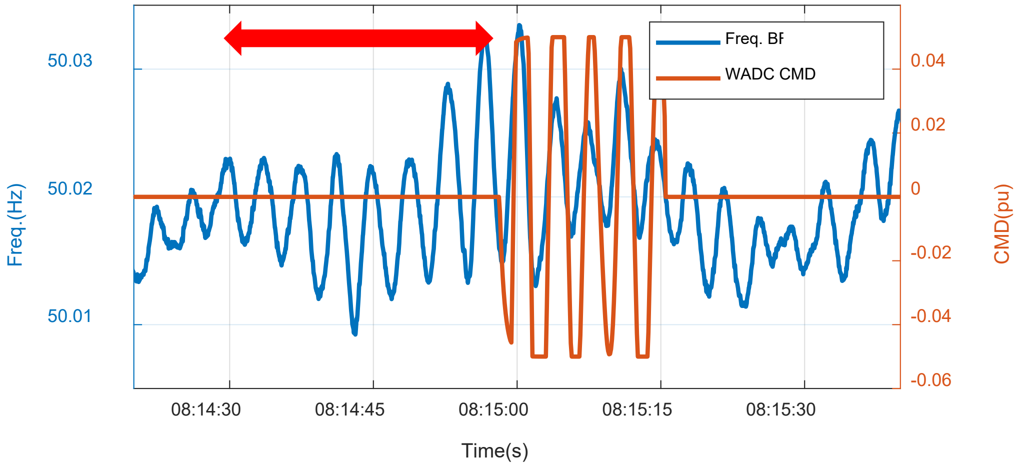


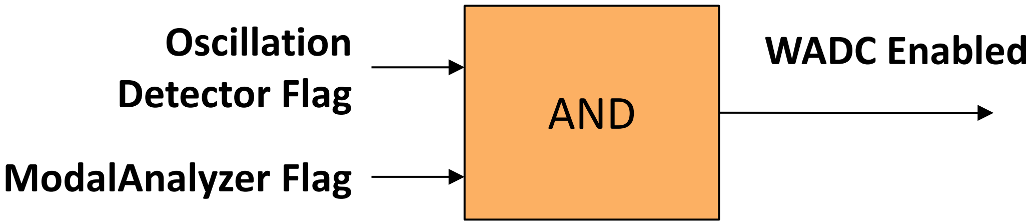


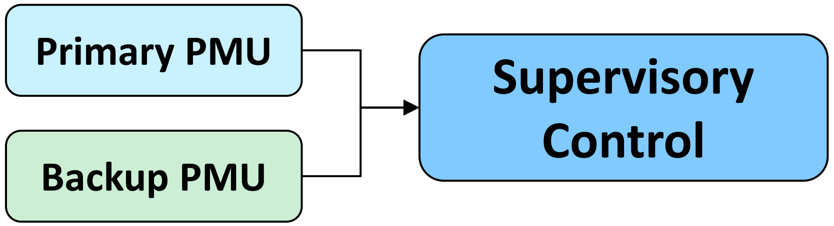
Lessons Learned, Cont'd

- Entire control loop delay (~250 ms)
  - WADC can be used to mitigate inter-area oscillations (Usually less than 0.8 Hz)
  - Local controller is expected to mitigate oscillations (> 1.0 Hz)
- "Do-No-Harm" is vital to real-time closed-loop applications
  - Oscillation detector, modal analysis, supervisory control, output limits, etc.
- TCP/IP is recommended to convey frequency measurements (controller input)
- UDP/IP is recommended to convey control commands (controller output)
- Time synchronization is critical to any WAMPAC applications
  - Observed "Negative" time delay due to incorrect time on server
  - Connect server to grandmaster clock directly and resynchronize every four seconds

Time window for oscillation detection







Selected Publications

1. L. Zhu, E. Farantatos, X. Jia, W. Yu, Y. Zhao, Y. Liu, S. Tessitore, P. Pau, G. Coletta, C. Pisani, and G. Giannuzzi, “Mitigating continental Europe North-South oscillations using an adaptive wide-area damping controller: Field implementation and testing,” *CIGRE Paris Session*, Aug. 25-28, 2024. (**Field Testing**)
2. X. Jia, Y. Zhao, W. Yu, Y. Liu, L. Zhu, E. Farantatos, C. Zhang, C. Pisani, G. Giannuzzi, G. Coletta, and S. Tessitore, "Hardware-in-the-Loop Testing of Wide-Area Damping Controller for Field Implementation in Large-scale Power Grid," *2024 IEEE Power & Energy Society General Meeting (PESGM)*, Seattle, WA, USA, 2024 (**HIL Testing**)
3. C. Zhang, Y. Zhao, Lin Zhu, Y. Liu, E. Farantatos, M. Patel, H. Hooshyar, C. Pisani, R. Zaottini, and G. Giannuzzi, “Implementation and Hardware-In-the-Loop testing of a wide-area damping controller based on measurement-driven models,” *IEEE Power & Energy Society General Meeting (PESGM)*, Washington, DC, USA, July 26-29, 2021. (**HIL Testing**)
4. L. Zhu, C. Zhang, Y. Zhao, H. Xiao, I. Altarjami, Y. Liu, E. Farantatos M. Patel, C. Pisani, G. Giannuzzi, R. Zaottini, L. Michi, and E. Carlini, “Mitigating inter-area oscillations using adaptive wide-area damping controller based on measurement-driven model: Case studies on realistic grid models and actual events,” *CIGRE Session 2020*, Paris, France, August 2020. (**Offline Simulation**)
5. L. Zhu, Y. Zhao, Y. Liu, E. Farantatos, M. Patel, P. Dattaray, D. Ramasubramanian, L. Michi, E. Carlini, G. Giannuzzi, and R. Zaottini, “Oscillation damping controller design using ring-down measurements for the Italian power grid”, *IEEE PES Powertech 2019*, Milano, Italy, June 23-27, 2019. (**Offline Simulation**)
6. H. Liu, L. Zhu, Z. Pan, F. Bai, Y. Liu, Y. Liu, M. Patel, E. Farantatos, and N. Bhatt, "ARMAX-Based Transfer Function Model Identification Using Wide-Area Measurement for Adaptive and Coordinated Damping Control," in *IEEE Transactions on Smart Grid*, vol. 8, no. 3, pp. 1105-1115, May 2017 (**Method Development**)
7. L. Zhu, H. Liu, Y. Ma, Y. Liu, E. Farantatos, M. Patel, and S. McGuinness, "Adaptive and coordinated oscillation damping control using measurement-driven approach," 2016 Power Systems Computation Conference (PSCC), Genoa, Italy, 2016. (**Method Development**)
8. L. Zhu, H. Liu, Z. Pan, Y. Liu, E. Farantatos, M. Patel, S. McGuinness, and N. Bhatt, "Adaptive wide-area damping control using measurement-driven model considering random time delay and data packet loss," *2016 IEEE Power and Energy Society General Meeting (PESGM)*, Boston, MA, USA, 2016 (**Method Development**)
9. F. Bai, L. Zhu, Y. Liu, X. Wang, K. Sun, Y. Ma, M. Patel, E. Farantatos, and N. Bhatt, “Design and implementation of a measurement-based adaptive wide-area damping controller considering time delays,” *Electric Power Systems Research*, Volume 130, 2016 (**Method Development**)
10. GridDamper: An Adaptive Power Grid Oscillation Damper, R&D 100 Awards Winner 2021. https://www.youtube.com/watch?v=-LKdCNUfW-I

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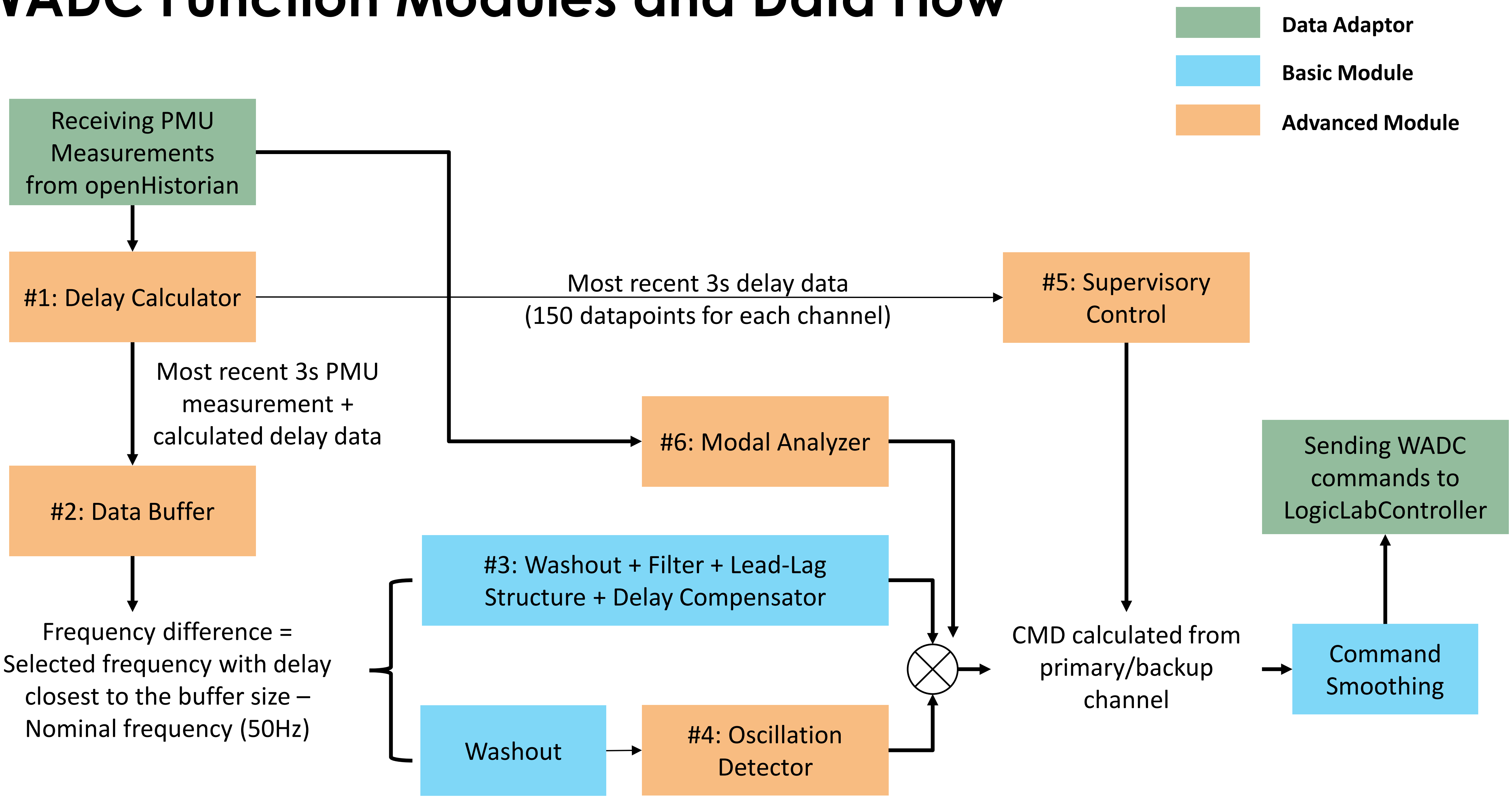
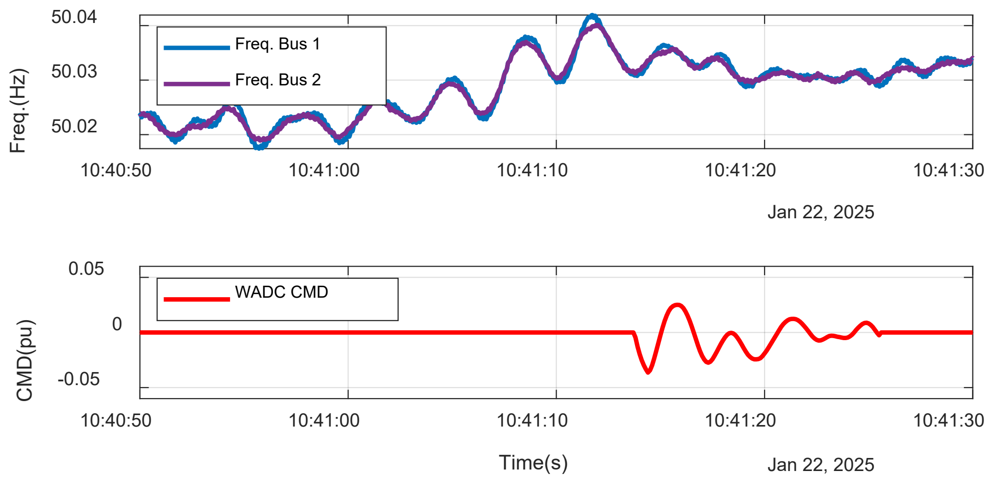
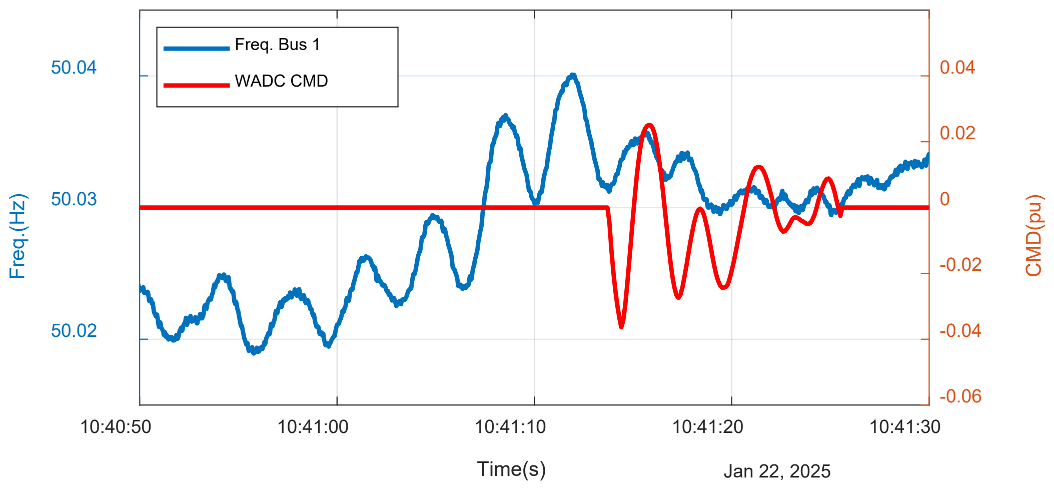
WADC Function Modules and Data Flow



Real Intervention of WADC System

- **Event 4:** Jan. 22, 2025 10:40:50 to 10:41:30





- **Event 5:** Jan. 24, 2025 09:53:20 to 09:54:20