Bianca Caiazzo

Distributed control of Cyber-Physical Energy Systems: Towards the Energy Transition

Tutor: Prof. Stefania Santini

co-Tutor: Prof. Amedeo Andreotti

Cycle: XXXV

Year: 2021/2022

Background & Info

- MSc degree in Management Engineering, University of Naples Federico II
- Research group: DAiSy Lab
- PhD start and end dates: 01/11/2019-31/01/2023
- Scholarship type: "UNINA"
- Periods abroad: Department of Electrical Engineering-Systems at Tel Aviv University, Israel from 13/10/2021 to 12/04/2022;
  Supervisor: Prof. Emilia Fridman

3rd Year: Study & Training Activities

- Focus of my third year activity has been the design of distributed controllers for Multi-Agent Systems (MASs) accounting for different communication constraints and control requirements. These novel theoretical tools was exploited for different applications, in particular for modern Cyber-Physical Energy Systems (CPES), i.e. the so-called *Microgrids*, in order to promote the current green energy transition.

Period abroad at Tel Aviv University (TAU)

Novel constructive time-delay approach to periodic averaging to study the stability of systems with fast-varying piacewise continuous coefficients with non-small delays, with application to switched affine systems.

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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.

Presentation of 2 papers at:
17th IFAC Workshop on Time Delay Systems 2022 Montrèal, Canada (September 27-30, 2022):

a. 'Synchronization of Multi-Agent Systems under Time-Varying Network via Time-Delay Approach to Averaging'
b. 'Cooperative Finite-time Control for autonomous vehicles platoons with nonuniform V2V communication delays'

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Summary of Study Activities over PhD years

50 attended seminars organized by ITEE, and other international societies

10 attended courses, both MSc and ad-hoc courses

2 Attended PhD Schools:

Model predictive control, organized by Scuola IMT Alti Studi di Lucca;

Time-Delay and Sampled-data Systems, organized by European Embedded Control Institute (EECI) 2020

Credits summary

PhD Year	Courses	Seminars	Research	Tutoring/ Supplementary Teaching
1^{st}	37.1	7.2	33.6	0
2^{nd}	11	7	42	0
3^{rd}	0	2.1	68.1	0
Total	**48.1**	**16.3**	**143.7**	**0**
Expected	min 30–max 70	min 10–max 30	min 80–max 140	min 0–max 4.8

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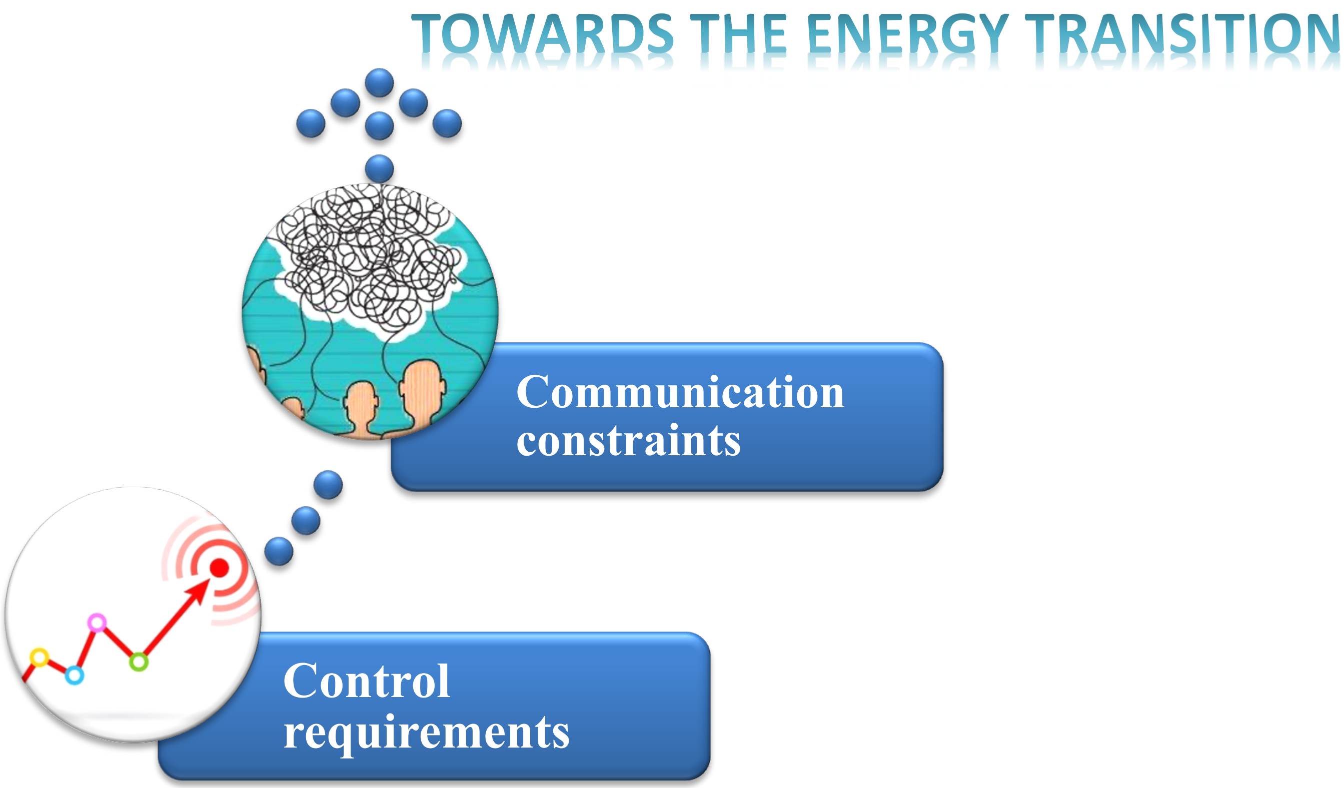
Research area

- My research is focused on the design of distributed control protocols for cyber-physical systems in a networked control system perspective with the aim to reach a common prescribed behaviour at the global level.

- Tailoring these theoretical results with respect to practical problems arising in modern Microgrids including different distributed smart generation sources, both conventional and renewable ones.



Research results

- Designing of different distributed cooperative control strategies able to answer some research questions emerging from the technical literature on cooperative control of Multi-Agent Systems, as well as on distributed control for CPESs, such as:

  1. Resilience with respect to **time-varying communication delays** by providing delay-dependent stability conditions with a gain-tuning rule guaranteeing a **finite-time** convergence;
  2. Resilience with respect to any kind of **unmodeled dynamics/unknown uncertainties/unbounded disturbances**, without requiring **any knowledge about global Microgrids information**;
  3. Move towards periodic and a-periodic inter-agents interaction in order to **reduce communication network workload and save its limited resources.**

- Extension of the novel constructive **time-delay approach to periodic averaging** to the class of systems with **fast-varying piecewise-continuous coefficients** with **non-small delays,** with application to stabilization of switched affine systems.

Research products (1/3)

[J1]	Andreotti, A., **Caiazzo**, B., Fridman, E., Petrillo, A., Santini, S., *Distributed Dynamic Event-Triggered control for voltage recovery in Islanded Microgrids by using Artificial Delays* ***Under Review***
[J2]	**Caiazzo**, B., Lui, D.G., Petrillo, A., Santini, S., *Cooperative adaptive PID-like voltage regulation in inverter-based islanded Microgrids under unknown uncertainties* ***Under Review***
[J3]	**Caiazzo**, B., Fridman, E., and Yang, X., *Averaging of systems with fast-varying coefficients and non-small delays with application to stabilization of affine systems via time-dependent switching,* ***Nonlinear Analysis: Hybrid Systems*** vol. 48, May 2023, 101307
[J4]	**Caiazzo**, B., Murino, T., Petrillo, A., Piccirillo, G., Santini, S., *An IoT-based and cloud-assisted AI-driven monitoring platform for smart manufacturing: design architecture and experimental validation,* ***Journal of Manufacturing Technology Management*** vol. ahead-of-print
[J5]	**Caiazzo**, B., Di Nardo, M., Murino, T., Petrillo, A., Piccirillo, G., & Santini, S. *Towards Zero Defect Manufacturing paradigm: A review of the state-of-the-art methods and open challenges* ***Computers in Industry*** Vol. 134, January 2022, 103548
[J6]	B. **Caiazzo**, A. Coppola, A. Petrillo, S. Santini, *Distributed nonlinear model predictive control for connected autonomous electric vehicles platoon with distance-dependent air drag formulation* ***Energies*** *14.16 (2021): 5122.*
[J7]	B. **Caiazzo**, D. G. Lui, A. Petrillo, S. Santini, *Distributed Double-Layer Control for Coordination of Multiplatoons Approaching Road Restriction in the Presence of IoV Communication Delays,* ***IEEE Internet of Things Journal*** *9.6 (2021): 4090-4109.*
[J8]	A. Andreotti, B. **Caiazzo**, A. Petrillo, S. Santini, *Distributed Robust Finite-Time Secondary Control for Stand-Alone Microgrids With Time-Varying Communication Delays,* ***IEEE Access,*** *9 (2021): 59548-59563.*

3^{rd} Year Product

Research products (2/3)

[J9]	A. Andreotti, B. **Caiazzo**, A. Petrillo, S. Santini, A. Vaccaro, *Hierarchical two-layer distributed control architecture for voltage regulation in multiple microgrids in the presence of time-varying delays,* ***Energies*** *13.24 (2020): 6507.*
[J10]	A. Andreotti, B. Caiazzo, A. Petrillo, S. Santini, A. Vaccaro, *Decentralized smart grid voltage control by synchronization of linear multiagent systems in the presence of time-varying latencies,* ***Electronics*** *8.12 (2019): 1470.*

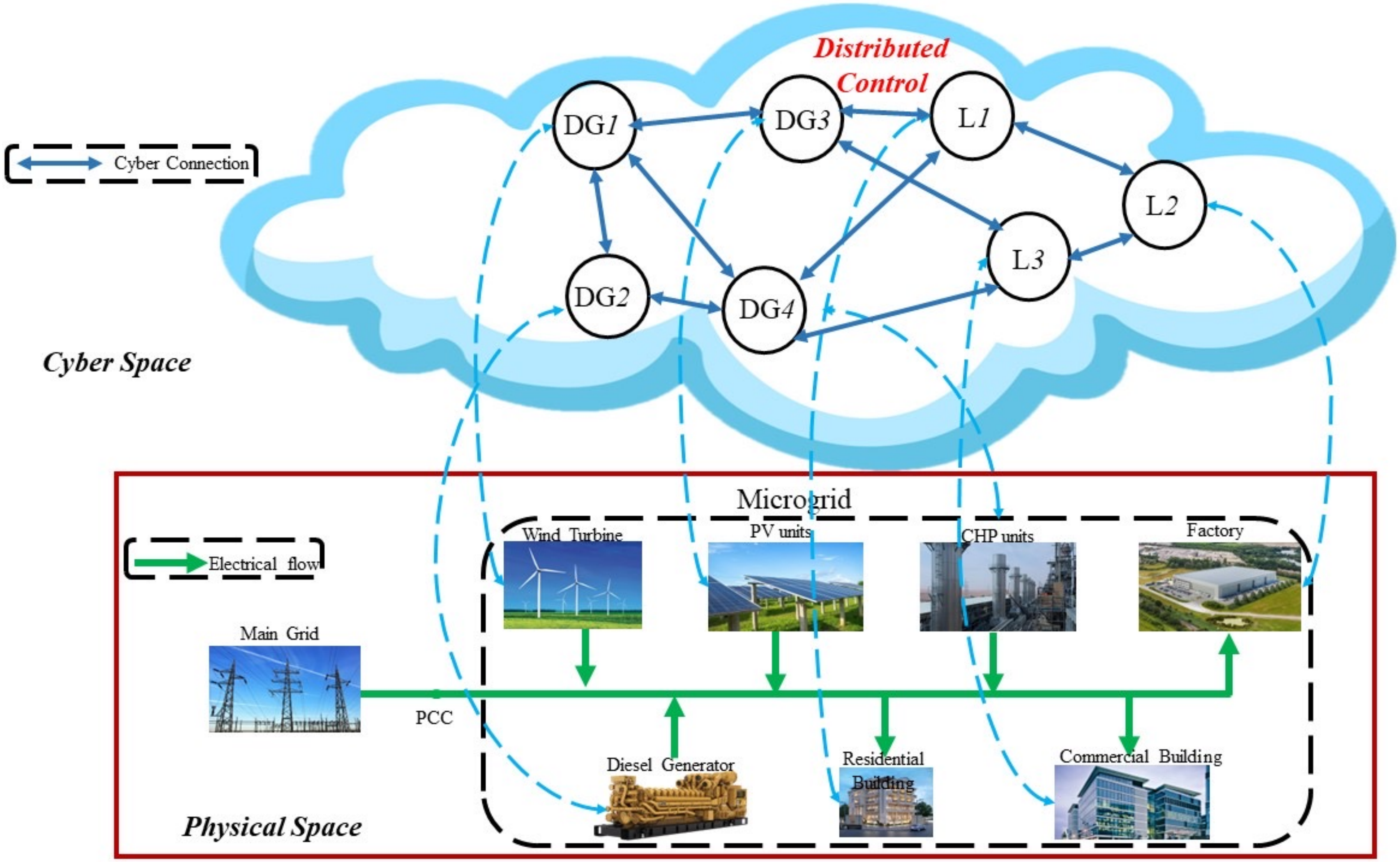
[C1]	**Caiazzo**, B., Fridman, E., Petrillo, A., & Santini, S., *Synchronization of Multi-Agent Systems under Time-Varying Network via Time-Delay Approach to Averaging,* ***17th IFAC Workshop on Time Delay Systems TDS 2022*** Montreal, Canada, September 27-30, 2022, IFAC
[C2]	**Caiazzo**, B., Fridman, E., Petrillo, A., & Santini, S., *Cooperative Finite-time Control for autonomous vehicles platoons with nonuniform V2V communication delays,* ***17th IFAC Workshop on Time Delay Systems TDS 2022*** Montreal, Canada, September 27-30, 2022, IFAC
[C3]	A. Andreotti, B. **Caiazzo**, A. Di Pasquale, M. Pagano, *On Comparing Regressive and Artificial Neural Network Methods for Power System Forecast* 2021 AEIT International Annual Conference (AEIT), (pp. 1-6). **IEEE**.
[C4]	B. **Caiazzo**, D. G. Lui, A. Petrillo, S. Santini, *Distributed Robust Finite-Time PID control for the leader-following consensus of uncertain Multi-Agent Systems with communication delay,* ***2021 29th Mediterranean Conference on Control and Automation (MED),*** Online-event, 22-25 June 2021, (pp. 759-764). IEEE.
[C5]	B. **Caiazzo**, E. Fridman, A. Petrillo, S. Santini, *Distributed Sampled-data PID Control for Voltage Regulation in Inverter-Based Islanded Microgrids Using Artificial Delays* ***16th IFAC Workshop on Time Delay Systems TDS 2021*** Guangzhou, China, 29 September-1 October 2021. IFAC-PapersOnLine 54.18 (2021): 186-191.

Research products (3/3)

[C6]	B. **Caiazzo**, D. G. Lui, A. Petrillo, S. Santini, *On the exponential leader-tracking control for high-order multi-agent systems via distributed PI strategy in the presence of heterogeneous time-varying delays,* ***16th IFAC Workshop on Time Delay Systems TDS 2021*** Guangzhou, China, 29 September-1 October 2021. IFAC-PapersOnLine 54.18 (2021): 139-144.
[C7]	B. **Caiazzo**, A. Coppola, A. Petrillo, S. Santini, *Energy-Oriented Inter-Vehicle Distance Optimization for Heterogeneous E-Platoons,* ***AIRO Workshop 2021, Optimization and Data Science: Trends and Applications. Springer, Cham, 2021.*** *113-125.*
[C8]	A. Andreotti, B. **Caiazzo**, A. Petrillo, S. Santini, A. Vaccaro *Robust Finite-time Voltage Restoration in Inverter-Based Microgrids via Distributed Cooperative Control in presence of communication time-varying delays* ***2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe). IEEE,*** *2020.*
[C9]	G.N. Bifulco, B. **Caiazzo**, A. Coppola, S. Santini, *Intersection crossing in mixed traffic flow environment leveraging v2x information,* ***2019 IEEE International Conference on Connected Vehicles and Expo (ICCVE). IEEE, 2019.*** *Graz, Austria, 04-08 November 2019*

PhD thesis Overview (1/2)

Study of modern Microgrids as a **Networked Control System** consisting of a set of spatially distributed intelligent systems, i.e., the electronically interfaced Distributed Energy Resources (DERs), in which the communication among sensors, actuators and controllers occurs through a shared band limited digital communication network.



PhD thesis Overview (2/2)

In order to guarantee effective, resilient and reliable Microgrids operations, it is required to proper manage and coordinate all the involved and geographically dispersed DERs via the design of appropriate distributed control strategies.

From a control perspective, a Microgrid can be tackled as a **Multi-Agent Systems (MASs)**, where *synchronization* and *consensus* theory can be exploited to guarantee the achievement of desired frequency and voltage values.

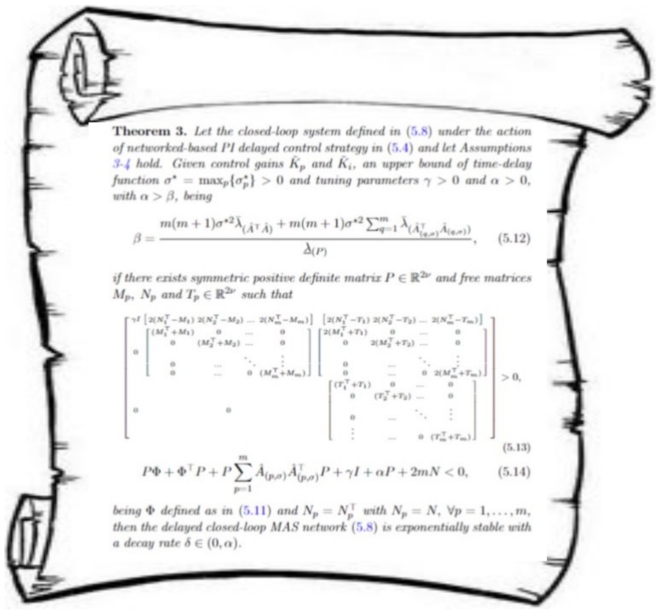
Open Challeges in Distributed Cooperative Control of MAS and Microgrids

- Communication Time-Delays
- Limited communication bandwidth
- Short convergence time
- Unknown model mismatches, external disturbances and uncertainties affecting Microgrids dynamic

Resilience with respect to communication time-delays

EXISTING DISTRIBUTED COOPERATIVE CONTROL STRATEGIES

- Constant and unique communication time-delays;
- Homogeneous time-varying delays;
- Distributed PI/PID protocols are still slightly covered, while their benefits are neglected.



Theorem 3. *Let the closed-loop system defined in (5.8) under the action of networked-based PI delayed control strategy in (5.4) and let Assumptions 3-4 hold. Given control gains $\bar{K}_p$ and $\bar{K}_i$, an upper bound of time-delay function $\sigma^\star = \max_p\{\sigma_p^\star\} > 0$ and tuning parameters $\gamma > 0$ and $\alpha > 0$, with $\alpha > \beta$, being*

$$\beta = \frac{m(m+1)\sigma^{\star 2}\bar{\lambda}_{(\hat{A}^\top \hat{A})} + m(m+1)\sigma^{\star 2}\sum_{q=1}^{m}\bar{\lambda}_{(\hat{A}^\top_{(q,\sigma)}\hat{A}_{(q,\sigma)})}}{\underline{\lambda}_{(P)}}, \quad (5.12)$$

if there exists symmetric positive definite matrix $P \in \mathbb{R}^{2\nu}$ and free matrices M_p, N_p and $T_p \in \mathbb{R}^{2\nu}$ such that

$$\begin{bmatrix} \gamma I & [2(N_1^\top - M_1)\; 2(N_2^\top - M_2) \;\dots\; 2(N_m^\top - M_m)] & [2(N_1^\top - T_1)\; 2(N_2^\top - T_2)\;\dots\; 2(N_m^\top - T_m)] \\ 0 & \begin{bmatrix} (M_1^\top + M_1) & 0 & \dots & 0 \\ 0 & (M_2^\top + M_2) & \dots & 0 \\ 0 & \dots & \ddots & \vdots \\ 0 & \dots & 0 & (M_m^\top + M_m) \end{bmatrix} & \begin{bmatrix} 2(M_1^\top + T_1) & 0 & \dots & 0 \\ 0 & 2(M_2^\top + T_2) & \dots & 0 \\ 0 & \dots & \ddots & \vdots \\ 0 & \dots & 0 & 2(M_m^\top + T_m) \end{bmatrix} \\ 0 & 0 & \begin{bmatrix} (T_1^\top + T_1) & 0 & \dots & 0 \\ 0 & (T_2^\top + T_2) & \dots & 0 \\ 0 & \dots & \ddots & \vdots \\ \vdots & \dots & 0 & (T_m^\top + T_m) \end{bmatrix} \end{bmatrix} > 0, \quad (5.13)$$

$$P\Phi + \Phi^\top P + P\sum_{p=1}^{m}\hat{A}_{(p,\sigma)}\hat{A}^\top_{(p,\sigma)}P + \gamma I + \alpha P + 2mN < 0, \quad (5.14)$$

being Φ defined as in (5.11) and $N_p = N_p^\top$ with $N_p = N$, $\forall p = 1, \dots, m$, then the delayed closed-loop MAS network (5.8) is exponentially stable with a decay rate $\delta \in (0, \alpha)$.

PROPOSED SOLUTION:

Designing of a **distributed PI-like controller** to solve leader-tracking consensus control problem in high-order delayed MASs such that:

- **Heterogeneous** communication time-delays are counteracted;
- The benefits of the PI structure are enjoyed;
- **Lyapunov-Krasovskii** theory for time-delay systems along with **Halanay Lemma** are combined to obtain **exponential stability conditions**;
- **Maximum delay bound** and **convergence rate** can be analytically found.

$$u_i(t, \tau_{ij}(t)) = -\bar{K}_p\sum_{j=0}^{N} a_{ij}\Big(x_i(t - \tau_{ij}(t)) - x_j(t - \tau_{ij}(t))\Big)$$
$$-\bar{K}_i\sum_{j=0}^{N} a_{ij}\int_0^{t-\tau_{ij}(t)}(x_i(s) - x_j(s))\,ds$$

PhD thesis Overview (2/2)

In order to guarantee effective, resilient and reliable Microgrids operations, it is required to proper manage and coordinate all the involved and geographically dispersed DERs via the design of appropriate distributed control strategies.

In this perspective, a Microgrid can be considered as a **Multi-Agent Systems (MASs)**, where *synchronization* and *consensus* theory can be exploited to guarantee the achievement of desired frequency and voltage values.

Open Challeges in Distributed Cooperative Control of MAS and Microgrids

Communication Time-Delays

Limited communication bandwidth

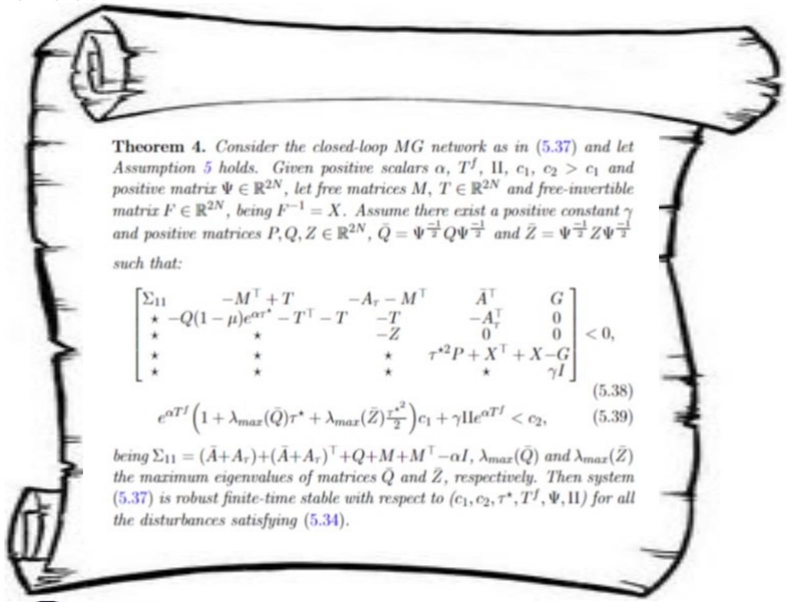
Short convergence time

Unknown model mismatches, external disturbances and uncertainties affecting Microgrids dynamic

Resilience with respect to communication time-delays & Short Convergence Time (1/2)

EXISTING DISTRIBUTED VOLTAGE REGULATION STRATEGIES

- Neglect the presence of communication time-delays or these latter are assumed to be constant and unique over the network.
- No delay-dependent gain tuning rules are provided.
- No finite-time voltage stability has been proven in the presence of communication latencies.



Theorem 4. *Consider the closed-loop MG network as in (5.37) and let Assumption 5 holds. Given positive scalars α, T^f, II, c_1, $c_2 > c_1$ and positive matrix $\Psi \in \mathbb{R}^{2N}$, let free matrices M, $T \in \mathbb{R}^{2N}$ and free-invertible matrix $F \in \mathbb{R}^{2N}$, being $F^{-1} = X$. Assume there exist a positive constant γ and positive matrices $P, Q, Z \in \mathbb{R}^{2N}$, $\bar{Q} = \Psi^{\frac{-1}{2}} Q \Psi^{\frac{-1}{2}}$ and $\bar{Z} = \Psi^{\frac{-1}{2}} Z \Psi^{\frac{-1}{2}}$ such that:*

$$\begin{bmatrix} \Sigma_{11} & -M^\top + T & -A_\tau - M^\top & \bar{A}^\top & G \\ \star & -Q(1-\mu)e^{\alpha\tau^\star} - T^\top - T & -T & -A_\tau^\top & 0 \\ \star & \star & -Z & 0 & 0 \\ \star & \star & \star & \tau^{\star 2} P + X^\top + X & -G \\ \star & \star & \star & \star & \gamma I \end{bmatrix} < 0, \quad (5.38)$$

$$e^{\alpha T^f}\left(1 + \lambda_{max}(\bar{Q})\tau^\star + \lambda_{max}(\bar{Z})\frac{\tau^{\star 2}}{2}\right)c_1 + \gamma \mathrm{II} e^{\alpha T^f} < c_2, \quad (5.39)$$

being $\Sigma_{11} = (\bar{A}+A_\tau)+(\bar{A}+A_\tau)^\top + Q + M + M^\top - \alpha I$, $\lambda_{max}(\bar{Q})$ and $\lambda_{max}(\bar{Z})$ the maximum eigenvalues of matrices $\bar{Q}$ and $\bar{Z}$, respectively. Then system (5.37) is robust finite-time stable with respect to $(c_1, c_2, \tau^\star, T^f, \Psi, \mathrm{II})$ for all the disturbances satisfying (5.34).

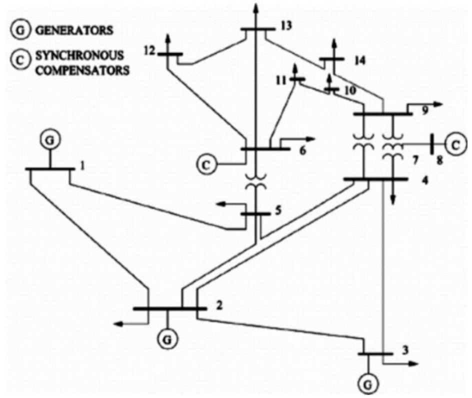
PROPOSED SOLUTION:

Designing of a **distributed controller** to solve voltage regulation problem in islanded Microgrids such that:

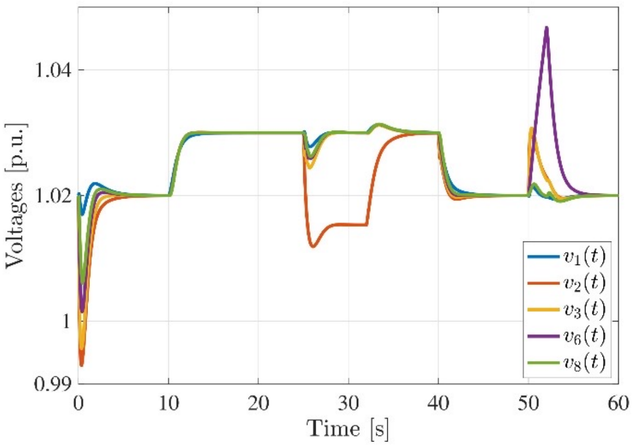
- DGs voltage are restored in a **finite time interval**;
- **Communication time-varying delays** are counteracted;
- **Lyapunov-Krasovskii** theory to prove the finite-time stability of the entire network;
- Linear Matrix Inequalities (**LMIs)-based delay-dependent stability conditions** are derived, which analytically provide control gains tuning, maximum delay bound and state trajectories threshold;
- Validation is carried-out on **IEEE 14 bus test system.**

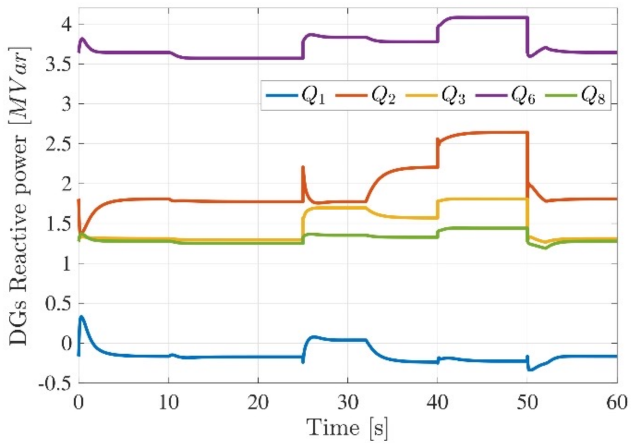
$$u_i^V(t, \tau(t)) = K \sum_{j \in \mathcal{N}_i^c} a_{ij}\big(x_i(t - \tau(t)) - x_j(t - \tau(t))\big)$$

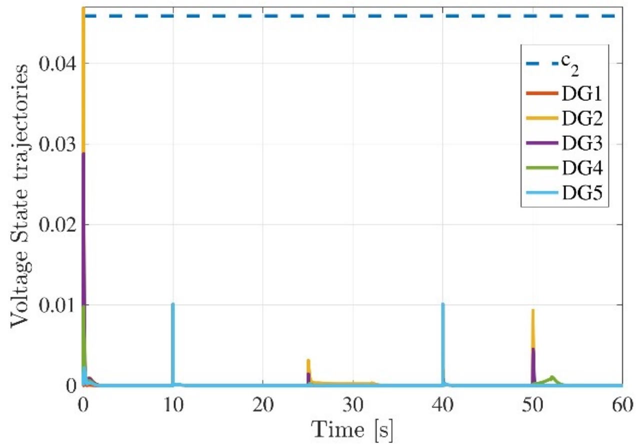
Resilience with respect to communication time-delays & Short Convergence Time (2/2)



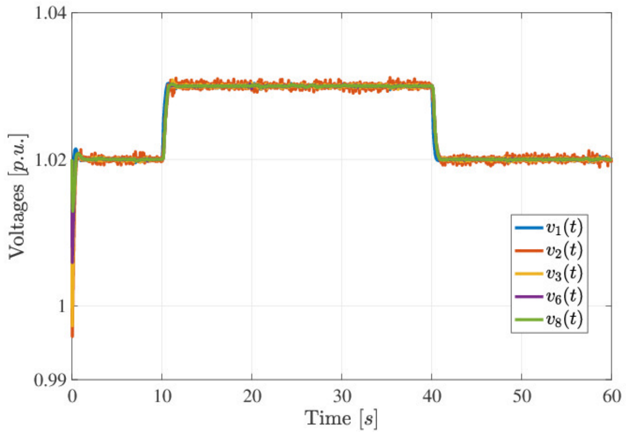
Exemplary Simulations in Plug-and-Play Scenario: DG2 and DG4 are unplugged at $t = 25[s]$ and $t = 50[s]$, respectively, and then plugged-in at $t = 32[s]$ and $t = 52[s]$, respectively.

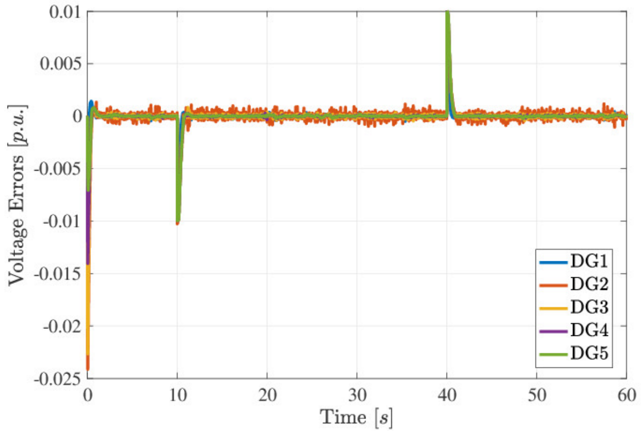






Comparison with other State-of-the-art delay-free voltage controller





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PhD thesis Overview (2/2)

In order to guarantee effective, resilient and reliable Microgrids operations, it is required to proper manage and coordinate all the involved and geographically dispersed DERs via the design of appropriate distributed control strategies.

In this perspective, a Microgrid can be considered as a **Multi-Agent Systems (MASs)**, where *synchronization* and *consensus* theory can be exploited to guarantee the achievement of desired frequency and voltage values.

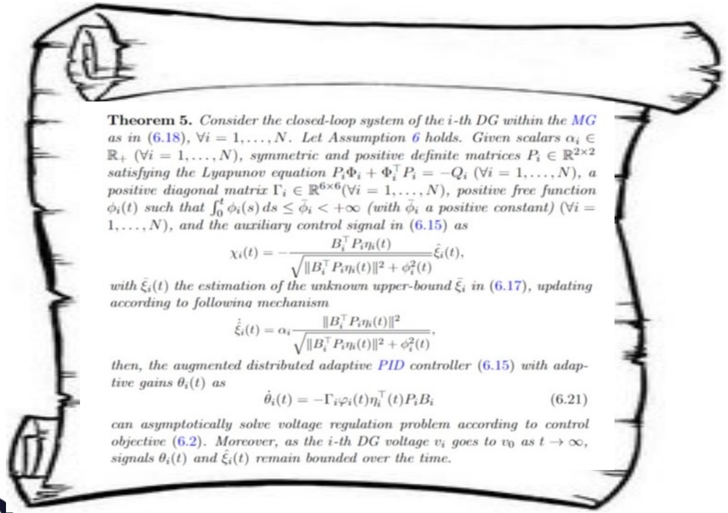
Open Challeges in Distributed Cooperative Control of MAS and Microgrids

- Communication Time-Delays
- Limited communication bandwidth
- Short convergence time
- Unknown model mismatches, external disturbances and uncertainties affecting Microgrids dynamic

Resilience with respect to unknown and unbounded uncertainties (1/3)

EXISTING DISTRIBUTED VOLTAGE REGULATION CONTROLLERS

- Uncertainties/disturbances/model mismatches are assumed to be known and bounded.
- High computational complexity and real-time implementation issues resulting from artificial neural networks/ backstepping/ fuzzy-based adaptive approaches;
- The solely Uniform Ultimately Bounded (UUB) stability for the voltage error trajectories are ensured.



Theorem 5. *Consider the closed-loop system of the i-th DG within the MG as in (6.18), $\forall i = 1,\dots,N$. Let Assumption 6 holds. Given scalars $\alpha_i \in \mathbb{R}_+$ ($\forall i = 1,\dots,N$), symmetric and positive definite matrices $P_i \in \mathbb{R}^{2\times 2}$ satisfying the Lyapunov equation $P_i\Phi_i + \Phi_i^\top P_i = -Q_i$ ($\forall i = 1,\dots,N$), a positive diagonal matrix $\Gamma_i \in \mathbb{R}^{6\times 6}$($\forall i = 1,\dots,N$), positive free function $\phi_i(t)$ such that $\int_0^t \phi_i(s)\,ds \le \bar{\phi}_i < +\infty$ (with $\bar{\phi}_i$ a positive constant) ($\forall i = 1,\dots,N$), and the auxiliary control signal in (6.15) as*

$$\chi_i(t) = -\frac{B_i^\top P_i \eta_i(t)}{\sqrt{\|B_i^\top P_i \eta_i(t)\|^2 + \phi_i^2(t)}}\hat{\xi}_i(t),$$

with $\hat{\xi}_i(t)$ the estimation of the unknown upper-bound $\bar{\xi}_i$ in (6.17), updating according to following mechanism

$$\dot{\hat{\xi}}_i(t) = \alpha_i \frac{\|B_i^\top P_i \eta_i(t)\|^2}{\sqrt{\|B_i^\top P_i \eta_i(t)\|^2 + \phi_i^2(t)}},$$

then, the augmented distributed adaptive PID controller (6.15) with adaptive gains $\theta_i(t)$ as

$$\dot{\theta}_i(t) = -\Gamma_i \varphi_i(t) \eta_i^\top(t) P_i B_i \qquad (6.21)$$

can asymptotically solve voltage regulation problem according to control objective (6.2). Moreover, as the i-th DG voltage v_i goes to v_0 as $t \to \infty$, signals $\theta_i(t)$ and $\hat{\xi}_i(t)$ remain bounded over the time.

PROPOSED SOLUTION:

Designing of a **distributed adaptive PID-like controller** to solve voltage regulation problem in islanded Microgrids such that:

- DGs voltage are restored **without requiring any global information;**
- The **self-tuning adaptive mechanisms** are derived from **Lyapunov theory** along with **Barbalat lemma;**
- The theoretical derivation allows guaranteeing the resilience to any **completely unknown disturbances/uncertainties**;
- The voltage tracking errors **asymptotically** converge to zero, while the adaptive signals remain bounded at steady-state;
- **Reduction of the maximum voltage deviation percentage** with respect to alternative adaptive voltage controllers.

$$u_i^v(t) = u_{i,PID}^v(t) + \chi_i(t) = K_{Pi}(t)\eta_i(t) + K_{Ii}(t)\int_0^t \eta_i(s)ds + K_{Di}(t)\dot{\eta}_i(t) + \chi_i(t),$$

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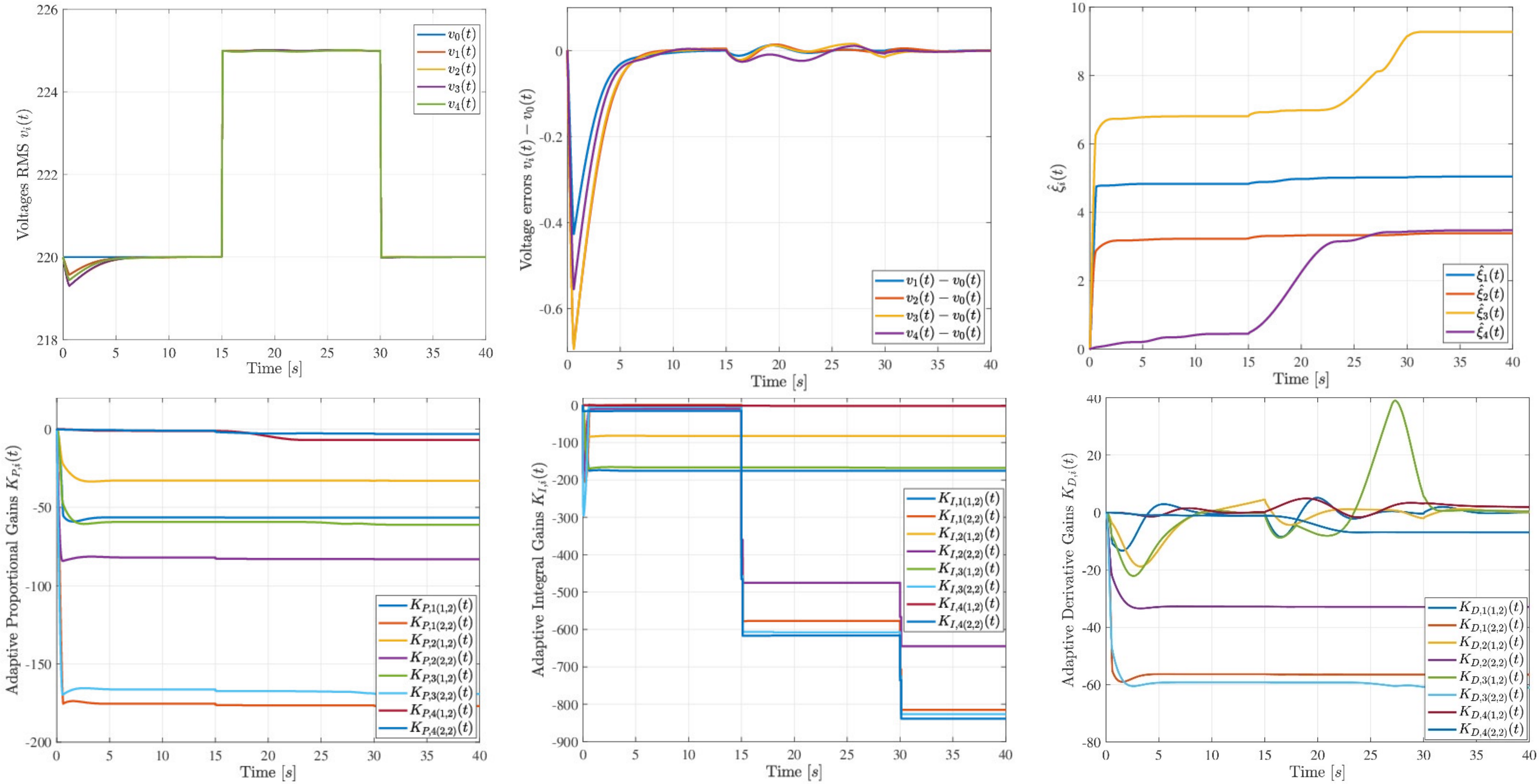
Resilience with respect to unknown and unbounded uncertainties (2/3)

Exemplary Simulations in Plug-and-Play Scenario: DG2 and DG3 are unplugged at $t = 10[s]$ and $t = 18[s]$, respectively, and then plugged-in at $t = 15[s]$ and $t = 27[s]$.



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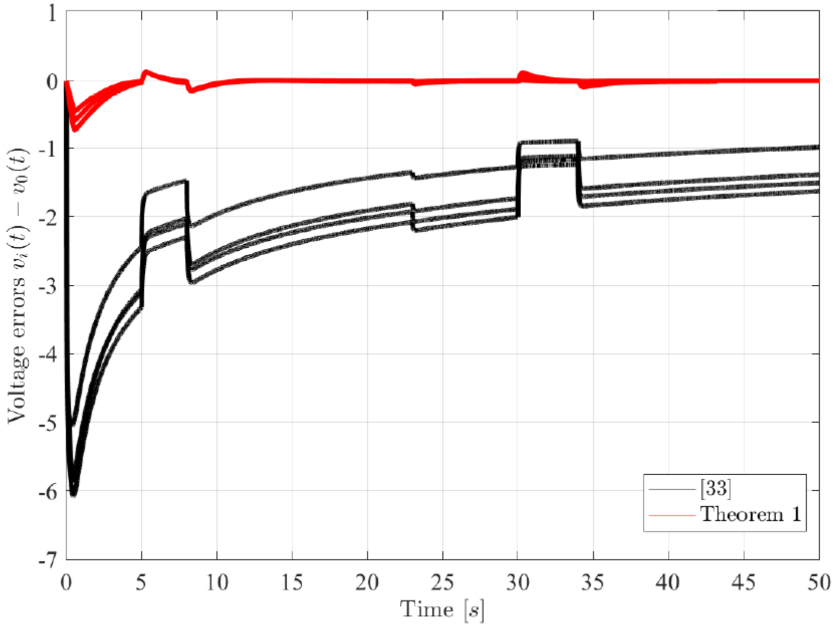
Resilience with respect to unknown and unbounded uncertainties (3/3)

Comparison with other State-of-the-art adaptive voltage controller



For the proposed controller, the maximum voltage deviation is **0.34%**, whereas for the comparative adaptive strategy it is **2.76%.**
This benefit straightly comes from the PID-like structure of the proposed control strategy.

PhD thesis Overview (2/2)

In order to guarantee effective, resilient and reliable Microgrids operations, it is required to proper manage and coordinate all the involved and geographically dispersed DERs via the design of appropriate distributed control strategies.

In this perspective, a Microgrid can be considered as a **Multi-Agent Systems (MASs)**, where *synchronization* and *consensus* theory can be exploited to guarantee the achievement of desired frequency and voltage values.

Open Challeges in Distributed Cooperative Control of MAS and Microgrids

Communication Time-Delays

Limited communication bandwidth

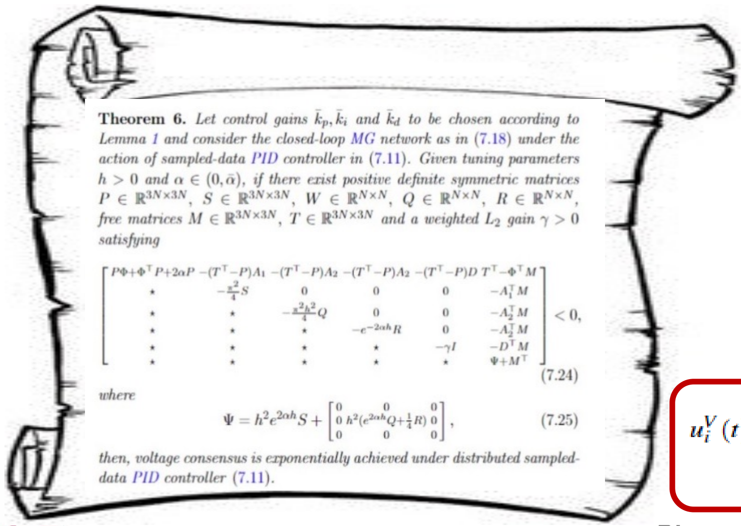
Short convergence time

Unknown model mismatches, external disturbances and uncertainties affecting Microgrids dynamic

From Continuous to periodic inter-agents interactions (1/2)

EXISTING DISTRIBUTED VONTAGE CONTROLLER

- Continuous update of the controllers.
- Practical issues in implementing continuous-time distributed controllers in digital control platform.
- Communication resources are assumed to be unlimited.
- Few attempts in designing communication resources saving-oriented control strategies.
- No sampling-dependent stability conditions are provided to analytically found maximum sampling period preserving the stability.



Theorem 6. *Let control gains $\bar{k}_p, \bar{k}_i$ and $\bar{k}_d$ to be chosen according to Lemma 1 and consider the closed-loop MG network as in (7.18) under the action of sampled-data PID controller in (7.11). Given tuning parameters $h > 0$ and $\alpha \in (0, \bar{\alpha})$, if there exist positive definite symmetric matrices $P \in \mathbb{R}^{3N\times 3N}$, $S \in \mathbb{R}^{3N\times 3N}$, $W \in \mathbb{R}^{N\times N}$, $Q \in \mathbb{R}^{N\times N}$, $R \in \mathbb{R}^{N\times N}$, free matrices $M \in \mathbb{R}^{3N\times 3N}$, $T \in \mathbb{R}^{3N\times 3N}$ and a weighted L_2 gain $\gamma > 0$ satisfying*

$$\begin{bmatrix} P\Phi+\Phi^\top P+2\alpha P & -(T^\top-P)A_1 & -(T^\top-P)A_2 & -(T^\top-P)A_2 & -(T^\top-P)D & T^\top-\Phi^\top M \\ \star & -\frac{\pi^2}{4}S & 0 & 0 & 0 & -A_1^\top M \\ \star & \star & -\frac{\pi^2 h^2}{4}Q & 0 & 0 & -A_2^\top M \\ \star & \star & \star & -e^{-2\alpha h}R & 0 & -A_2^\top M \\ \star & \star & \star & \star & -\gamma I & -D^\top M \\ \star & \star & \star & \star & \star & \Psi+M^\top \end{bmatrix} < 0, \quad (7.24)$$

where

$$\Psi = h^2 e^{2\alpha h} S + \begin{bmatrix} 0 & 0 & 0 \\ 0 & h^2(e^{2\alpha h}Q+\frac{1}{4}R) & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad (7.25)$$

then, voltage consensus is exponentially achieved under distributed sampled-data PID controller (7.11).

PROPOSED SOLUTION:

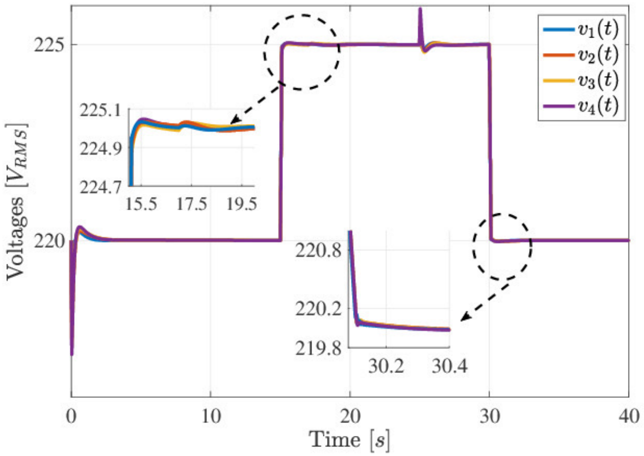
Designing of a **distributed sampled-data PID-like controller** to solve voltage regulation problem in islanded Microgrids such that:

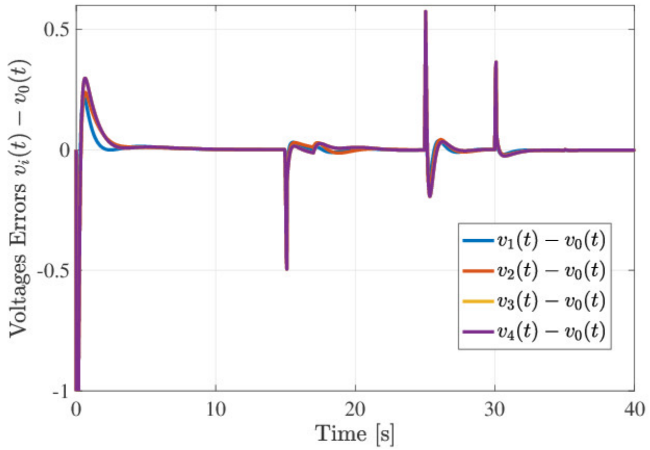
- **No continuous information sharing** among DGs;
- The sampled-data implementation results from the application of **Artificial Delays** approach, which confirms that the **presence of delays is not always detrimental;**
- **Lyapunov-Krasovskii theory** to prove the stability of the Microgrids voltage;
- **LMI-based stability criteria** are derived, which analytically provide maximum sampling period preserving the stability;
- **Reduction of the amount of the control signals** used for stabilization.

$$u_i^V(t) = k_p \sum_{j\in\mathcal{N}_i^c} a_{ij}(e_i(t_k) - e_j + k_i h \sum_{j\in\mathcal{N}_i^c} \sum_{s=0}^{k-1} (e_i(t_s) - e + k_d \sum_{j\in\mathcal{N}_i^c} a_{ij}(\bar{e}_i(t_{k-1}) - \bar{e}_j(t_{k-1})),$$
$$t \in [t_k, t_{k+1}),\ k \in \mathbb{N}_0$$

From Continuous to Periodic inter-agents interactions (5/5)

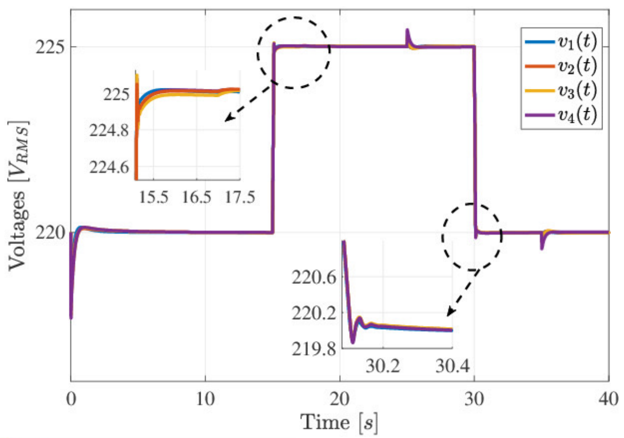
Exemplary Simulations with proposed Sampled-Data Controller: the proposed sampled-data PID controller requires to transmit $\frac{40}{h} + 1 = 20001$ control signals during 40[s] of simulation, thus reducing the total amount of transmitted signal by almost $\mathbf{75\%}$.

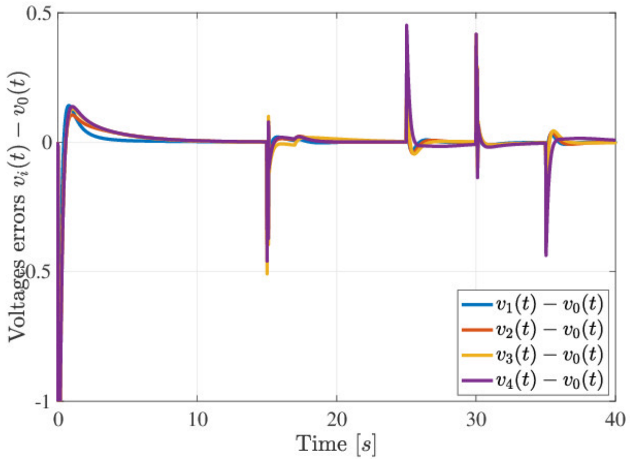




- DG3 is unplugged at $t = 15[s]$, and then plugged-in at $t = 25[s]$.
- Load 4 is removed at $t = 25[s]$ and readded at $t = 35$ $[s]$.

Classical continuous-time PID Controller





PhD thesis Overview (2/2)

In order to guarantee effective, resilient and reliable Microgrids operations, it is required to proper manage and coordinate all the involved and geographically dispersed DERs via the design of appropriate distributed control strategies.

In this perspective, a Microgrid can be considered as a **Multi-Agent Systems (MASs)**, where *synchronization* and *consensus* theory can be exploited to guarantee the achievement of desired frequency and voltage values.

Open Challeges in Distributed Cooperative Control of MAS and Microgrids

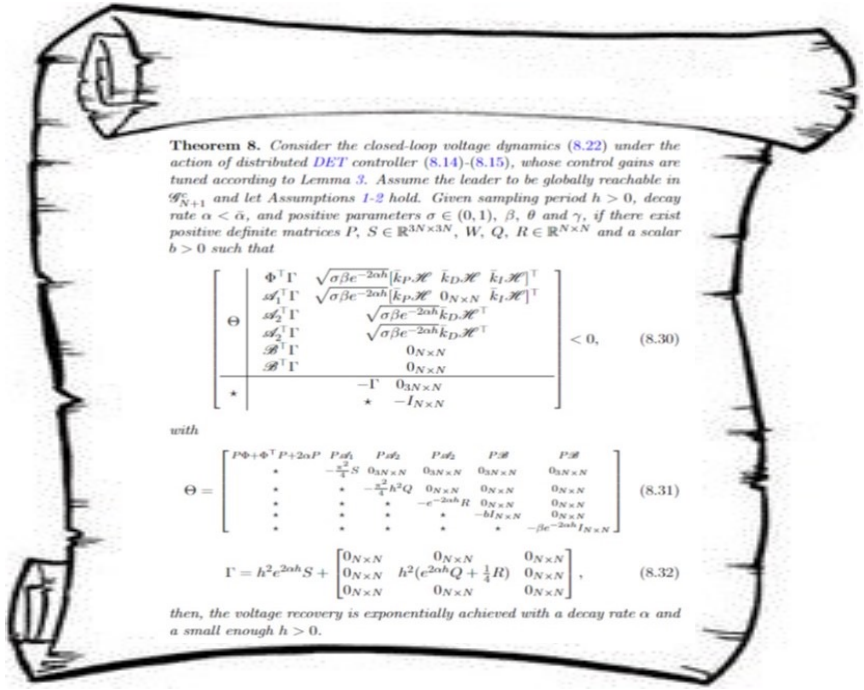
- Communication Time-Delays
- Limited communication bandwidth
- Short convergence time
- Unknown model mismatches, external disturbances and uncertainties affecting Microgrids dynamic

Is it possible to achieve a further reduction of the communication network workload from controller to actuator?

Towards Distributed A-Periodic Control (1/2)

EXISTING DISTRIBUTED EVENT-TRIGGERED VONTAGE CONTROLLERS

- Disturbances acting on DGs dynamics are usually neglected and, hence, Zeno-freeness property cannot be ensured.
- Static Event-triggered rules.
- Parameters of the triggering rules fixed *a-priori*.



Theorem 8. *Consider the closed-loop voltage dynamics (8.22) under the action of distributed DET controller (8.14)-(8.15), whose control gains are tuned according to Lemma 3. Assume the leader to be globally reachable in $\mathscr{G}^c_{N+1}$ and let Assumptions 1-2 hold. Given sampling period $h > 0$, decay rate $\alpha < \bar{\alpha}$, and positive parameters $\sigma \in (0,1)$, β, θ and γ, if there exist positive definite matrices $P,\ S \in \mathbb{R}^{3N\times 3N}$, $W,\ Q,\ R \in \mathbb{R}^{N\times N}$ and a scalar $b > 0$ such that*

$$\left[\begin{array}{c|c} \Theta & \begin{array}{cc} \Phi^\top\Gamma & \sqrt{\sigma\beta e^{-2\alpha h}}[\bar{k}_P\mathscr{H}\ \ \bar{k}_D\mathscr{H}\ \ \bar{k}_I\mathscr{H}]^\top \\ \mathscr{A}_1^\top\Gamma & \sqrt{\sigma\beta e^{-2\alpha h}}[\bar{k}_P\mathscr{H}\ \ 0_{N\times N}\ \ \bar{k}_I\mathscr{H}]^\top \\ \mathscr{A}_2^\top\Gamma & \sqrt{\sigma\beta e^{-2\alpha h}}\bar{k}_D\mathscr{H}^\top \\ \mathscr{A}_2^\top\Gamma & \sqrt{\sigma\beta e^{-2\alpha h}}\bar{k}_D\mathscr{H}^\top \\ \mathscr{B}^\top\Gamma & 0_{N\times N} \\ \mathscr{B}^\top\Gamma & 0_{N\times N} \end{array} \\ \hline \star & \begin{array}{cc} -\Gamma & 0_{3N\times N} \\ \star & -I_{N\times N} \end{array} \end{array}\right] < 0, \qquad (8.30)$$

with

$$\Theta = \begin{bmatrix} P\Phi+\Phi^\top P+2\alpha P & P\mathscr{A}_1 & P\mathscr{A}_2 & P\mathscr{A}_2 & P\mathscr{B} & P\mathscr{B} \\ \star & -\frac{\pi^2}{4}S & 0_{3N\times N} & 0_{3N\times N} & 0_{3N\times N} & 0_{3N\times N} \\ \star & \star & -\frac{\pi^2}{4}h^2Q & 0_{N\times N} & 0_{N\times N} & 0_{N\times N} \\ \star & \star & \star & -e^{-2\alpha h}R & 0_{N\times N} & 0_{N\times N} \\ \star & \star & \star & \star & -bI_{N\times N} & 0_{N\times N} \\ \star & \star & \star & \star & \star & -\beta e^{-2\alpha h}I_{N\times N} \end{bmatrix} \qquad (8.31)$$

$$\Gamma = h^2 e^{2\alpha h}S + \begin{bmatrix} 0_{N\times N} & 0_{N\times N} & 0_{N\times N} \\ 0_{N\times N} & h^2(e^{2\alpha h}Q + \frac{1}{4}R) & 0_{N\times N} \\ 0_{N\times N} & 0_{N\times N} & 0_{N\times N} \end{bmatrix}, \qquad (8.32)$$

then, the voltage recovery is exponentially achieved with a decay rate α and a small enough $h > 0$.

PROPOSED SOLUTION:

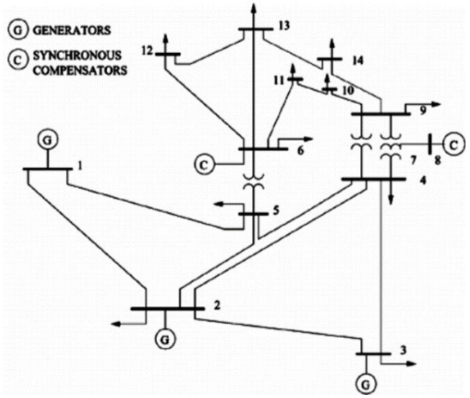
Designing of a **distributed Dynamic Event-Triggered (DET) controller** to solve voltage regulation problem in islanded Microgrids such that:

- **Fewer control update** are required with respect to conventional Static Event-Triggered mechanisms;
- **Artificial Delays** approach is combined with **DET mechanism**, where **Zeno freeness** property is ensured;
- **Lyapunov-Krasovskii** theory is exploited to prove the stability of the entire Microgrid voltage;
- **LMIs-based stability conditions** provide both sampling period and DET parameters preserving the stability;
- Validation is carried-out on **IEEE 14 bus test system.**

$$\hat{u}_i(t) = \hat{u}_i(t_k) = \begin{cases} u_i(t_k), & \text{if (8.15) is true,} \\ \hat{u}_i(t_{k-1}), & \text{otherwise,} \end{cases}$$

$$\gamma\lambda_i(t_k) + \sigma\beta|u_i(t_k)|^2 - \beta|\epsilon_i(t_k)|^2 < 0,$$

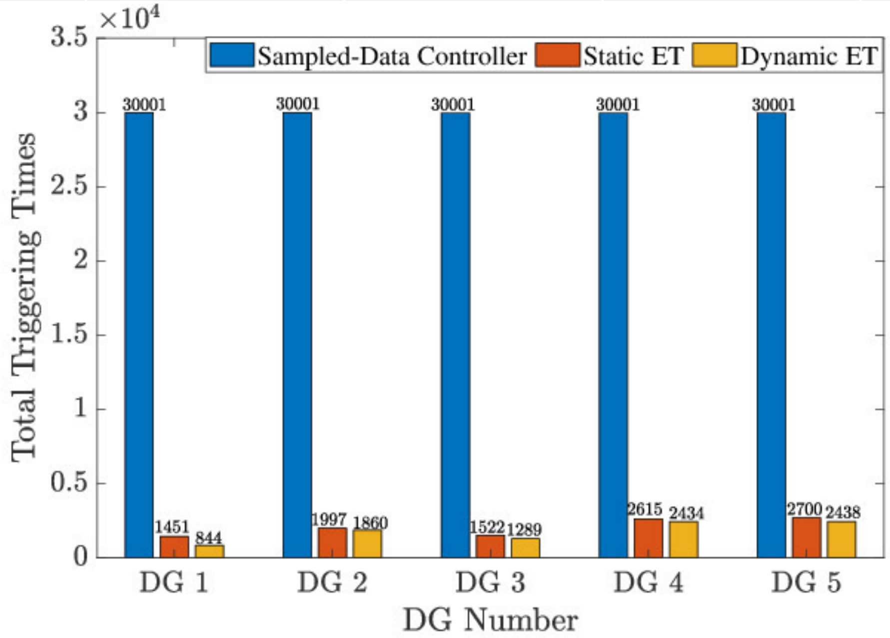
Towards Distributed A-Periodic Control (2/2)



Comparison with conventional Static Event-Triggered Strategy and previous Sampled-Data Controller

The reduction of the computational burden with respect to Sampled-Data controller and Static ETM are about **94.1%** and **13.81%**, respectively.

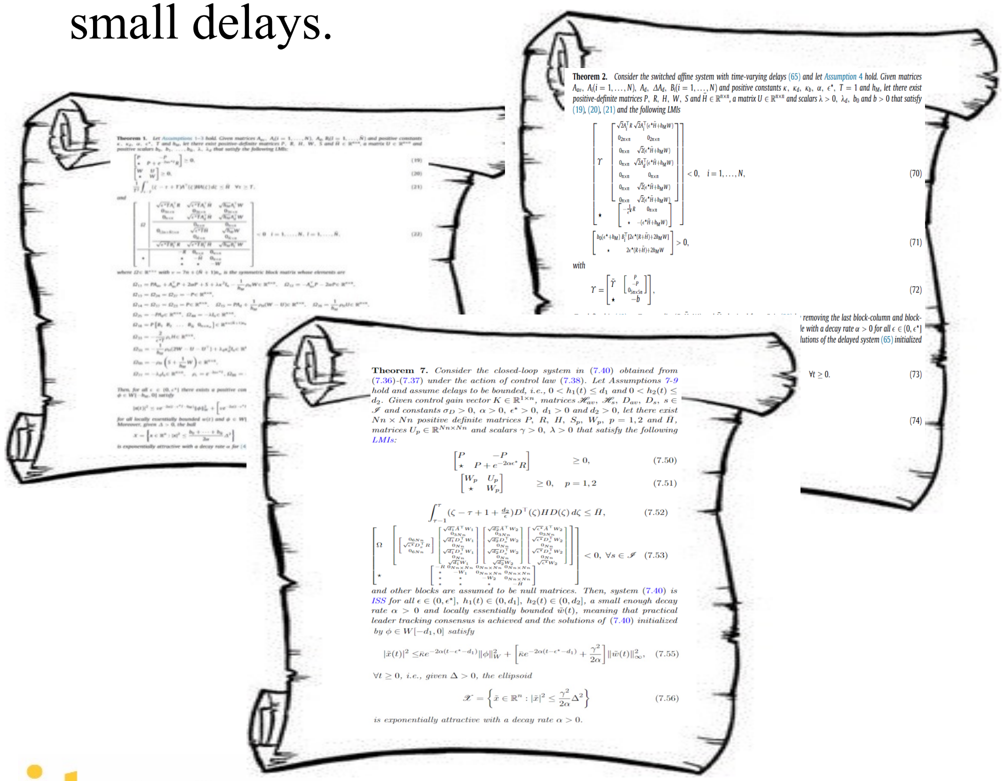
Controller	DG1	DG2	DG3	DG4	DG5	Total
Sampled Data Controller	-97.18	-93,8	-95.7	-91.89	-91.87	-94.1
Static ETM	-41.83	-6.87	-15.31	-6.92	-9.70	-13.81



Novel Time-Delay Approach to Periodic Averaging

CLASSICAL AVERAGING THEORY

- Inabil ty to provide an efficient quantitative upper ound on the small parameter ϵ till which st bility is still ensured.
- System c efficient are assumed to be continuous i e.
- The novel constr ay approach does not cover the class o ystems with non-small delays.



PROPOSED SOLUTION

- Extension of the **novel time-delay approach to periodic averaging** to the class of systems with fast-varying piecewise coefficients and **non-small delays**.
- Parameter ϵ and non-small delays bound are numerically found as **LMIs** solutions.
- Application to the stabilization of **switched affine systems**, useful to model **DC power converter**.
- **Lyapunov-Krasovskii** analysis to prove the input-to-state stability, which leads to LMI-based stability criteria able to provide also the ultimate bound value of the solutions.
- Application of this novel tool to solve **leader-tracking synchronization** problem in MAS in the presence of **switching communication topologies, even disconnected.**

Conclusions

- The study and training activities carried out during the third year of the PhD program have been highlighted, which were mainly devoted to the acquisition of new knowledge on time-delay systems control during the period abroad, as well as on the final PhD thesis writing.

- The main results arising from my PhD program have been highlighted, which aim to answer some open challenges in the field of distributed control of modern cyber-physical energy systems.

- A general overview of my PhD thesis has been provided, whose final objective is to promote the current green energy revolution by moving towards cyber-physical energy systems paradigm.

Thanks for the attention!

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