Benefits of Closed-Loop Decentralized Power System Control Via Combined Frequency Control and Congestion Management

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What's new about this presentation?

The methodology of Unified Control (UC) developed by S. Low et al presented at Champery'2017 and PSCC'2016

Claims of benefits challenged by the audience (M. O'Malley)

This presentation: demonstration and quantification of benefits

Also a modified UC – Decoupled Unified Control (DUC) – as the original UC had some stability problems

Journal paper in IEEE Trans. PWRS under second review (fingers crossed)

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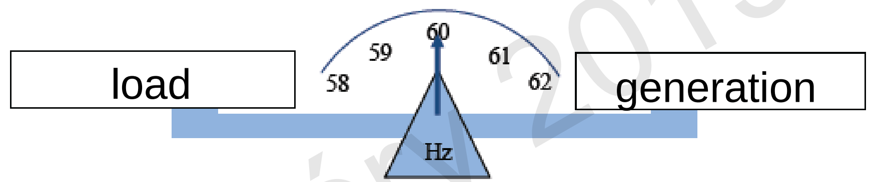
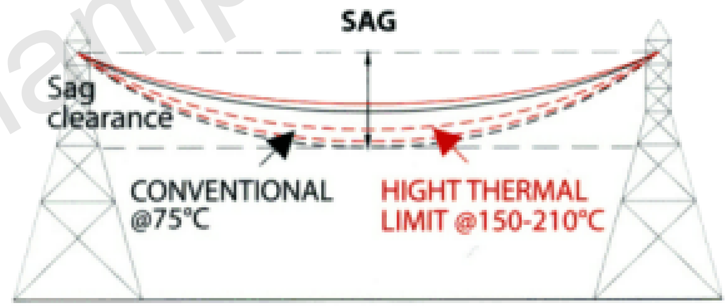
Main functions of power system control

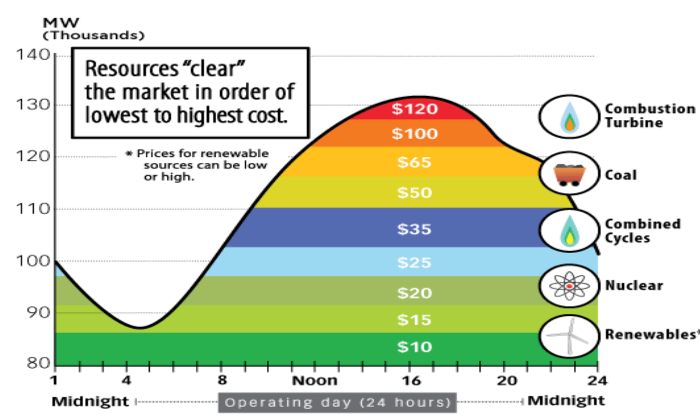
Balance generation & load / regulate **frequency**



Operational constraints, particularly **line limits**

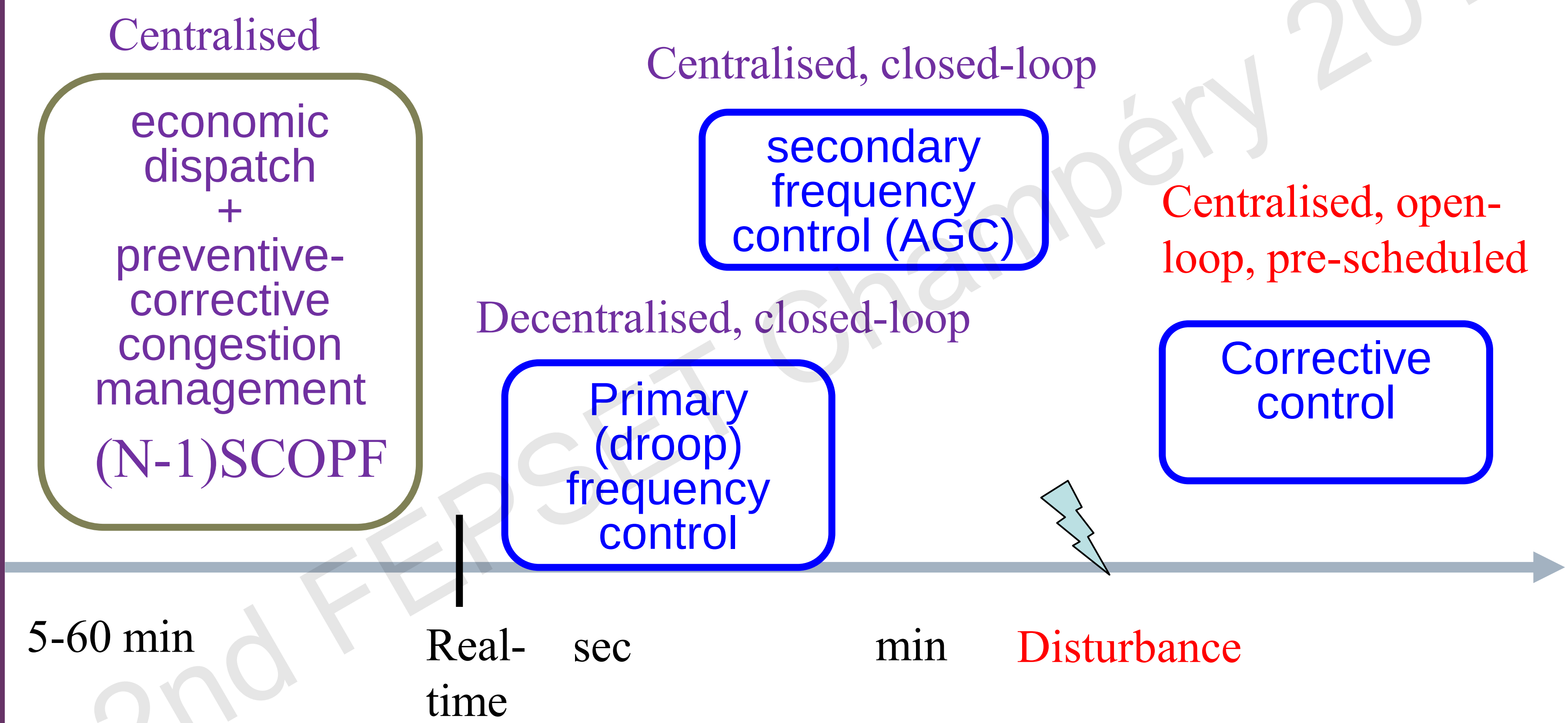


Economic dispatch



Control architecture today

Adjust generation to follow the load



Evolved organically – taken for granted

Challenge

Distributed resources, high volatility, uncertainty, lower inertia, lower controllability, higher cost

Move from open-loop centralized to closed-loop distributed control

Distributed closed-loop control

- A number of methodologies proposed – see the survey in
  D. K. Molzahn, F. Dörfler, H. Sandberg, S. H. Low; S. Chakrabarti, R. Baldick, J. Lavaei, "A Survey of Distributed Optimization and Control Algorithms for Electric Power Systems," *IEEE Transactions on Smart Grids*, vol. 8, Nov. 2017.
- This paper uses Unified Control (UC) to demonstrate the benefits but the conclusions would be similarly applicable to other methodologies
- Advantages:
  - Can harness distributed resources in a plug-and-play manner
  - Closed-loop control: responds to the actual operating conditions rather than assumed – important in the presence of uncertainties
  - Does not have to wait for SCADA to report a disturbance
    - SCADA introduces delays and may be erroneous (see 2013 US/Canada blackout)
  - Reduction in costs – the focus of this paper

Unified Control: static optimization problem

Derive generation control *p* such that, given any disturbance *r*, the closed-loop system is asymptotically stable at an equilibrium which solves

Power injection due to UC

$$\min_{p,P} \sum_i c_i(p_i) = \sum_{i \in G} \frac{1}{2\alpha_i} p_i^2$$

min disruption from to the last optimal operating point

$$\text{s.t.} \quad r_i + p_i - \sum_{j:j\sim i} P_{ij} = 0 \quad \forall \text{node } i$$

disturbance

Line flow

Nodal power balance

$$\sum_{i,j} \hat{C}_{ij,k} P_{ij} = 0 \quad \forall \text{area } k$$

restore inter-area flow

$$\underline{P}_{ij} \leq P_{ij} \leq \overline{P}_{ij} \quad \forall \text{line } ij$$

enforce line limits

Similar to centralized OPF but the disturbance r_i is unknown and we want to solve it in a decentralized manner

Key idea of Unified Control

power network dynamics
(with droop control)
+
secondary freq. control
+
congestion management

derive as
gradient descent
algorithm

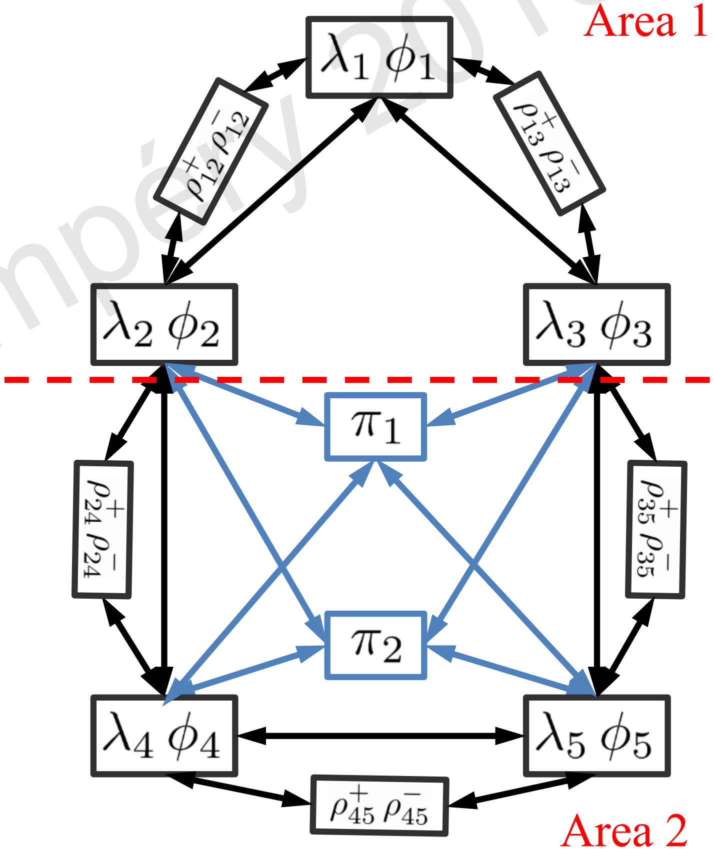
converge to
optimal solution

equivalent to
gradient descent algorithm
(on primal and dual variables)

optimization problem
+
additional
vars./objs./constraints

Distributed communication architecture

- Local measurements of frequency ω, line flows P_{ij} at each bus
- Exchange Lagrange multipliers between physical neighbors (buses)
- Fibre optic cables usually run along power lines and link substations
- Black: frequency control and congestion management:
  - only between neighbours
- Blue: Inter-area control (ACE):
  - across tie-lines (as at present)



Cyber network

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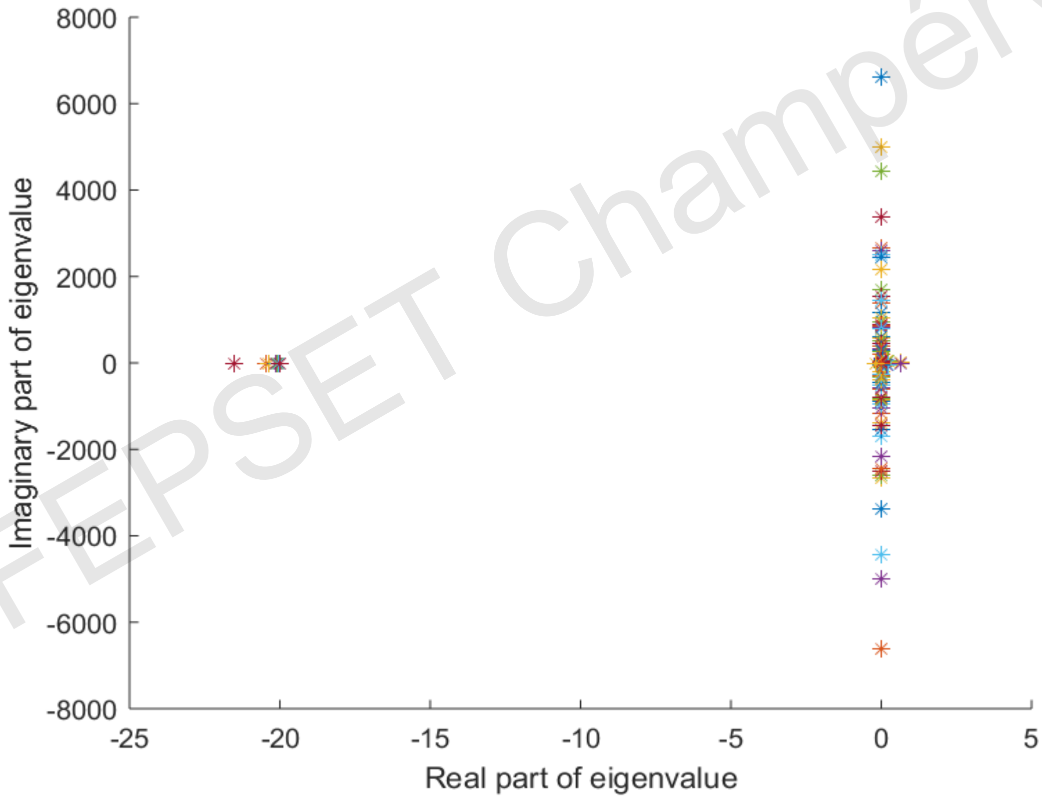
Stability analysis of Unified Control

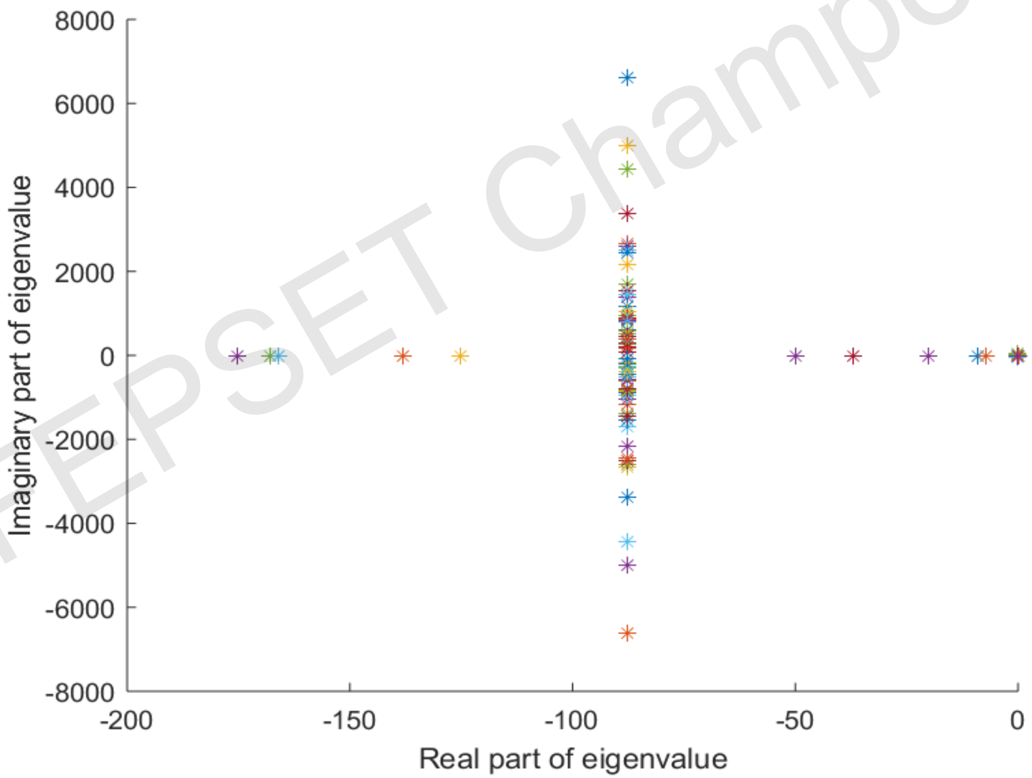
- The original algorithm (PSCC'2016, Champery'2017) was proved to be stable when turbine-governor (TG) was first-order
- Unstable modes when TG was second-order



O. O. Khamisov, T. S. Chernova, J. W. Bialek, S. Low: "Corrective power system control: stability analysis of Unified Controller combining frequency control and congestion management," *IEEE Conf. NEIS 2018*, Sept. 20 – 21, 2018. Pre-print: https://arxiv.org/abs/1806.10303

Decoupled Unified Control (DUC)

- Approximately decoupling the controller from the dynamic system moves eigenvalues to the left and assures stability



DUC algorithm

$$\hat{P}_{ij} = B_{ij}\sin(\phi_i - \phi_j), ij \in \mathcal{E}, \quad (10a)$$

$$\dot{\lambda}_i = K_i^{\lambda}\left(M_i\dot{\omega}_i + D_i\omega_i + \sum_{ij\in\mathcal{E}}(P_{ij} - \hat{P}_{ij}) - \alpha_i\lambda_i - \tilde{p}_i^M\right), i \in G, \quad (10b)$$

$$\dot{\lambda}_i = K_i^{\lambda}\left(D_i\omega_i + \sum_{ij\in\mathcal{E}}(P_{ij} - \hat{P}_{ij}) - \alpha_i\lambda_i - p_i\right), i \in L, \quad (10c)$$

$$\dot{\phi}_i = K_i^{\phi}\sum_{ij\in\mathcal{E}} B_{ij}\left(\lambda_i - \lambda_j - \rho_{ij}^+ + \rho_{ij}^- - \sum_{k:ij\in A_k}\pi_k\right), i \in N \quad (10d)$$

$$\dot{\rho}_{ij}^+ = K_{ij}^{\rho^+}\left[\hat{P}_{ij} - \overline{P}_{ij}\right]_{\rho_{ij}^+}^+, ij \in \mathcal{E}, \quad (10e)$$

$$\dot{\rho}_{ij}^- = K_{ij}^{\rho^-}\left[\underline{P}_{ij} - \hat{P}_{ij}\right]_{\rho_{ij}^-}^+, ij \in \mathcal{E}, \quad (10f)$$

$$\dot{\pi}_k = K_k^{\pi}\left(\sum_{ij\in A}\hat{P}_{ij} - P_k^{area}\right), k \in \Gamma, \quad (10g)$$

$$p_i = -\alpha_i(\omega_i + \lambda_i), i \in N, \quad (10h)$$

$$\tilde{T}^t\dot{\tilde{p}}_i^M = -\tilde{p}_i^M + \tilde{v}_i, i \in G, \quad (10i)$$

$$\tilde{T}^g\dot{\tilde{v}}_i = -\tilde{v}_i + p_i, i \in G. \quad (10j)$$

Estimation of P_m and the disturbance

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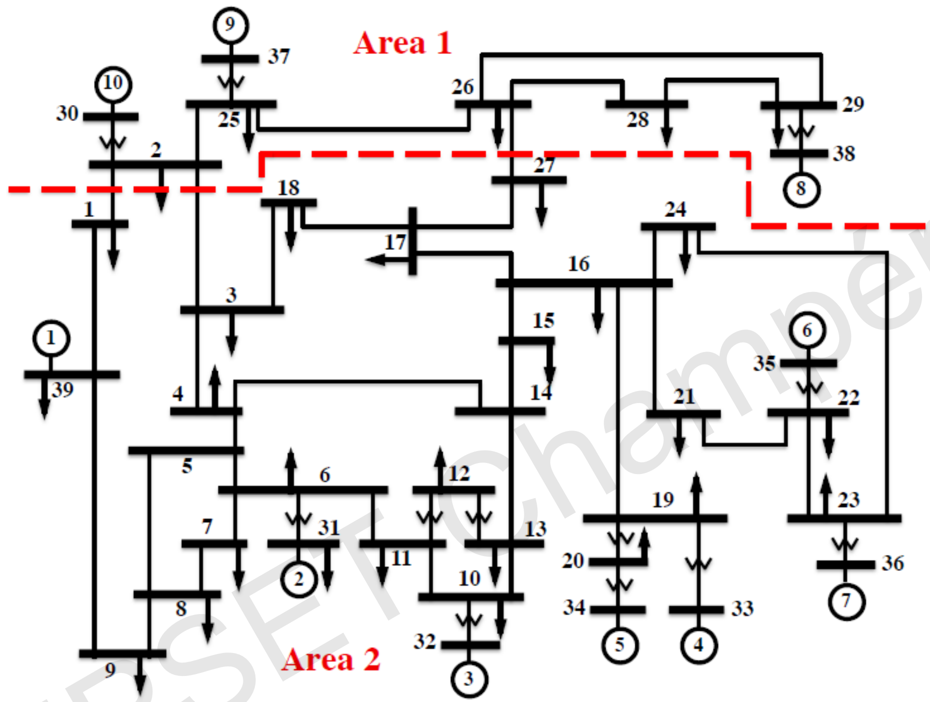
IEEE 39-bus (New England) system



- AC network model
- 4^{th} order generator and IEEE DC1 exciter model
- 3^{rd} order turbine-governor model (inherently models ramp-up/down rates)
- Power System Toolbox (PST) simulation package

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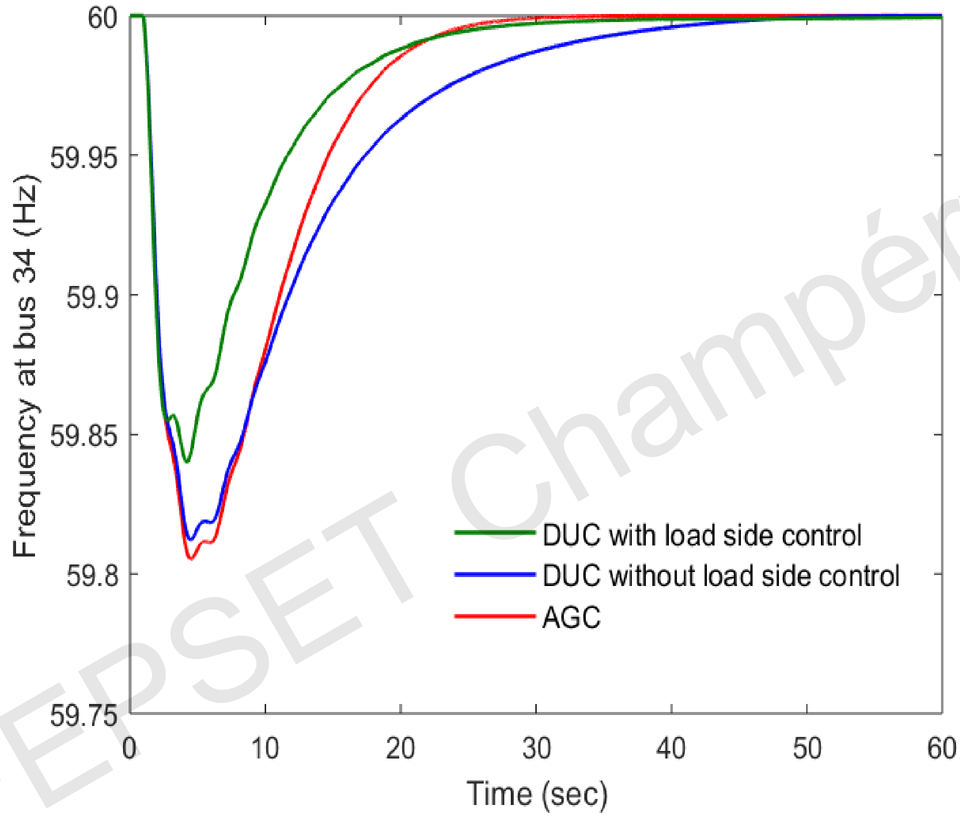
Frequency control: outage of generator at bus 38



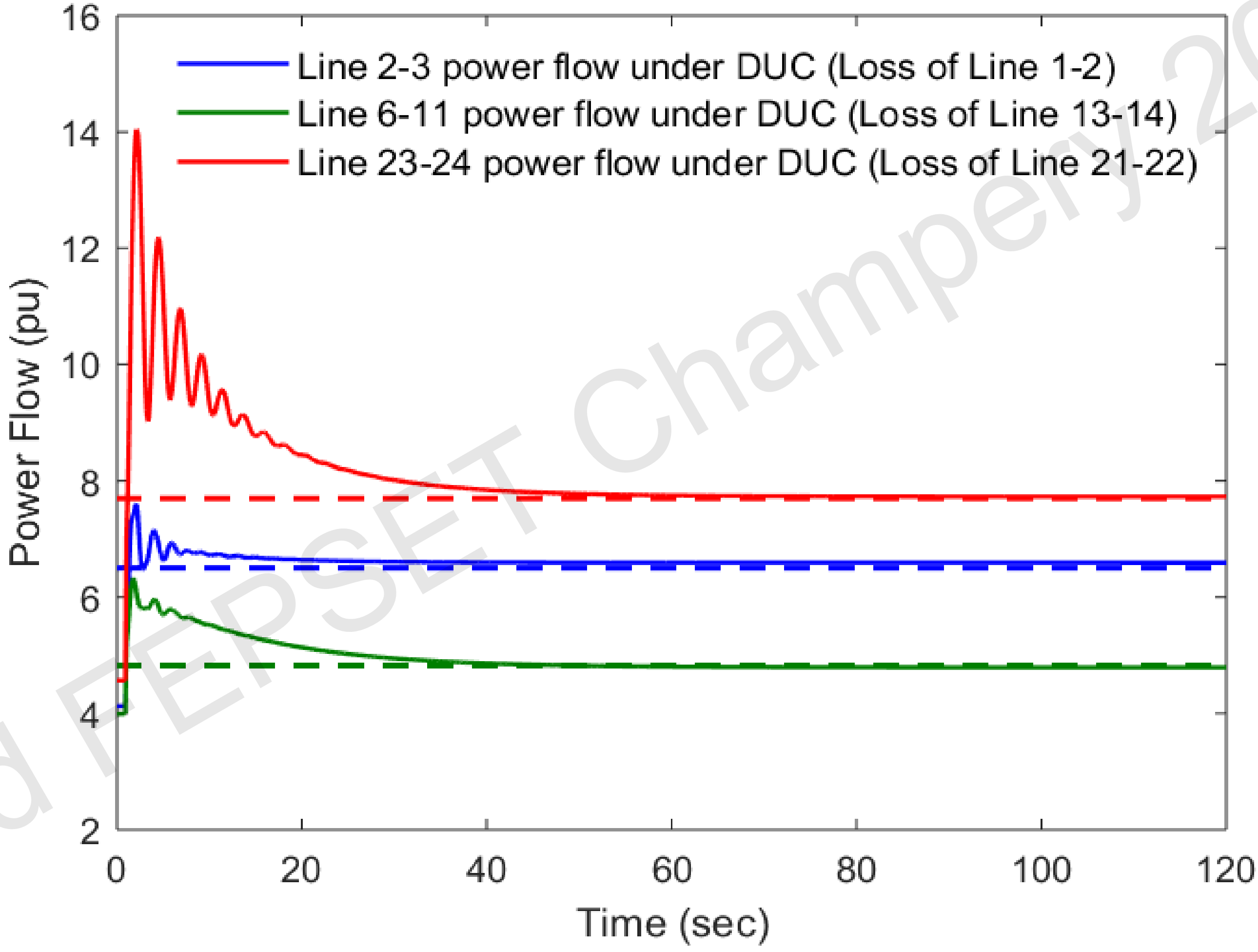
V. similar to AGC (red) until 15 secs (droop control) but longer settling time (blue) due to performing two functions rather than one

Including load-side control (green) reduces nadir and speeds up the response.

Relieving post-contingency overloads

- Proposition:
  - *if* UC can remove all post-contingency overloads quickly enough (before lines overheat)
  - then you can determine dispatch using OPF rather than SCOPF (no need for preventive control)
  - Significant operating and congestion cost savings
- Dispatch procedure:
  - Run SCOPF to determine the reserves needed
  - If SCOPF is secure then UC will find a secure post-contingency re-dispatch
  - Run OPF to determine the actual dispatch
  - If there is a contingency, UC will clear it before lines overheat
- It's conservative as SCOPF determines just one dispatch that is secure for all the contingencies while UC seeks a particular dispatch clearing a particular contingency (much easier)
- Current research

Testing for all binding contingencies (only 3 shown) when UC starts from OPF



Making secure (N-1) insecure dispatch

- Some contingencies can be so severe that SCOPF cannot secure them and emergency controls are needed (e.g. inter-tripping)
- Can UC secure contingencies that were not secured under SCOPF?
- Yes in the cases studied (responses not shown) but of course it may not always be possible
- But possible replacement of some emergency controls (hard-wired, inflexible) by UC closed-loop control (flexible)
- Another advantage of UC (and other closed-loop controllers)

Estimation of benefits

- In the case studied all the post-contingency overloads were cleared quickly enough
- Saving: 24% of operating costs (SCOPF payments) due to removing all the contingencies from dispatch
- In practice the benefits are expected to be less as some contingencies can be so severe that they would require preventive control (a reduced SCOPF)
- Also UC does not deal with voltage-related contingencies – have to be dealt with by SCOPF
- Annual congestion costs of a large system (e.g. Germany, some of US ones) could be above $1B
- Even a relatively limited reduction in congestion costs due to UC could still mean a large amount of money saved

Technical challenges to be addressed

- Feedback delay
- Digital control
- Partial observation and control
- Uncertainties in parameter values
- Gain tuning

Summary

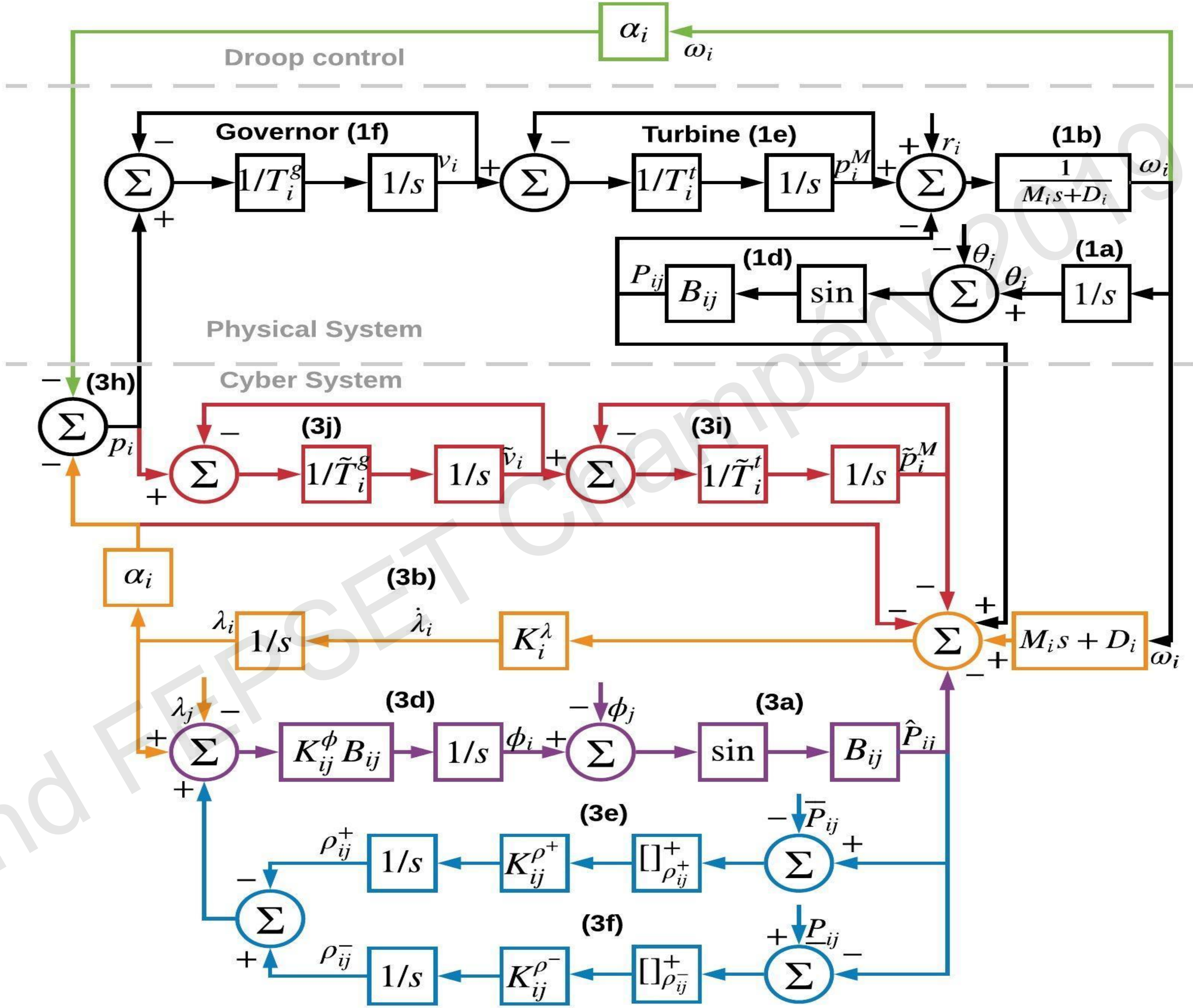
1. UC is an example of a distributed closed-loop controller
2. It can harness distributed resources, reduce security margins due to uncertainty, reduce operation and congestion costs, and does not rely on SCADA
3. Primal-dual algorithm of the static optimisation problem combines network dynamics and control strategy
4. Decoupled Unified Control assures stability when turbine-governor is second-order or higher
5. Potential significant cost savings
6. Also may remove the need for some emergency controls
7. Significant implementation challenges

QUESTIONS?

Will System Operators implement distributed closed-loop power system control

- System operators are VERY conservative
- But two drivers can force them to look seriously at distributed closed-loop control

1. Significant potential savings
2. Replacement of traditional big generators by distributed resources (renewable generation, flexible loads, energy storage) – UC can harness them for control in a distributed plug-and-play manner



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