Robust decentralized control in power systems

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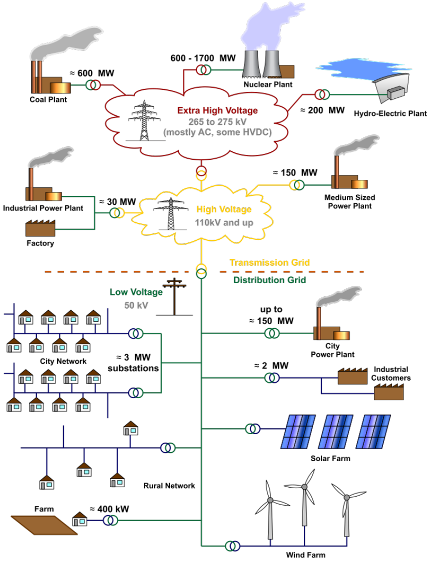
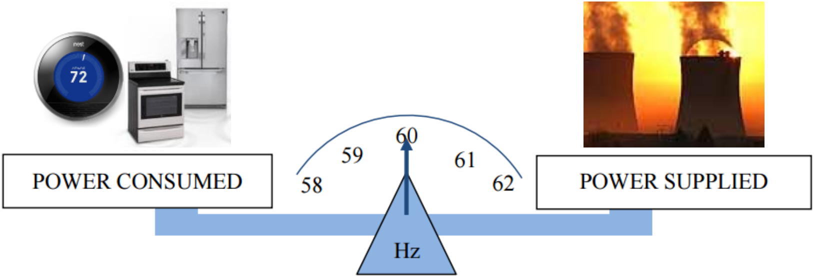
Joint work with Weitenberg (RUG), Jiang-Mallada (Johns Hopkins), Zhao (NREL), Dörfler (ETH)

AC power systems



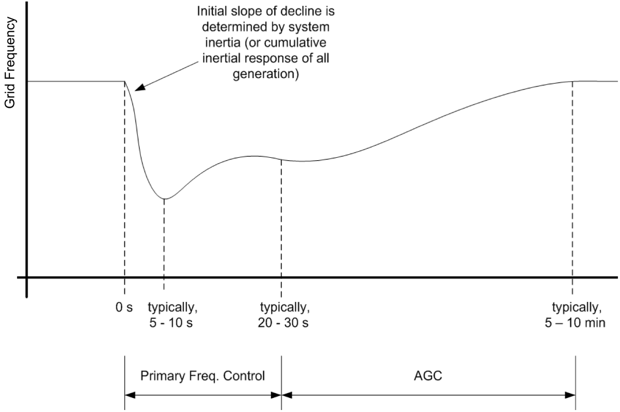
- Power system = network of generation, loads, transmission lines
- Power system control = maintain system security at minimal cost
- Basic security requirement = keeping frequency around nominal value

Frequency control



- Any instantaneous load-generation imbalance results in a frequency deviation from the nominal one (50-60 Hz)
- Small load changes on a fast time scale are dealt with the Automatic Generation Control (AGC)

The three control layers



[figure EPRI]

- Primary control counteracts initial frequency drop and implemented via local droop control of turbine governors
- Secondary AGC is centralized and uses integral control to restore frequency

Conventional operational strategy

Central control authority

- AGC is implemented with a central regulator
- Frequency deviation ω is measured at low-voltage network and integrated to generate the regulator output signal p

$$T\dot{p} = \omega$$

- The incremental contribution of the individual generating units to the total generation is obtained via participations factors K_i^{-1}

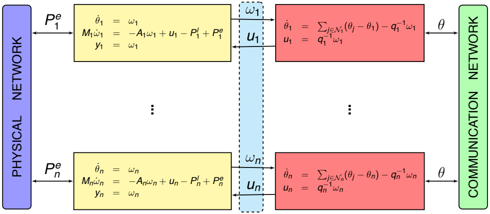
$$u_i = -K_i^{-1} p, \quad i = 1, 2, \ldots, n$$

Conventional operational strategy

- The conventional strategy is developed for conventional generators which have high inertia, hence abrupt changes are better absorbed by the system, thus easing the task of frequency restoration
- Renewable generation leads to significant reduction of inertia, hence to a more volatile network, which challenges existing control schemes

Distributed control

An answer to this challenge has leveraged the use of local controllers that cooperate over a communication network



- Semi-centralized

$$T\dot{p} = \sum_i \omega_i, \quad u_i = -K_i^{-1} p$$

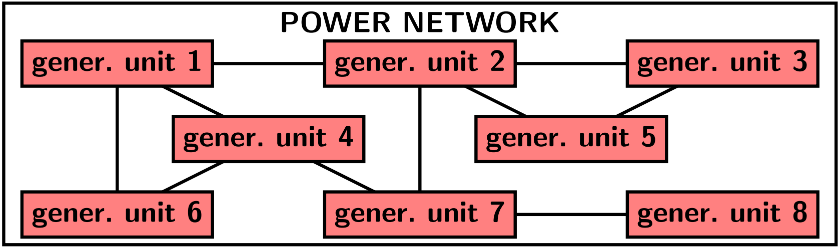
- Distributed averaging integral

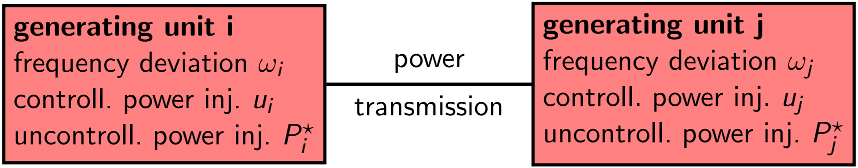
$$\begin{aligned} T_i\dot{p}_i &= \sum_{j\in\mathcal{N}_i^c}(p_j - p_i) + K_i^{-1}\omega_i \\ u_i &= -K_i^{-1} p_i \end{aligned}$$

Yet, due to security, robustness and economic concerns, it is desirable to regulate the frequency without relying on communication

Power network

Lossless, network-reduced power system with n generating units





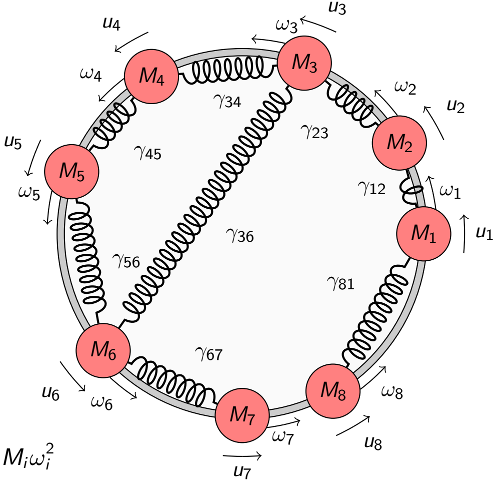
[figure Stegink]

Frequency dynamics

$$\dot{\theta}_i = \omega_i, \qquad M_i\dot{\omega}_i = -A_i\omega_i - \sum_{j\in\mathcal{N}_i} \overbrace{V_i V_j B_{ij}}^{\gamma_{ij}} \sin(\theta_i - \theta_j) + u_i - P_i^\star$$

Local measurements: ω_i

- Swing equations
- ω_i frequency deviation
- θ_i phase angle deviation
- voltages V_i constant
- purely inductive lines $B_{ij} = B_{ji}$
- mechanical equivalent $\Rightarrow$



Energy function:

$$H = -\frac{1}{2}\sum_{i\neq j} B_{ij} V_i V_j \cos(\theta_i - \theta_j) + \frac{1}{2}\sum_i M_i\omega_i^2$$

[figure Stegink]

Synchronization frequency control

$$\begin{aligned}\dot{\theta}_i &= \omega_i \\ M_i\dot{\omega}_i &= -D_i\omega_i + u_i + P_i^\star - \sum_j B_{ij}E_iE_j\sin(\theta_i - \theta_j)\end{aligned}$$

- Synchronous solution $\omega_i = \omega_{\mathrm{sync}}$
- Synchronous frequency $\omega_{\mathrm{sync}} = \frac{\sum_i P_i^\star + \sum_i u_i}{\sum_i D_i}$

  Case $n = 2$

  $$\begin{aligned}M_1\dot{\omega}_1 &= -D_1\omega_1 + u_1 + P_1^\star - B_{12}E_1E_2\sin(\theta_1 - \theta_2) \\ M_2\dot{\omega}_2 &= -D_2\omega_2 + u_2 + P_2^\star - B_{21}E_2E_1\sin(\theta_2 - \theta_1)\end{aligned}$$

  If $\omega_1 = \omega_2 = \omega_{\mathrm{sync}} = const$, summing up

  $$0 = -(D_1 + D_2)\omega_{\mathrm{sync}} + u_1 + u_2 + P_1^\star + P_2^\star$$

- Zero frequency deviation $0 = \sum_i P_i^\star + \sum_i u_i$

Optimal frequency restoration

Manifold choices of $u_i^\star$ to achieve

$$0 = \sum_i P_i^\star + \sum_i u_i^\star$$

Optimal dispatch problem

$$\begin{array}{ll} \text{minimize}_{u \in \mathbb{R}^n} & \sum_i a_i u_i^2 \\ \text{subject to} & \sum_i P_i^* + \sum_i u_i = 0 \end{array}$$

Solution

$$u_i^\star = -a_i^{-1} \frac{\sum_i P_i^\star}{\sum_i a_i}$$

Fair proportional sharing

$$a_i u_i^\star = a_j u_j^\star \quad \forall i, j$$

Optimal frequency restoration

Given unknown $P_i^\star$, design

$$u_i(\omega_i)$$

that stabilizes the power system model to

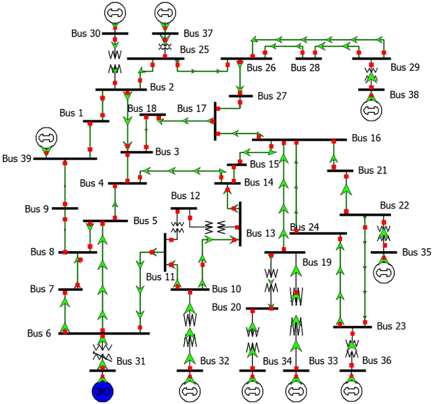
$$(\theta_i^\star, \omega_i^\star = 0, u_i^\star)$$

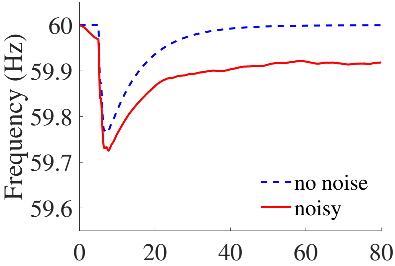
Fully decentralized frequency control

$$T_i \dot{p}_i = \omega_i$$
$$u_i = -p_i$$

- No communication required ✓
- Frequency regulation $\omega \to \mathbb{0}$ ✓

IEEE 39-node 'New England' benchmark network



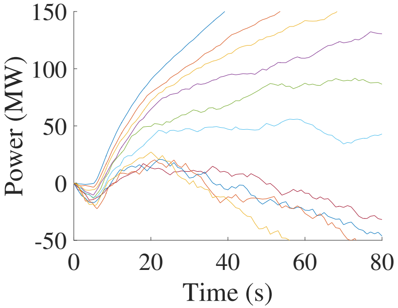


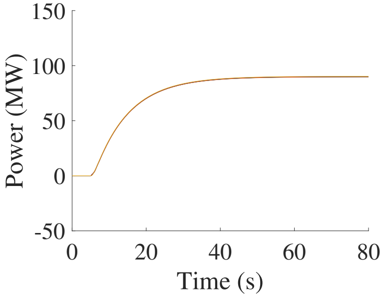
- Frequency at G1
- Noisy measurements $\omega_i + \eta_i$
- Non-zero mean noise η
- Noise bound $\overline{\eta} = 0.01\text{Hz}$

Fully decentralized frequency control

- No optimality
  $u \to u(p(0), \theta(0)) \neq u^{\star}$

Active power output of all generators (no noise)





- Unstable behavior
- Steady state

$$\begin{aligned} 0 &\approx T_i \dot{p}_i = \omega_i + \eta_i \neq \\ 0 &\approx T_j \dot{p}_j = \omega_j + \eta_j \end{aligned}$$

Active power output of all generators (noise)

Leaky integral control

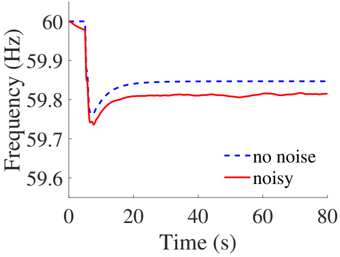
$$T_i \dot{p}_i = \omega_i - K_i p_i$$
$$u_i = -p_i$$

- No communication required ✓
- Synchronous frequency

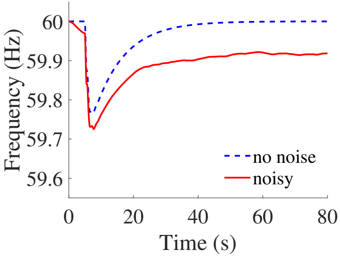
$$\omega_{\text{sync}} = \frac{\sum_i P_i^\star}{\sum_i D_i + \sum_i K_i^{-1}}$$

- Banded frequency regulation ✓

$$\sum_i K_i^{-1} \geq \frac{\sum_i P_i^\star}{\varepsilon} - \sum_i D_i \Rightarrow |\omega_{\text{sync}}| \leq \varepsilon$$



Leaky integral control $T_i = 0.05\text{s}$, $K_i = 0.005$ for G3, G5, G6, G9, G10, $K_i = 0.01$ for the others



Decentralized pure integral control

Leaky integral control

$$\begin{aligned} T_i \dot{p}_i &= \omega_i - K_i p_i \\ u_i &= -p_i \end{aligned}$$

- Steady-state

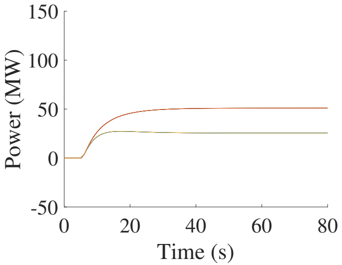
$$u_i^\star = -K_i^{-1} \omega_{\text{sync}}$$

- Power sharing ✓

$$K_i u_i^* = K_j u_j^*$$

- Approx steady-state optimality

$$\begin{aligned} &\text{minimize}_{u \in \mathbb{R}^n} && \textstyle\sum_i K_i u_i^2 \\ &\text{subject to} && \textstyle\sum_i P_i^* + \sum_i (1 + D_i K_i) u_i = 0 \end{aligned}$$



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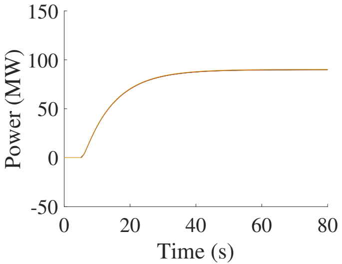
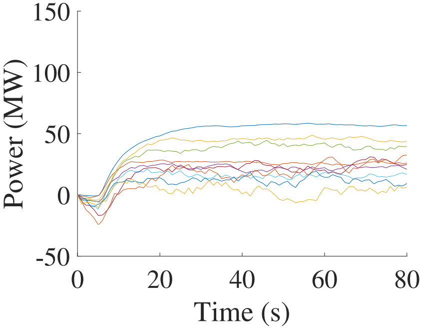


Decentralized pure integral control

Leaky integral control

$$\begin{aligned} T_i \dot{p}_i &= \omega_i + \eta_i - K_i p_i \\ u_i &= -p_i \end{aligned}$$

- Noisy measurements $\omega_i + \eta_i$
- Non-zero mean noise η
- Noise bound $\overline{\eta} = 0.01\text{Hz}$



Leaky integral control $T_i = 0.05\text{s}$, $K_i = 0.005$ for G3, G5, G6, G9, G10, $K_i = 0.01$ for the others

Robust frequency regulation (ISS) ✓

$$\|x(t)\|^2 \leq \lambda e^{-\hat{\alpha} t}\|x(0)\|^2 + \gamma(\sup_{t \in \mathbb{R}_{\geq 0}} \|\eta(t)\|)^2$$

where $\lambda, \hat{\alpha}, \gamma$ are positive constants and

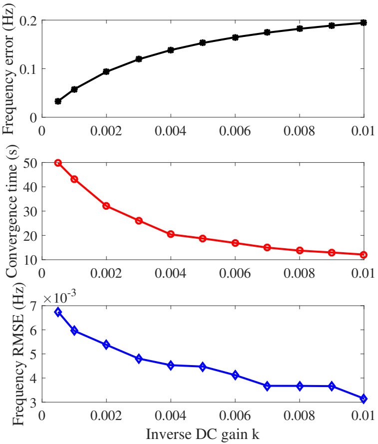
$$x = \text{col}(\delta - \delta^\star, \omega - \omega^\star, p - p^\star)$$

measures the deviation from the synchronous solution

Impact of control parameters

Tuning of the gains K_i

$K_i = k \quad \text{for G3 G5 G6 G9 G10}$
$K_i = 2k \quad \text{for others}$
$T_i = \tau = 0.05\text{s}$



As $k \nearrow$

- Noise-free steady-state frequency error $\nearrow$
- $\hat{\alpha} \nearrow$ implies convergence time $\searrow$
- $\gamma \searrow$ implies RMSE $\searrow$

Increasing gains K_i leads to

- reduced accuracy in frequency regulation
- faster response
- increased robustness to noise

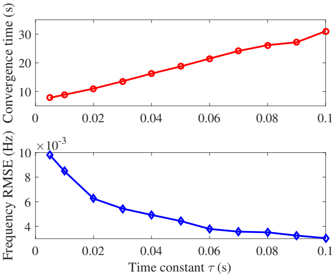
Impact of control parameters

Tuning of the time constants T_i

$$K_i = 0.005 \quad \text{for G3 G5 G6 G9 G10}$$
$$K_i = 0.01 \quad \text{for the others}$$
$$T_i = \tau$$

As $\tau \nearrow$

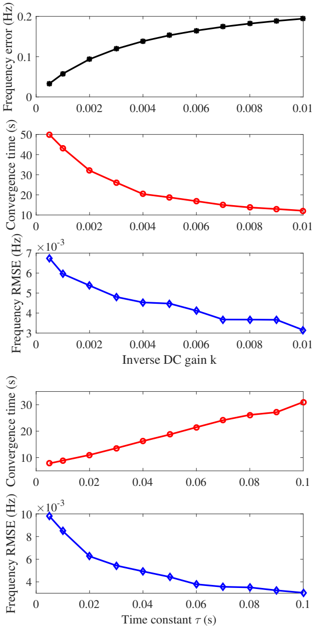
- $\hat{\alpha} \searrow$ implies convergence time $\nearrow$
- $\gamma \searrow$ implies RMSE $\searrow$



Increasing time constants T_i leads to

- slower response
- increased robustness to noise

Tuning recommendations



- Fix ratios between K_i^{-1} from generating units operation costs

$$u_i^\star = -K_i^{-1}\omega_{\text{sync}}$$

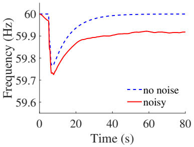
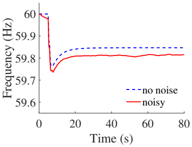
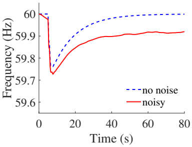
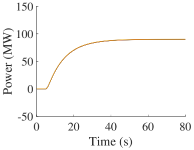
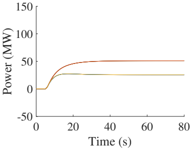
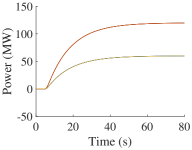
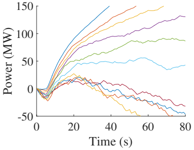
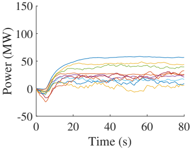
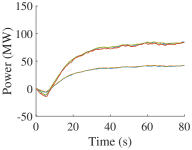
- Fix $\sum_i K_i^{-1}$ for banded frequency regulation

$$\sum_i K_i^{-1} \geq \frac{\sum_i P_i^\star}{\varepsilon} - \sum_i D_i$$

- Fix T_i to strike a trade-off between frequency rejection rate and noise rejection

$$T_i \nearrow \quad \Rightarrow \quad \hat{\alpha} \searrow \text{ and } \gamma \searrow$$

A further comparison

<table>
<tr><th></th><th>Decentralized integral</th><th>Decentralized leaky</th><th>DAI</th></tr>
<tr><td>Frequency</td><td></td><td></td><td></td></tr>
<tr><td>Power no noise</td><td></td><td></td><td></td></tr>
<tr><td>Power with noise</td><td></td><td></td><td></td></tr>
</table>

DAI $T_i \dot{p}_i = \sum_{j \in \mathcal{N}_i^c} (p_j - p_i) + K_i^{-1} \omega_i \quad u_i = -K_i^{-1} p_i$

Robust stability

Proof is Lyapunov-based, using a strict Lyapunov function

$$\begin{aligned} W = {} & U(\delta) - U(\delta^*) - \nabla U(\delta^*)^\top(\delta - \delta^*) \\ & + \frac{1}{2}(\omega - \omega^*)^\top M(\omega - \omega^*) + \frac{1}{2}(p - p^*)^\top T(p - p^*) \\ & + \epsilon(\nabla U(\delta) - \nabla U(\delta^*))^\top M(\omega - \omega^*). \end{aligned}$$

- $U(\delta) = -\frac{1}{2}\sum_{i\neq j} B_{ij} V_i V_j \cos(\delta_i - \delta_j)$ potential energy
- W with $\epsilon = 0$ is the “shifted” energy function $H + \frac{1}{2}p^\top Tp$
- For sufficiently small ϵ, W is strictly decreasing along the solutions
- This allows for quantification of robustness to noise

Conclusions

A fully decentralized stabilizing integral control for achieving robust noise-rejection, satisfactory steady-state regulation, desirable transient performance

- These objectives are not aligned and trade-offs must be found
- Tuning guidelines are provided
- Resulting time constants T_i/K_i compatible with actuator response time
- Low-pass filter compares favourably wrt droop (noise rejection)

Future work

- Lead compensators could improve transient performance
- Extension more accurate physical models
- Impact of topology on the diffusion of noise and scalability

Reference

Weitenberg, Jiang, Zhao, Mallada, De Persis, Dörfler (2018). Robust decentralized secondary frequency control in power systems: merits and trade-offs. *IEEE Transactions on Automatic Control*, in press, available as arXiv:1711.07332

•Weitenberg, De Persis, Monshizadeh (2018). Exponential convergence under distributed averaging integral frequency control. *Automatica*, 98, 103-113.

⋆Weitenberg, De Persis (2018). Robustness to noise of distributed averaging integral controllers. *Systems & Control Letters*, 119, 1-7.

Thank you!

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