A Robust Design of Consensus Protocols for Simultaneous Real-Time Frequency Restoration and Load-Generation Balancing

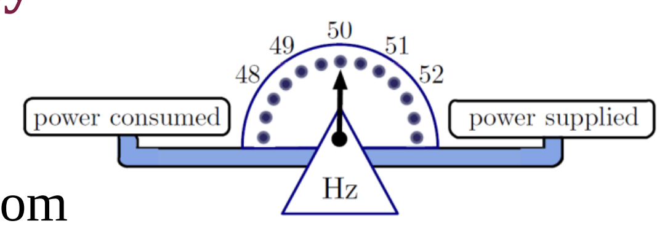
S. Alghamdi[1], J. Schiffer[1], and E. Fridman[2]
[1]School of Electronic and Electrical Engineering, University of Leeds, UK
[2]School of Electrical Engineering, Tel-Aviv University, Israel

Motivation

- Worldwide use of renewable energy sources (RES) has increased significantly in recent years
- Structure and dynamics of power systems with large amount of RES differ from conventional power systems
- Many challenges arise in control and operation of power systems with large amount of RES

Distributed Secondary Frequency Control

Secondary Frequency Control & Economic Optimality



- Overarching objective in power system operation: balance load and generation in real-time
- If power balance is not met, then power system frequency deviates from its nominal value
- Load demand is usually uncertain → Need controllable power to compensate for this uncertainty and bring frequency back to nominal value
- Optimal secondary control seeks to restore frequency, while simultaneously allocating secondary control injections via an economic generation dispatch

Consensus-Based Distributed Control Algorithm

- Consensus algorithms are distributed control schemes (peer to peer) that allow to reach an agreement between agents in a network by relying only on data exchange between nearest neighbours
- We employ the following consensus-based algorithm for secondary frequency control [3,4]

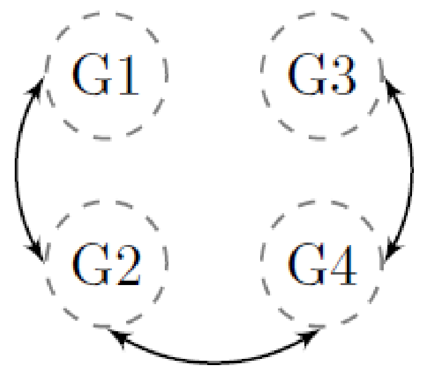
$$\begin{aligned} u_{\text{sec}} &= -p \\ \dot{p} &= \kappa K\left(\omega - 1_n\omega^d\right) - \kappa K A \mathcal{L} A p \end{aligned}$$

- $A > 0$ is fixed by economic considerations, $K > 0$ is a diagonal feedback gain matrix, ω^d is the reference frequency, κ is a parameter, p is the controller state and $\mathcal{L} = \mathcal{B}\mathcal{Z}\mathcal{B}^T \geq 0$ is the Laplacian matrix of a weighted, undirected, connected graph with node-edge incidence matrix $\mathcal{B}$ and diagonal matrix of edge weights $\mathcal{Z}$
- It has been shown in [3,4] that the above control provides a solution to the optimal secondary control problem

Problem Statement

Cyber-Physical Aspects in Distributed Frequency Control

- Closed-loop power system with distributed frequency control is a cyber-physical system
- Despite all recent advances, communication-based controllers are subject to considerable uncertainties (e.g., message delays)
- Both electrical and cyber layer are continuously exposed to exogenous perturbations

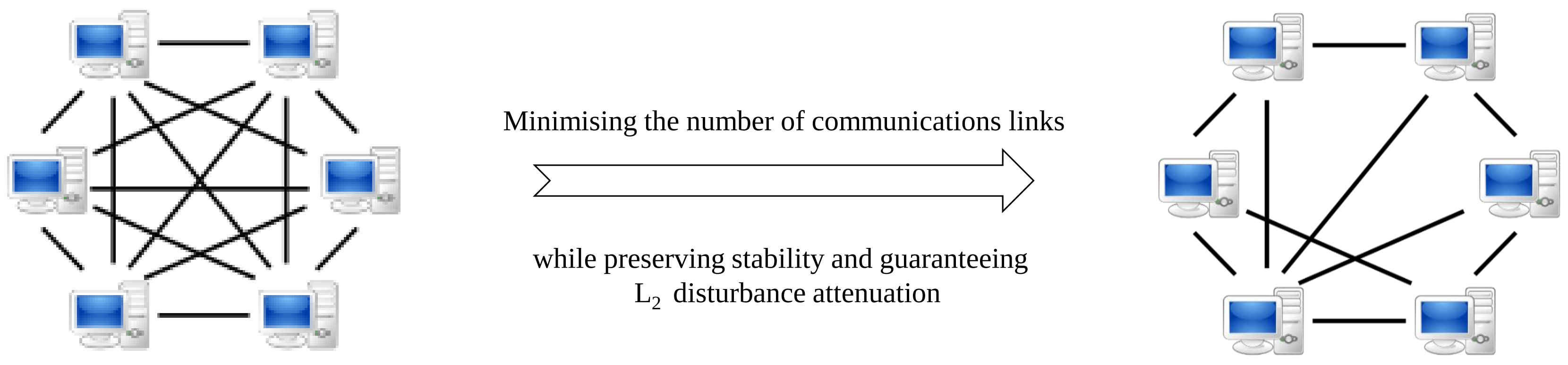


Exemplary distributed communication network topology with 4 generators

Main objectives

Determine the parameters κ and $\mathcal{Z}$ of the consensus-based secondary frequency controller, such that the closed-loop system satisfies the following four requirements:

1. It possesses a uniformly stable equilibrium point.
2. It is robust with respect to time-varying delays.
3. It exhibits a guaranteed L_2 disturbance attenuation.
4. The number of required communication links is minimised.



Proposed solution

Overview of Approach

- Derive controller synthesis guaranteeing robust stability by minimising the L_2-gain of the closed-loop system, while simultaneously taking into account time-varying communication delays [5]
- Approach is based on Lyapunov-Krasovskii method [6]
- Proposed synthesis allows to trade-off robustness and required communication links
- Design criteria are operating point independent and formulated in terms of linear matrix inequalities (LMIs), which can be solved very efficiently even for large-scale systems

Bibliography

1. J. Schiffer, F. Dörfler, and E. Fridman, “Robustness of distributed averaging control in power systems: Time delays & dynamic communication topology,” Automatica, vol. 80, pp. 261–271, 2017
2. J. Schiffer, D. Zonetti, R. Ortega, A. Stankovic, T. Sezi, and J. Raisch, “Modeling of microgrids - from fundamental physics to phasors and voltage sources,” Automatica, 74, no. 12, pp. 135-150, 2016
3. F. Dörfler, J. W. Simpson-Porco, and F. Bullo, “Breaking the hierarchy: Distributed control and economic optimality in microgrids,” IEEE Transactions on Control of Network Systems, vol. 3, no. 3, pp. 241–253, 2016
4. J. Schiffer and F. Dörfler, “On stability of a distributed averaging PI frequency and active power controlled differential-algebraic power system model”, in European Control Conference, pp. 1487-1492, 2016
5. S. Alghamdi, J. Schiffer and E. Fridman, “Distributed Secondary Frequency Control Design for Microgrids: Trading off L_2-Gain Performance and Communication Efforts under Time-Varying Delays”, in preparation for European Control Conference 2018
6. E. Fridman, Introduction to time-delay systems: analysis and control. Birkhäuser, 2014
7. J. Schiffer, R. Ortega, A. Astolfi, J. Raisch, and T. Sezi, “Conditions for stability of droop-controlled inverter-based microgrids,” Automatica,vol. 50, no. 10, pp. 2457–2469, 2014

Main Result: Design Criterion in Form of Convex Optimisation Problem

- Fix matrices $A > 0$ as well as $K > 0$ and an upper bound $h > 0$ for the delays
- Fix nonnegative weighting factors to trade off L_2-gain performance (α), frequency error convergence (β) and number of communication links ($W_{\mathcal{Z}}$)
- Suppose that there exist a parameter $\kappa > 0$ and matrices $\mathcal{Z} \geq 0, R > 0, S > 0, S_{12}$, such that the following optimisation problem is feasible:

$$\min_{\kappa,\mathcal{Z}} \alpha\gamma - \beta\kappa + \text{trace}(W_{\mathcal{Z}}\mathcal{Z})$$

$$\text{subject to}$$

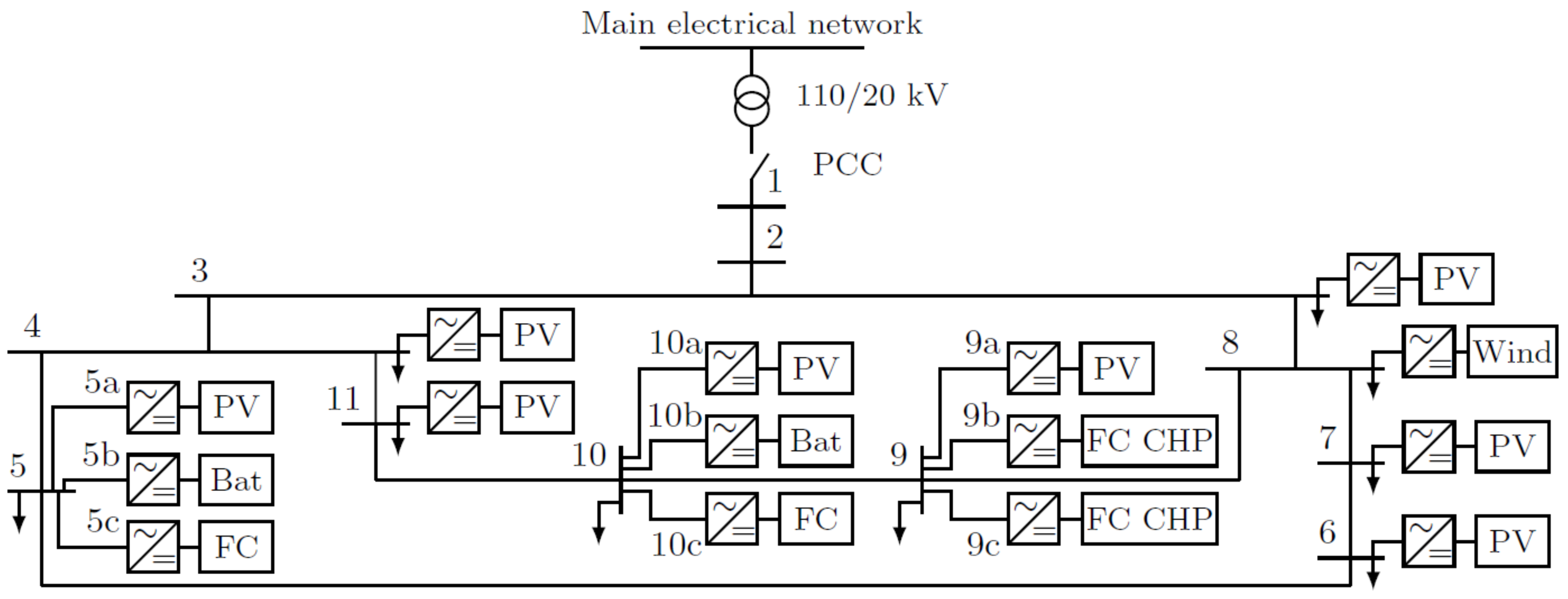
$$\begin{bmatrix} R & S_{12} \\ * & R \end{bmatrix} \geq 0$$

$$\mathrm{Q}(\gamma, \kappa, \mathrm{h}, \mathcal{Z}, \mathrm{R}, \mathrm{S}, S_{12}) < 0$$

- Then for all time-varying delays $\tau(t) \leq h$, the power system system’s operating point (if it exists) is locally uniformly asymptotically stable
- In addition, the power system has a small-signal L_2-gain less than or equal to γ with respect to exogenous perturbations d_ω, d_p acting on the local frequencies ω and the controller states p

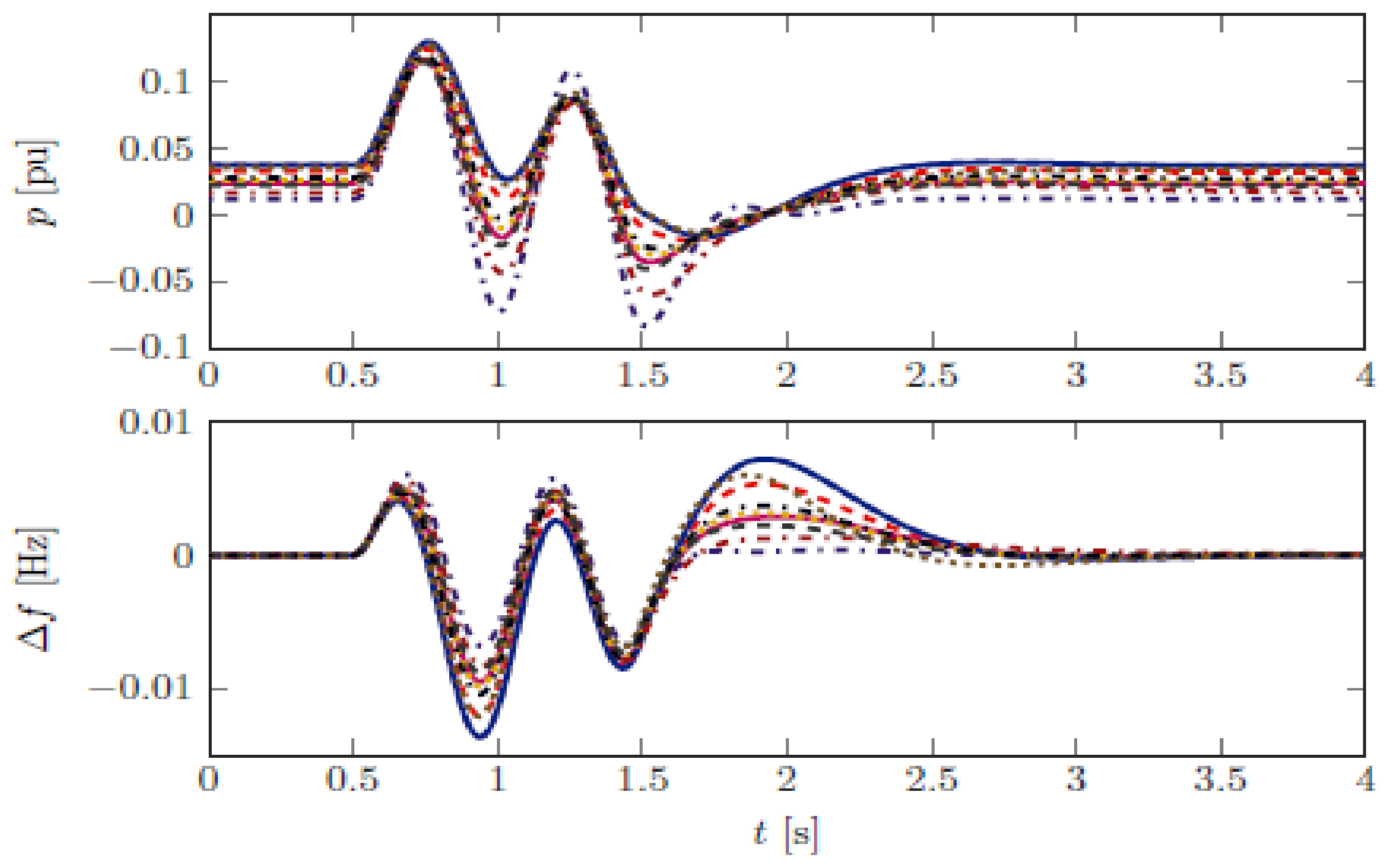
Case Study

- The performance of the proposed solution is demonstrated via simulation based on the CIGRE three phase medium voltage distribution network
- This network consists of 11 main buses and 10 generation units



Simulation results

- The presented results illustrate the convergence of the system trajectories to a synchronized motion after being subjected to external perturbations



Trading off L_2-gain performance and communication links

- The obtained results show a trade-off between the value of γ and the sparsity structure of the Laplacian matrix, i.e., the number of communication links.