Carnegie Mellon

Advanced Primary Frequency Regulation (APFR):

Coordination between energy storage and conventional generation in power systems with renewables

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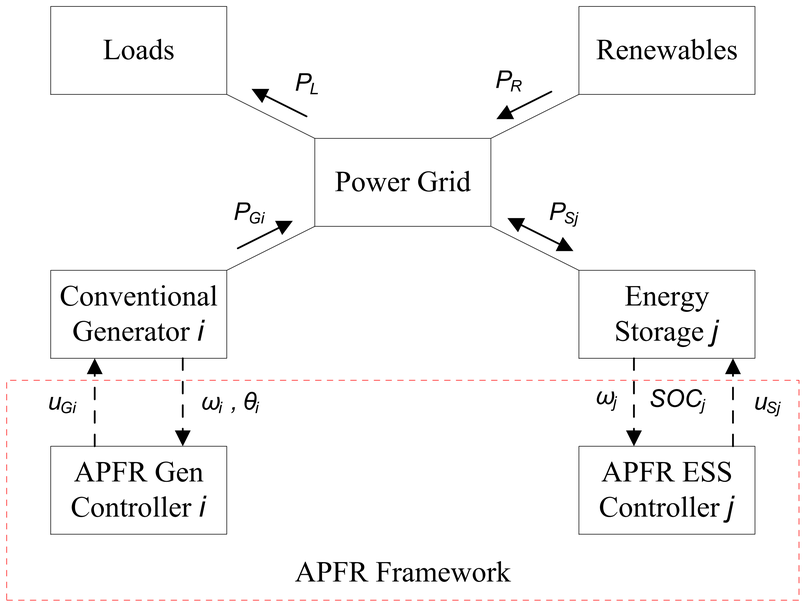
Motivation

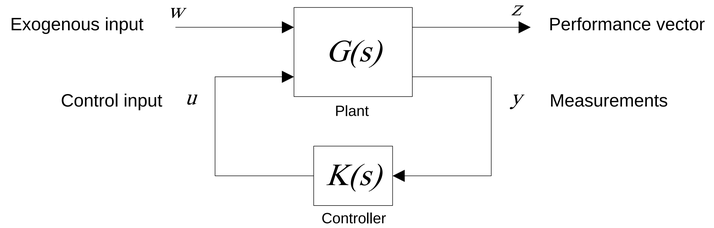
- Impacts of renewable energy sources (RESs) on the power system frequency control:
  - ➢ Poor prediction accuracy and large variations,
  - ➢ Increased fluctuations in the medium frequency region.
- Continuous development of energy storage technologies:
  - ➢ Fast response capability,
  - ➢ Reduced capital costs.

APFR Overview



- Frequency separation:
  - ➢ Conventional generation in APFR: to balance the low frequency component of the generator speed deviations;
  - ➢ Energy storage in APFR: to compensate the relatively high frequency component of frequency deviations.
- APFR overall control objectives: 1) to minimize frequency deviations; 2) to minimize the SOC of energy storage devices.
- H_∞-based static output feedback control design

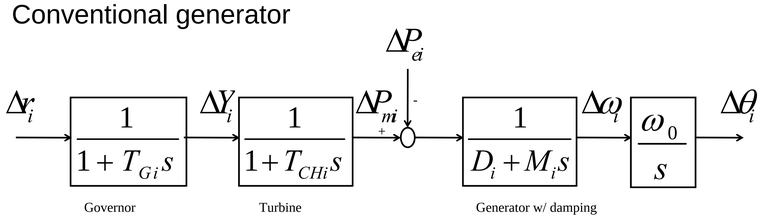
H_∞ Control Basics



$$\min_{K(s)} \left\| W_z(s) \cdot T_{zw}(s) \cdot W_w(s) \right\|_\infty$$

System Modeling

- Conventional generator



- RESs
  - ➢ Negative load
  - ➢ Power injection
- Energy storage devices

$$\frac{d\Delta SOC_j}{dt} = -\frac{1}{E_{capj}} \cdot \Delta P_{Sj}$$

- Power network (DC flow)

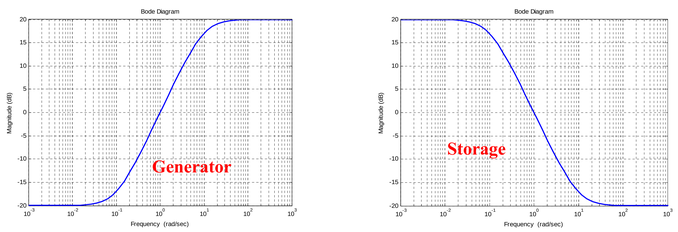
$$\begin{bmatrix} \mathbf{P_G} \\ \mathbf{P_L} \end{bmatrix} = -\begin{bmatrix} \mathbf{B_{GG}} & \mathbf{B_{GL}} \\ \mathbf{B_{LG}} & \mathbf{B_{LL}} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{\theta}_\mathbf{G} \\ \boldsymbol{\theta}_\mathbf{L} \end{bmatrix}$$

- Frequencies at non-generator buses

$$\boldsymbol{\omega}_\mathbf{L} = -\mathbf{B}_\mathbf{LL}^{-1}\mathbf{B}_\mathbf{LG}\boldsymbol{\omega}_\mathbf{G}$$

Controller Design

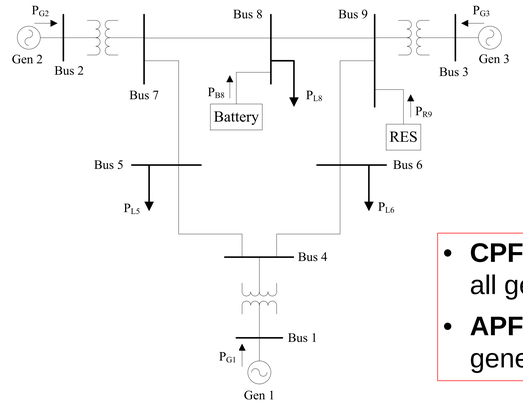
- Frequency separation via dynamic weighting functions:



- Static output feedback synthesis:

$$\Delta r_i = -k_{1i} \cdot \Delta\omega_i - k_{2i} \cdot \Delta\theta_i; \quad \Delta P_{Bj} = -k_{3j} \cdot \Delta\omega_j - k_{4j} \cdot \Delta SOC_j$$

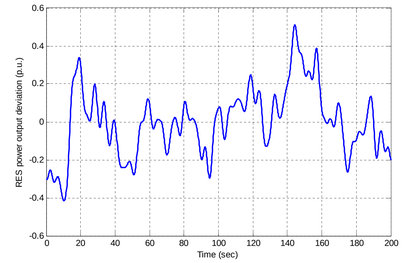
Simulation



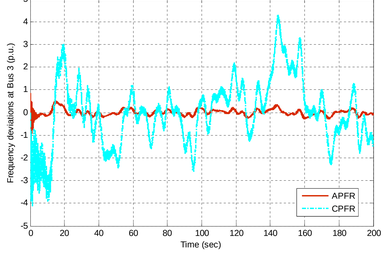
$S_N = 100MVA$
$S_1 = 247.5MVA,\ H_1 = 9.5515s$
$S_2 = 192MVA,\ H_2 = 3.3333s$
$S_3 = 128MVA,\ H_3 = 2.3516s$
$E_{cap} = 2MWh$

- **CPFR**: *5%* droop control for all generators, no battery
- **APFR**: APFR control for all generators and the battery

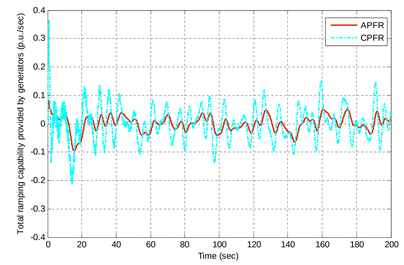
- RES output data (deviation)



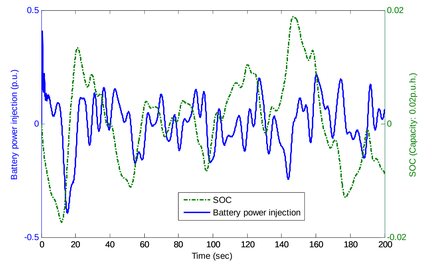
- Frequency at Bus 3 (Gen 3)



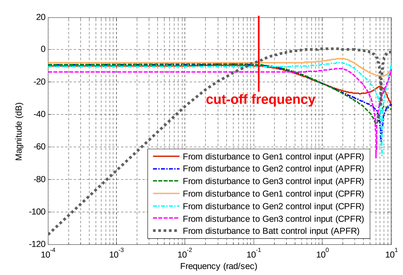
- Ramping provided by Gens



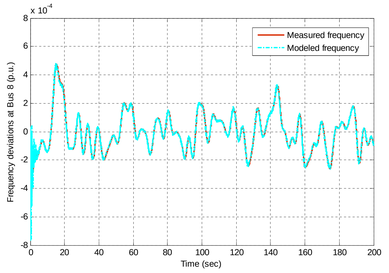
- Battery response (Bus 8)



- Frequency separation



- Frequency at Bus 8 (Load)



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