UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

itee PhD information technology electrical engineering

DIETI UNINA

Sara Leccese

From Theory to Digital Implementation: Distributed Control for Cyber-Physical Systems

Tutor: Prof. Stefania Santini
Cycle: XXXVIII
Year:Third

itee PhD

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Background & Info

- MSc degree in Automation and Robotics Engineering, University of Naples Federico II
- Working team: DAiSY Lab (Prof. Stefania Santini)
- PhD start date: Academic Year 2022-2023
- Scholarship type: PNRR - DM 351 Ricerca
- Period abroad: Department of System Engineering at the University of Seville (US), Spain, from 28/09/2024 to 20/03/2025;
  Supervisor: Prof. Alexander Seuret.

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3rd Year: Study & Training Activities

The focus of my third year of PhD is on designing communication-efficient and resilient control strategies for Cyber-Physical Energy Systems (CPESs), applying dynamic event-triggered mechanisms and validating their performance through experimental testing and realistic simulations to ensure robust operation in practical energy applications.

Period abroad at University of Seville (US)

Theoretical development of distributed sampled-data and event-triggered control for multi-agent systems, leveraging tools such as hybrid systems theory.

Escuela Técnica Superior de INGENIERÍA DE SEVILLA

Presentation of a papers at: 2nd IFAC Workshop on Control of Complex Systems (COSY): *Weighted Average consensus in perturbed Multi-Agent System.*

Attended Seminars:
10 attended seminars during this 3rd year, organized by different international societies, such as IFAC Working group on Time-Delay Systems and IEEE.

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Research Area

- Designing novel distributed control strategies ensuring the efficiency, robustness, and adaptability of multi-agent cyber-physical systems (CPS) on various domains, such as:
  - Smart Transportation Systems
  - Smart Grids / Micro Grids
  - Smart Cities

- Hence, it is crucial to explore new control strategies for multi-agent CPS to boost collaboration, efficiency, and adaptability, enhancing system performance in dynamic environments.

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Research results

- The aim of my research is to design novel **distributed control strategies** aimed at addressing key research challenges in the control of networked CPSs, such as:

  1. Transition from **continuous to digital implementation**, through **sampled-data** control techniques that **preserve stability and performance** under discretization and sampling-induced effects;
  2. Improve the **communication efficiency**, by implementing **event-triggered mechanisms** that reduce unnecessary transmissions while ensuring convergence and robustness with respect to **unknown uncertainties/unbounded disturbances**;
  3. Resilient distributed coordination under **network-induced phenomena and cyber threats**, ensuring stable and cooperative behavior despite large delays, packet losses, bandwidth limitations, disturbances, and attacks.

- Tailor theoretical results to real-world control problems in **Cyber-Physical Energy Systems (CPES)** through **real-time** simulations performed on **high-fidelity platform**, providing a critical bridge between theoretical design and practical implementation.

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Research Products

[J1]	Caiazzo, B., **Leccese, S.**, Pepe, P., Petrillo, A., & Santini, S. *Global Exponential Stability Preservation under Sampling and Approximated Delay-Dependent Feedbacks for Nonlinear Systems with Time-Varying Delays* **IEEE Transactions on Automatic Control,** vol. 70, no. 10, pp. 6984-6991, Oct. 2025
[J2]	Andreotti, A., Caiazzo, B., **Leccese, S.,** Petrillo, A., Santini, S., & Vaccaro, A. *Real-Time Assessment of Dynamic Event-Triggered Controllers for Islanded Microgrids via High-fidelity Cyber-Physical Platform* **Under review**
[J3]	**Leccese,S.**, Albea,C., Santini,S., Zaccarian,L., & Seuret,A. *Uniform dwell-time and robustness in distributed event-triggered weighted consensus* **Under review**
[J4]	**Leccese, S.,** Lui, D. G., Petrillo, A., & Santini, S. *Virtual Coupling Formation Control for Heterogeneous High-Speed-Trains with Uncertain Dynamics, Nonuniform Communication Delays and Switching Topologies* **IEEE Transaction on Intelligent Transportation Systems,** *to appear.*
[J5]	Basile, G., **Leccese, S.**, Petrillo, A., Rizzo, R., & Santini, S. *Sustainable DDPG-based Path Tracking for Connected Autonomous Electric Vehicles in extra-urban scenarios* **IEEE Transactions on Industry Applications,** 2024, pp. 1-13, 2024

[C1]	**Leccese, S.,** Caiazzo, B., Petrillo, A., Santini, S., & Seuret, A. *Weighted network design for practical average consensus in perturbed Multi-Agent Systems.* **2nd IFAC Workshop on Control of Complex Systems (COSY)** Paris, France, Jun 2025, IFAC-PapersOnLine, 59(11), 102-107.
[C2]	Caiazzo, B., **Leccese, S.,** Petrillo, A., & Santini, S. *Improving the communication overhead in vehicles platoon: a novel dynamic event-triggered predictor method* **IEEE International Conference on Intelligent Transportation Systems (ITSC)** Gold Coast, Australia, November 2025, *to appear*

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Research Products

[C3]	Andreotti, A., Caiazzo, B., **Leccese, S.,** Petrillo, A., Redi, L., & Santini, S. *Grid Interactive Smart Buildings Coordination in Multi-Area Power Systems: A Delay-Robustness Analysis.* **International Conference on Smart Cities and Green ICT Systems, SMARTGREENS,** Proceedings (pp. 48-55). Science and Technology Publications, Lda.
[C4]	Caiazzo, B., **Leccese, S.,** Pepe, P., Petrillo, A., Santini, S. *From piece-wise constant to continuous time-varying delays: Global Exponential Stability Preservation for Nonlinear Systems Under Sampling* **IEEE Conference on Decision and Control (CDC)** Milan, Italy, Dec. 2024, pp. 948-953.
[C5]	Andreotti, A., Caiazzo, B., **Leccese, S.,** Lui, D. G., Petrillo, A., & Santini, I. S. *Prescribed-Time Consensus Control for the Voltage Restoration in Inverter-based Islanded Microgrids* **IEEE American Control Conference (ACC)** Toronto, Canada, Jul. 2024, (pp. 1783-1788). IEEE. .
[C6]	Andreotti, A., Caiazzo, B., **Leccese, S.**, Petrillo, A., & Santini, S. *A Unified Distributed Digital Control Architecture for Secondary Control in Islanded Microgrids* **IFAC Control of Power and Energy Systems (CPES)** Rabat, Morocco, Jul. 2024, IFAC-PapersOnLine, 58(13), 74-79.
[C7]	Andreotti, A., Caiazzo, B., **Leccese, S.,** Petrillo, A., Santini, S., & Vaccaro, A. *Assessment of a Dynamic Event-Triggered Voltage Control for Islanded Microgrids Using High-Fidelity Cyber-Physical Platform* **International Conference on Smart Energy Systems and Technologies (SEST)** Torino, Italy, Sept. 2024, (pp. 1-6), IEEE.
[C8]	B. Caiazzo, E. Fridman, **S. Leccese,** A. Petrillo, S. Santini *Voltage Recovery in SOA-based Virtual Microgrids via Time-Delay Approach to Averaging* **IFAC, 22nd World Congress 2023 of the International Federation of Automatic Control** Yokohama, Japan, IFAC-PapersOnLine, vol 56 (pp 905-910), Elsevier
[C9]	G. Basile, **S. Leccese**, A. Petrillo, R. Rizzo and S. Santini, *Sustainable DDPG-based Path Tracking For Connected Autonomous Electric Vehicles in extra-urban scenarios*, **2023 IEEE IAS Global Conference on Renewable Energy and Hydrogen Technologies (GlobConHT),** Male, Maldives, 2023, (pp. 1-7), IEEE

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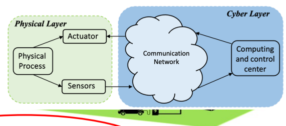
PhD thesis overview (1/2)

- Modern CPSs can be seen as **Networked Control Systems (NCS)** composed of spatially distributed intelligent agents, where sensors, actuators, and controllers communicate through shared digital networks.
- The paradigm is shifting towards **distributed control**, ensuring efficient and resilient operation in interconnected environments.
- However, each agent has **limited computation and communication** resources.

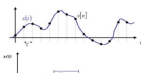


THE CHALLENGE

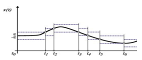
achieving **global coordination and stability** despite **network constraints** (limited bandwidth, delays, packet drops)

- To overcome these constraints, modern control theory relies on two main concepts:

Sampled-Data control → periodic sampling and digital updates



Event-Triggered control → Control and communication are triggered by specific events



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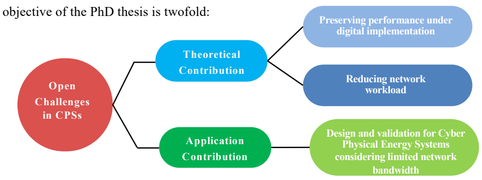
PhD thesis overview (2/2)

- Applying sampled-data and event-triggered strategies is often challenging when dealing with:
  - Nonlinear behaviour and delays;
  - Interaction between multiple agents;
  - External disturbances;

Classical results must be enhanced and extended to deal with more realistic plants

Once developed, the **ultimate goal** is tailor theoretical results to solve real-word CPSs applications problem.

- The objective of the PhD thesis is twofold:



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PhD thesis overview (2/2)

- Applying sampled-data and event-triggered strategies is often challenging when dealing with:
  - Nonlinear behaviour and delays;
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Classical results developed for linear systems must be adapted and extended to deal with more realistic plants

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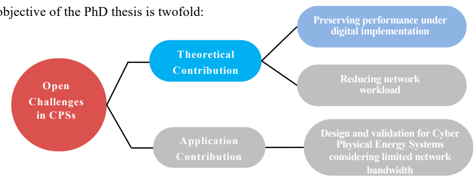

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Preserving performance under digital implementation(1/2)

Consider **a nonlinear retarded system**

$$\begin{aligned} \dot{x}(t) &= f(d(t), x_t, u(t)) \quad t \geq 0, \quad a.e., \\ x(\tau) &= x_0(\tau), \quad \tau \in [-\Delta, 0], \quad x_0 \in \mathscr{C}, \end{aligned} \tag{1}$$

Objective: Ensure the sampled-data system preserves the stability properties of the continuous-time design.

EXISTING STABILITY GUARATEES

- Constant time-delays.
- Stabilization in sampled and hold sense.

PPROPOSED SOLUTION:

Global exponential stability preservation for nonlinear systems under time-varying delays

- ✓ Handle unviable paste states via spline approximation scheme.
- ✓ **Lyapunov-Krasovskii** theory for time-delay systems along with **Halanay Lemma** are combined to obtain **exponential stability condition.**
- ✓ The maximum sampling interval guaranteeing preservation of GES is analytically derived:

$$\boxed{\delta_{max} = \frac{\alpha_1 \alpha_3}{\alpha_2 L_v L_f^2 L_k (1 + L_k)(1 + 2\sqrt{n} + L_d)}.}$$

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Preserving performance under digital implementation(3/3)

Numerical Validation

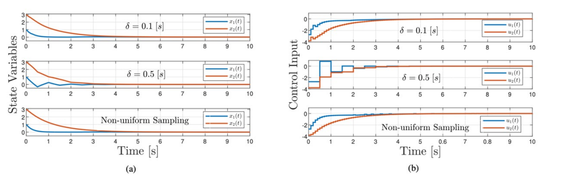
- Hopfield Neural Network Model:

$$\begin{aligned} \dot{x}(t) &= -Ax(t) + W_0 g_0(x(t)) + W_1 g_1(x(t - d(t))) + u(t) \\ x(\theta) &= x_0(\theta), \quad \theta \in [-\Delta, 0], \end{aligned} \tag{2}$$

- Maximum intersampling time: $\delta_{max} = 0.55$
- Spline-based digital control input:

$$\begin{aligned} u(t) = &-\bar{K} P_{l,a,\delta}(\mathscr{B}_{\mathscr{S}}(j), \mathscr{B}_{\mathscr{T}}(j))(0) - W_0 g_0\Big(P_{l,a,\delta}(\mathscr{B}_{\mathscr{S}}(j), \mathscr{B}_{\mathscr{T}}(j))(0)\Big) \\ &- W_1 g_1\Big(P_{l,a,\delta}(\mathscr{B}_{\mathscr{S}}(j), \mathscr{B}_{\mathscr{T}}(j))(-d(t_j))\Big), \end{aligned} \tag{3}$$

Time history of: a) state variable; b) spline approximated delay-dependent digital state feedback.



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PhD thesis overview (2/2)

- Applying sampled-data and event-triggered strategies is often challenging when dealing with:
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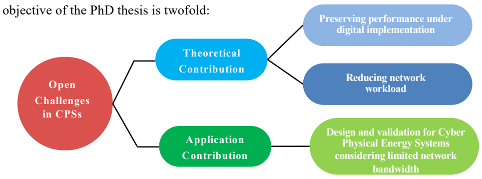

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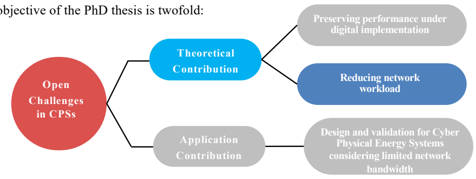

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Reducing Network Workload(1/4)

Consider a homogeneous perturbed MAS:

$$\dot{x}_i = u_i + \omega_i, \qquad \forall i \in \mathscr{V}, \qquad (4)$$
$$u_i(t) = -\sum_{j\in\mathscr{N}_i} L_{a(ij)}(\hat{x}_i(t) - \hat{x}_j(t)),$$

Objective: design a distributed **event-triggered control** law that guarantees **practical** consensus under bounded in average disturbances while reducing communication burden.

EXISTING CONTROL STRATEGIES

- Focus mainly on ideal disturbance-free MAS.
- Assume uniformly bounded disturbances, not time-varying or realistic perturbations.
- Often lack robustness guarantees under uncertainties and unknown couplings.

PROPOSED SOLUTION:

Propose a distributed control strategy ensuring practical stability in perturbed MASs with unknown bounded-in-average disturbance

- ✓ Introduce an approach that does not require uniform boundedness of disturbances, unlike previous works.
- ✓ Derive **LMI-based** stability conditions to determine Laplacian weights, ensuring system convergence within a specific attractor region.
- ✓ Ensures **Zeno-free** operation and minimum inter-event times:

$$\boxed{t^i_{k+1} = \min\Big\{t \geq t^i_k : \ |\chi_i(t)|^2 \geq \sum_{j\in\mathscr{N}_i} L_{b(ij)}(\hat{x}_i(t) - \hat{x}_j(t))^2 + \rho\Big\}}$$

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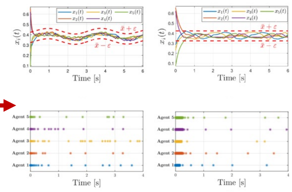
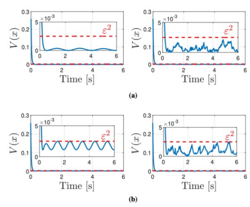
Reducing Network Workload(2/4)

Numerical Validation

- Based on disturbance magnitude, **two scenario** are considered:
  - *Nominal scenario*
  - *Worst Case scenario*

Performance of the proposed Distributed ET under nominal and worst disturbance condition.





Time histories of Lyapunov functions

PRACTICAL STABILITY WITHIN THE SPECIFIED REGION OF ATTRACTION

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Reducing Network Workload(3/4)

Consider a heterogeneous perturbed MAS:

$$C_i\dot{x}_i = u_i + w_i \qquad \forall i \in \mathscr{V},$$
$$u_i(z) = -\sum_{j\in\mathscr{V}} a_{ij}(z_i - z_j),\ \forall i \in \mathscr{V} \qquad (5)$$

Objective: design a distributed **event-triggered control** law that guarantees **exponential** consensus under bounded in average disturbances while reducing communication burden.

EXISTING CONTROL STRATEGIES

- Non uniform dwell time guarantee.
- Often lack robustness guarantee w.r..t uncertainties and unknown couplings.

PROPOSED SOLUTION:

Propose a distributed control strategy ensuring practical stability in perturbed MASs

- ✓ **No require uniform boundedness of disturbances**, unlike previous works.
- ✓ **Exponential stability** of the closed-loop **guarantee.**
- ✓ Stability analysis via **Hybrid Dynamical Systems** framework.
- ✓ Ensures the existence of a **uniform uniform global average dwell time :**

$$t_{k+1}^i = \left\{ \min_{t > t_k^i + T} t \text{ s.t. } \rho q_i(z) - \tilde{x}_i\left(2u_i(z) + \varepsilon C_i \tilde{x}_i\right) \le 0 \right\}$$

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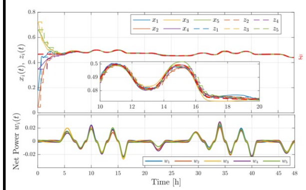
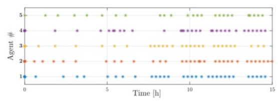
Reducing Network Workload(1/2)

Numerical Validation

Performance of the proposed Distributed ET under: evolution of states (solid curves) and their sampled versions zi (dashed curves) (top); evolution of the disturbance (bottom).



triggering instants for t ∈ [0, 15] [h]



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PhD thesis overview (2/2)

- Applying sampled-data and event-triggered strategies is often challenging when dealing with:
  - Nonlinear behaviour and delays;
  - Interaction between multiple agents;
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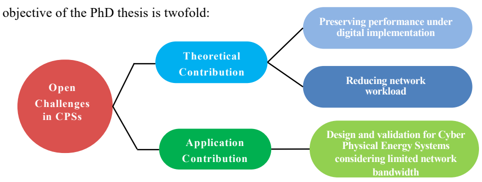
- The objective of the PhD thesis is twofold:



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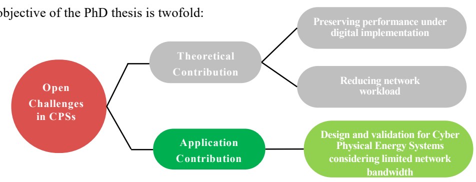

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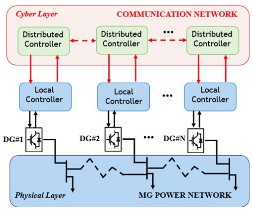
Application Side: Cyber-Physical Energy Systems

Micrograds (MGs) represent a paradigmatic example of **Cyber-Physical Energy Systems (CPES),** combining distributed generation units, control algorithms, and digital communication networks to achieve reliable and efficient energy coordination.

- The design of **distributed controllers** aims to enhance grid performance, reliability, and coordination in modern power networks.
- MGs can be modelled as networked control systems composed of spatially distributed units—i.e., **Distributed Energy Resources (DERs)**—that exchange information through a shared, **bandwidth-limited digital communication network.**



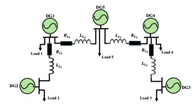
The presence of a shared communication network motivates the design of **distributed controllers that are digitally implementable**, robust, and capable of coordinating MG components despite bandwidth and update constraints.

Unified Digital Secondary Control(1/2)

Main objective: design a fully distributed digital controller for inverter-based islanded microgrids that achieves voltage and frequency restoration at the secondary control layer while

EXISTING CONTROL STRATEGIES

- Continuous update of the controllers.
- Practical issues in implementing continuous-time distributed controllers in digital control platform.
- Limited communication resources.
- No sampling dependent stability conditions are provided to analytically find a sampling period preserving the stability.



PROPOSED SOLUTION:

Design a unified **distributed sampled-data PID-like** controller to restore the both **voltage and frequency setpoints:**

- ✓ The sampled-data implementation results from the application of **Artificial Delays** approach.
- ✓ Lyapunov-Krasovskii theory to prove the stability of the Microgrids voltage/frequency.
- ✓ Derive **LMI-based** stability criteria which analytically provide a maximum sampling period preserving the stability.
- ✓ Validation of the unified digital architecture in a **high-fidelity MG system.**

$$u_i^{\omega}(t) = k_P \sum_{j\in\mathcal{N}_i} a_{ij}\left(e_i(t_k)-e_j(t_k)\right) + k_I \sum_{j\in\mathcal{N}_i} a_{ij} \sum_{s=0}^{k-1}\left(e_i(t_s)-e_j(t_s)\right) \quad t\in[t_k,t_{k+1}),\ k\in\mathbb{N}_0.$$

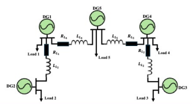
Application Side: ET Secondary Control (2/2)

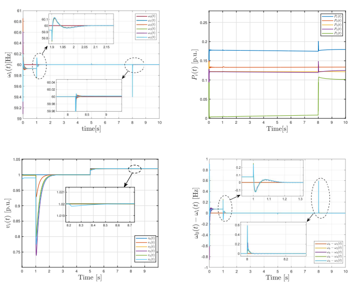
Main objective: design a fully distributed digital controller for inverter-based islanded microgrids that achieves voltage and frequency restoration at the secondary control layer while

VALIDATION RESULTS

Performance of the proposed Distributed Digital SC Architecture with sampling period h=0.002. Time-history of:

a) DGs frequency;
b) DGs frequency errors w.r.t setpoint;
c) DGs voltage ;
d) DGs active power;





Application Side: Resilient and communication-efficient Secondary Control(1/2)

Main objective: design and experimental validate a distributed secondary event-tigger control strategy combined with a **predictor-based control**, achieving **resilient and communication-efficient** voltage and regulation despite the presence of **network vulnerabilities.**

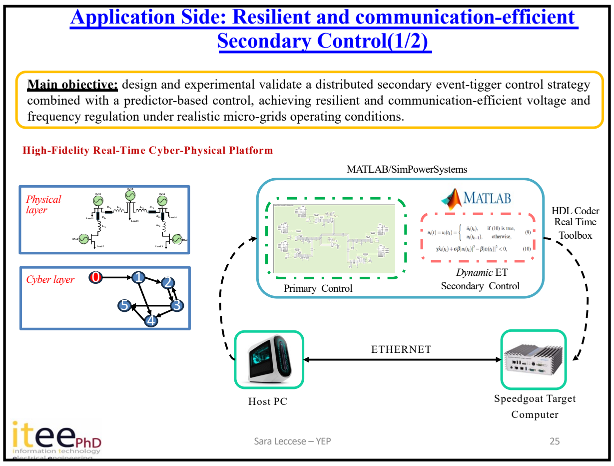
EXISTING CONTROL STRATEGIES

- Typically relies on periodic sampling and synchronous updates among DGs to restore voltage, frequency, and power sharing;
- Vulnerable to limited bandwidth, packet drops, delays, and cyber-attacks;
- No sampling dependent stability conditions are provided to analytically find a sampling period preserving the stability;
- Most approaches address disturbances, delays, or cyber-attacks separately, not simultaneously;
- Limited experimental validation, with communication efficiency and resilience under realistic conditions often untested;

PPROPOSED SOLUTION:

Design a unified **distributed sampled-data PID-like** controller to restore the **voltage setpoint:**

- ✓ Use **dynamic triggering rules** to adaptively update control only when necessary, reducing communication workload;
- ✓ Incorporate **predictor-based** approach to reconstruct missing neighbor information during delays or DoS attacks;
- ✓ Reduces unnecessary communication while maintaining stability and performance;
- ✓ Implementation on a **Speedgoat real-time platform** with **MATLAB/Simscape Electrical**, faithfully reproducing microgrid dynamics and digital communication constraints.



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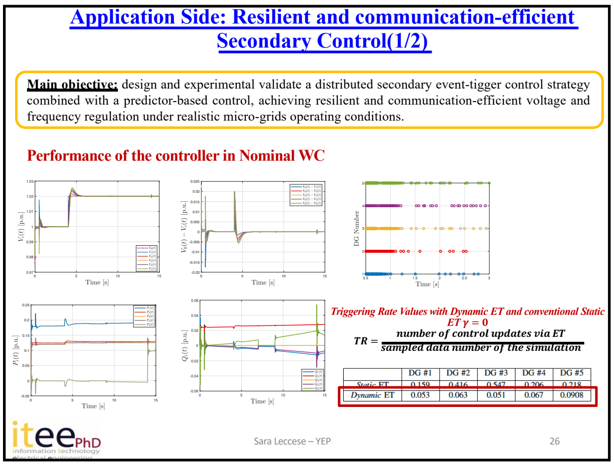

	DG #1	DG #2	DG #3	DG #4	DG #5
Static ET	0.159	0.416	0.547	0.206	0.218
Dynamic ET	0.053	0.063	0.051	0.067	0.0908

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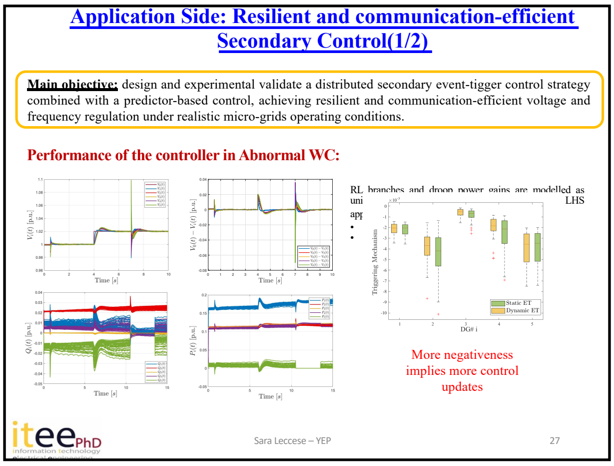

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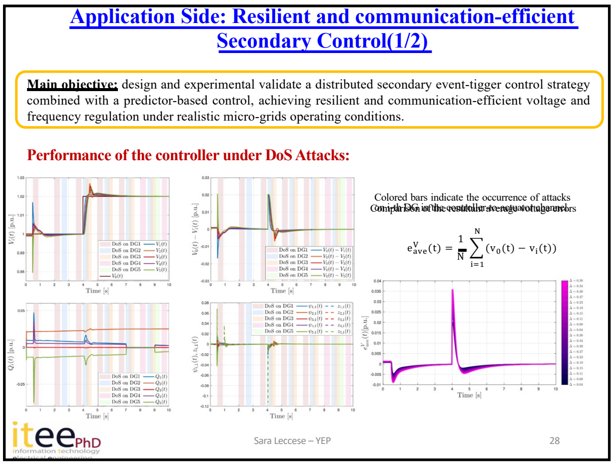

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Conclusions

- The study and research activities conducted during the third year of the PhD program have been summarized, focusing on the development and validation of communication-efficient and resilient control strategies for cyber-physical energy systems.

- The main achievements of the PhD work have been outlined, addressing open challenges related to the digital implementation of distributed control laws, stability preservation under sampling and delays, and efficient coordination through event-triggered mechanisms.

- A comprehensive overview of the PhD thesis has been presented, whose ultimate goal is to contribute to the digitalization of modern power networks by enabling the practical deployment of distributed and resilient control architectures for cyber-physical energy systems.

THANKS FOR THE ATTENTION !

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