Dynamic Simulation of the Imbalance Netting Process and Cross-Border Activation of the Automatic Frequency Restoration Process

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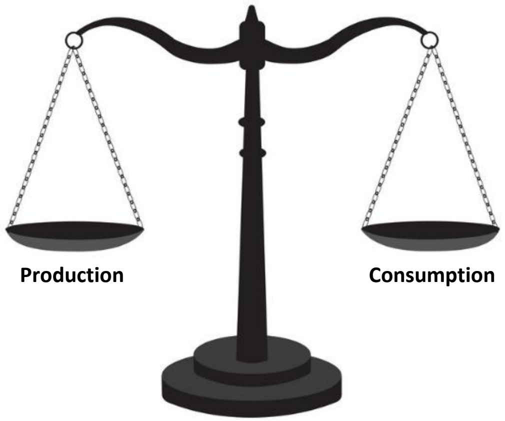
■ Frequency control

- **Imbalance** between production and consumption causes **frequency deviation** from nominal value.
- The **size and duration** of the frequency deviation must stay **within given target values**.



Nominal frequency

■ Load control between Control Areas (CAs)

- The production within the CA must be controlled in order to maintain **scheduled power interchanges** between CAs due to the tie-lines.
- Deviation from scheduled power interchanges may lead to additional power flows that can exceed the **transmission capacities** of the tie-lines.

Load-Frequency Control (LFC) decreases:

- Frequency deviations

$$\Delta f_i = f_{ai} - f_{si}$$

- Interchange power variations

$$\Delta P_i = P_{ai} - P_{si}$$

- Area Control Error is given as

$$ACE_i' = \Delta P_i + B_i \Delta f_i$$

- P_{ai} and f_{ai} – measured values
- P_{si} and f_{si} – scheduled values
- B_i – frequency bias coefficient
- LPF – Low Pass Filter
- PI – Proportional-Integral Controller
- SH – Sample and Hold (2 s)
- ΔP_{sci} – Scheduled Control Power
- ΔP_{ei} – Electrical Control Power

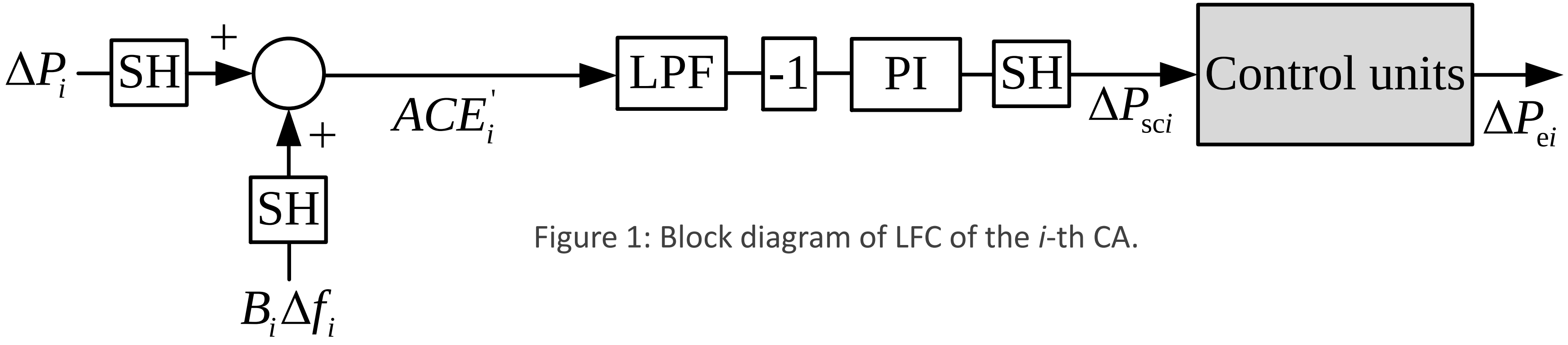


Figure 1: Block diagram of LFC of the *i*-th CA.

Implementation of INP in LFC structrure

- Input variable is demand power

$$P_{\mathrm{d}i}' = \Delta P_{\mathrm{e}i} - ACE_i'$$

- Output variable is correction power

$$P_{\mathrm{cor}i}' = -P_{\mathrm{d}i}$$

$$ACE_i = \left(\Delta P_i + B_i \Delta f_i\right) - P_{\mathrm{cor}i}'$$

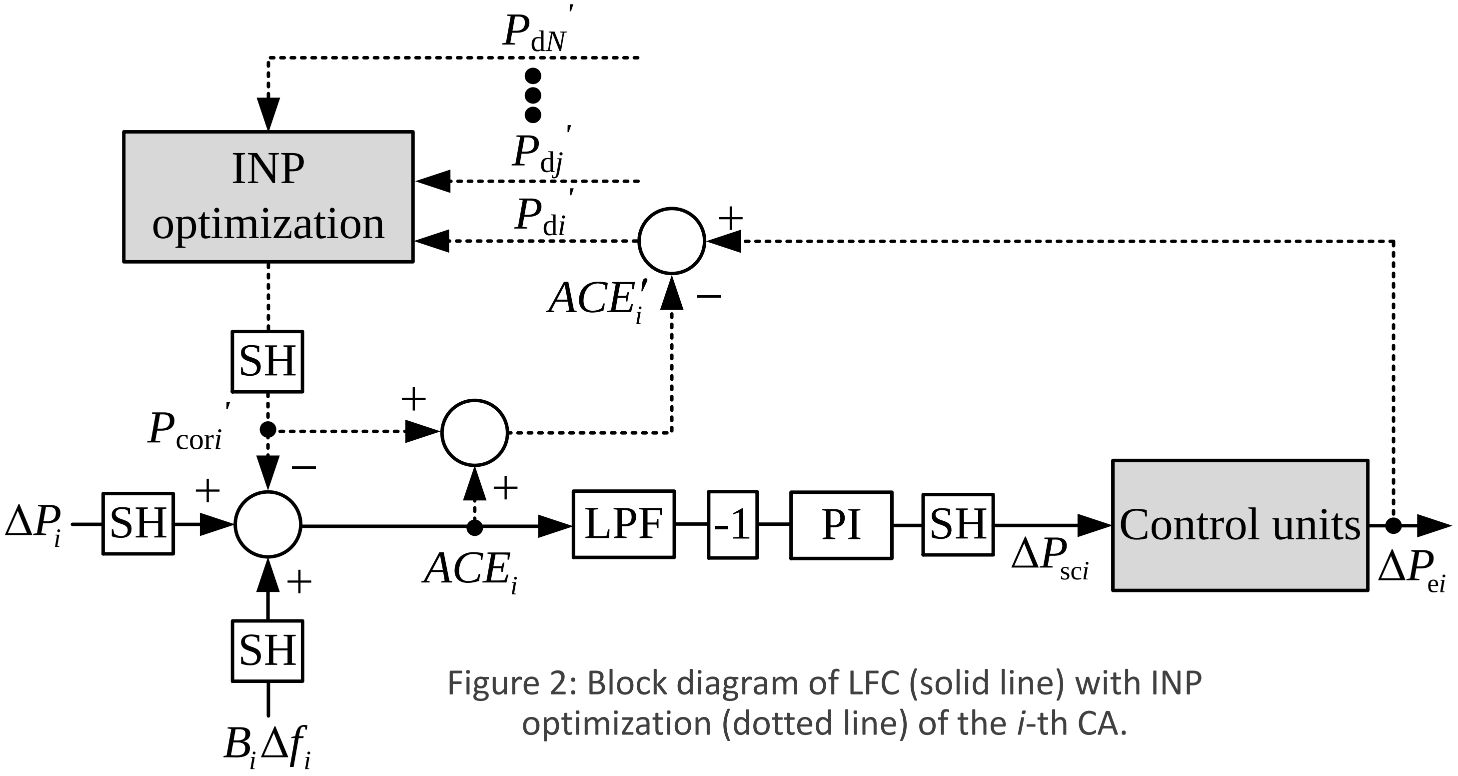


Figure 2: Block diagram of LFC (solid line) with INP optimization (dotted line) of the *i*-th CA.

INP optimization

- Maximal compensation with a **limit of P_{di}'** and the **limit of** available transmission capacity **P_{ATCij}**.
- **Proportional to imbalance** distribution is used.

Objective of INP

- To **compensate** power deviations between CAs with **opposite signs**.
- To **eliminate** the activation of control reserve with **opposite signs**.
- To **reduce** the activation of secondary control reserve.

Economical view

- Developed due to the **high cost** of balancing energy.
- To **reduce** power deviations between CAs.
- By regulating the activation of the balancing energy between CAs, **high economic savings** are possible.

Technical view

- **Release** of control reserve and reduction of balancing energy.

- **Physical** connection between CA_1-CA_2 and CA_2-CA_3.
- All three CAs connected with INP optimization through **virtual tie-lines**.
- **Condition** for INP:

  $(\text{sign})P_{d1} \neq (\text{sign})P_{d2} \neq (\text{sign})P_{d3}$

CA_1 and CA_2 – **long** → **export**
CA_3 – **short** → **import**

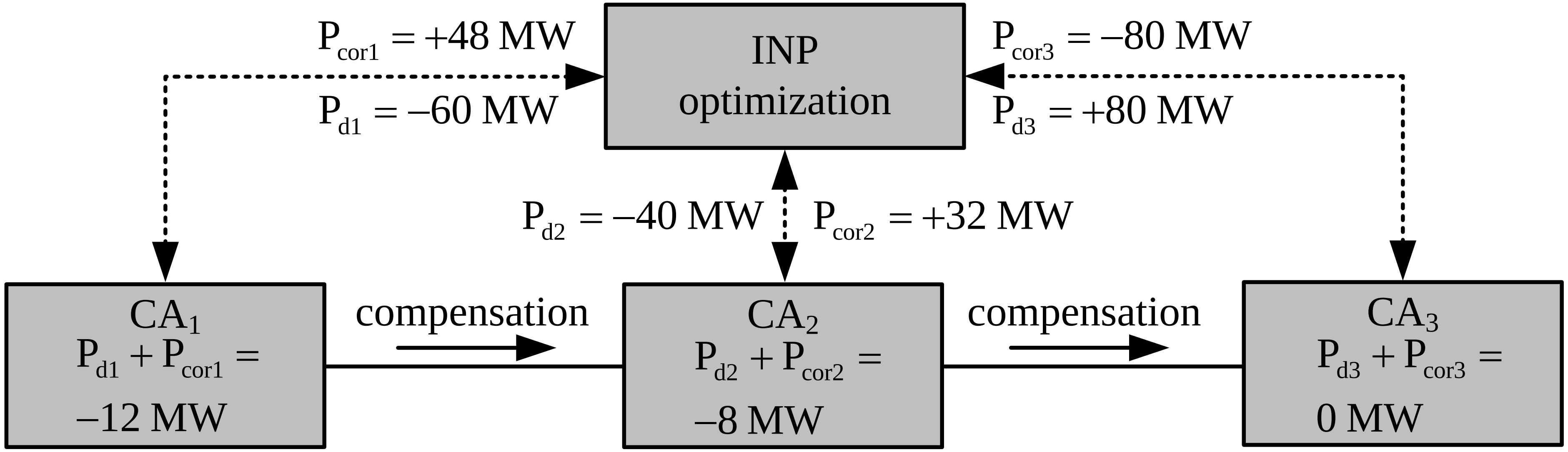


Figure 3: Steady-state correction value calculation with INP optimization.

Implementation of the cross-border activation of aFRP in LFC structrure

- Input variable is demand power

$$P_{di}^{\ *} = \Delta P_{ei} - ACE_i^{*}$$

- Output variable is correction power

$$P_{cori}^{\ *} = -P_{di}^{\ *}$$

$$ACE_i^{\ *} = \left(\Delta P_i + B_i \Delta f_i\right) - P_{cori}^{\ *} - K_j P_{corj}^{\ *}$$

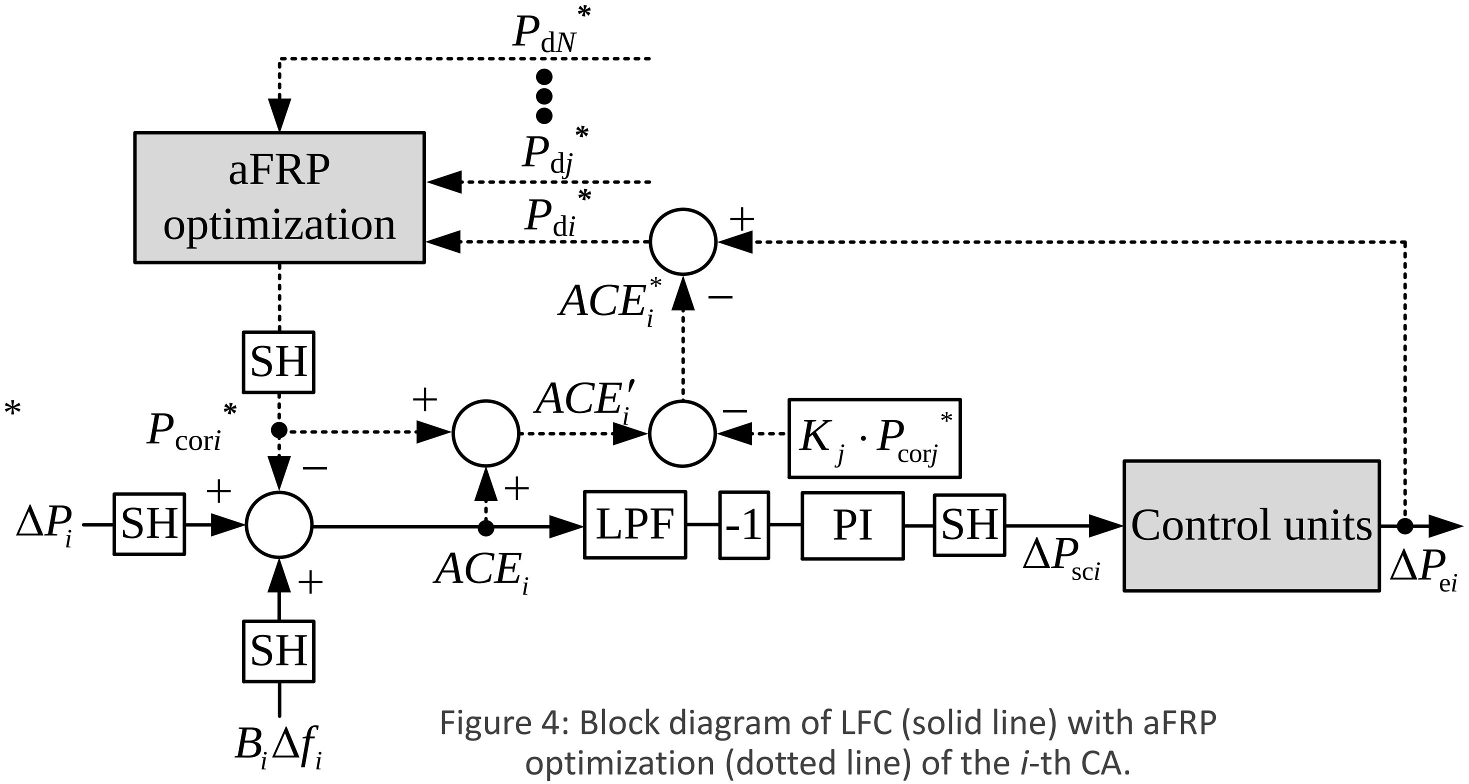


Figure 4: Block diagram of LFC (solid line) with aFRP optimization (dotted line) of the *i*-th CA.

AFRP optimization

- Maximal compensation with a **limit of $P_{di}{}'$** and the **limit of** available transmission capacity P_{ATCij}.

Objective of the cross-border activation of aFRP

- To **compensate** power deviations between CAs with **equal signs**.
- To **activate** the secondary control reserve in neigbouring CAs.
- To **reduce** the activation of secondary control reserve in its own CA.

Economical view

- Developed due to the additional **cost optimization** and **high cost** of balancing energy.
- By activating the secondary control reserve in neigbouring CAs, **high economic savings** are possible.

Technical view

- **Release** of control reserve and reduction of balancing energy.

CROSS-BORDER ACTIVATION OF aFRP BASED CORRECTION

- **Physical connection** between CA_1-CA_2 and CA_2-CA_3.
- All three CAs connected with aFRP optimization through **virtual tie-lines**.
- **Condition** for aFRP:

$$(\text{sign})P_{d1} = (\text{sign})P_{d2} = (\text{sign})P_{d3}$$

CA_1, CA_2 and CA_3 – **short → import**

CA_3 activated:

- $\mathbf{0.3}\boldsymbol{P}_{\mathbf{cor3}}$ in CA_1
- $\mathbf{0.7}\boldsymbol{P}_{\mathbf{cor3}}$ in CA_2

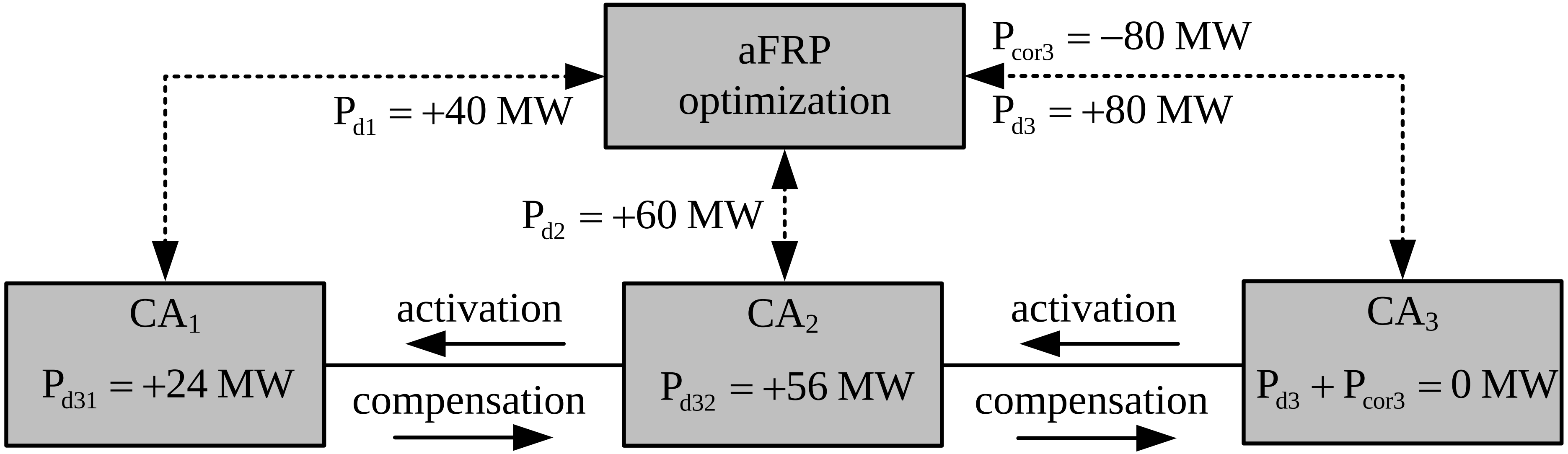


Figure 5: Steady-state correction value calculation with aFRP optimization.

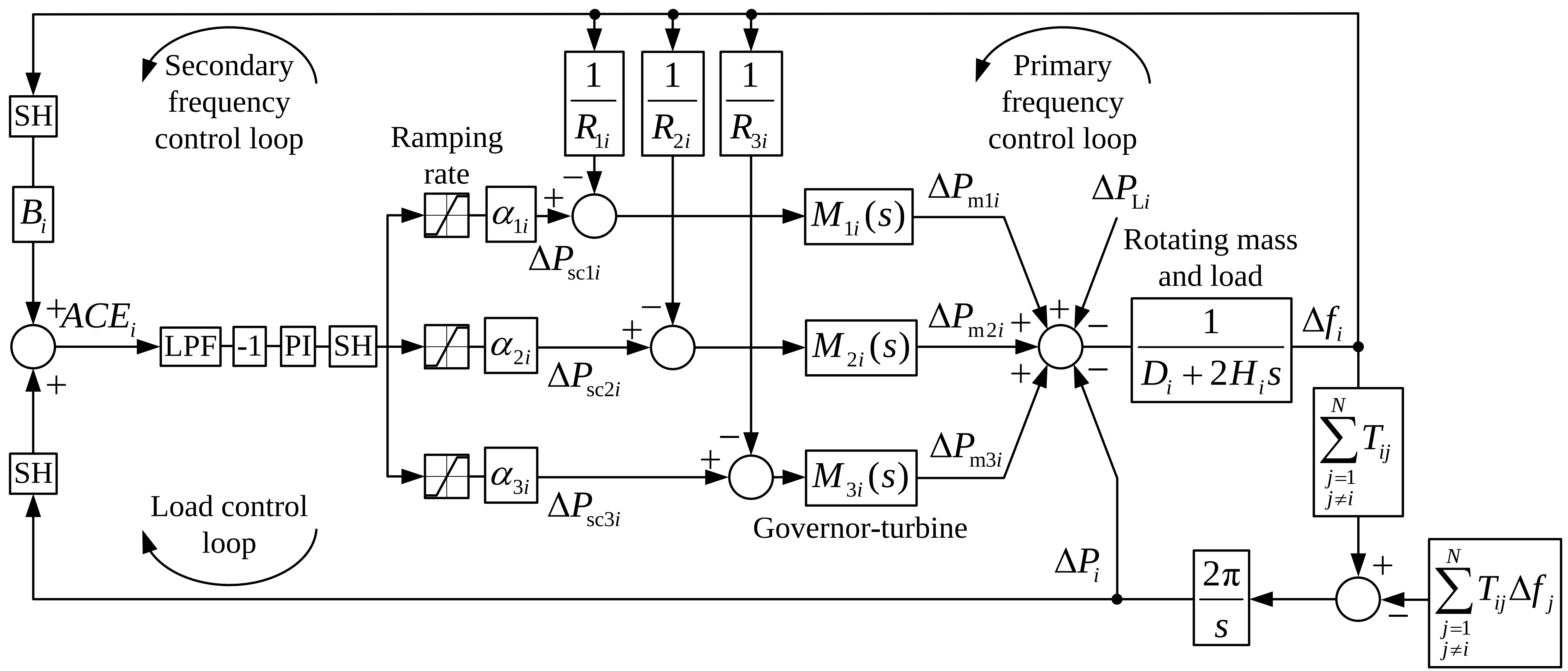


Figure 6: Block diagram of a single *i*-th CA.

- **Separate dynamic simulations** for the system with INP and **separate** for the system with aFRP.
- **Step changes of loads for three CAs with INP**
  - Case 1: at t = 10 s, ΔP_{L1} = – 0,06 pu, ΔP_{L2} = – 0,04 pu and ΔP_{L3} = 0,08 pu
  - Case 2: at t = 100 s, ΔP_{L1} = 0,06 pu, ΔP_{L2} = – 0,04 pu and ΔP_{L3} = – 0,08 pu

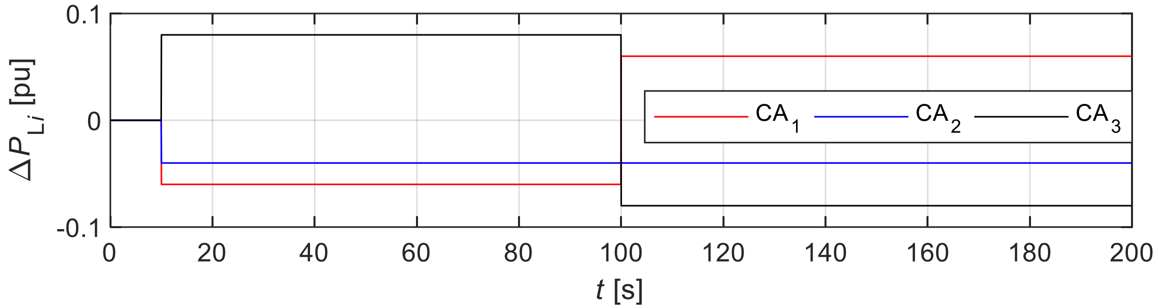


Figure 7: Step change of ΔP_{Li} used in numerical simulations for three CAs with aFRP.

- **Step changes of loads for three CAs with cross-border activation of aFRP**
  - Case 1: at t = 10 s, ΔP_{L1} = 0,04 pu, ΔP_{L2} = 0,06 pu in ΔP_{L3} = 0,08 pu
  - Case 2: at t = 100 s, ΔP_{L1} = – 0,04 pu, ΔP_{L2} = – 0,06 pu in ΔP_{L3} = – 0,08 pu

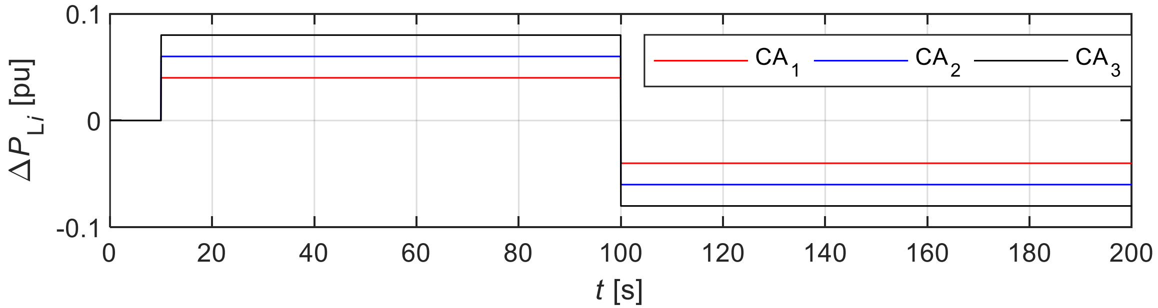


Figure 8: Step change of ΔP_{Li} used in numerical simulations for three CAs with INP.

- Frequency deviation Δf_i, area Control error ACE_i and scheduled control power ΔP_{sci}
- Reduced Δf_i in Case 1, increased absolute value of Δf_2 and Δf_3 in Case 2 with INP
- Reduced ACE_i and ΔP_{sci} with INP

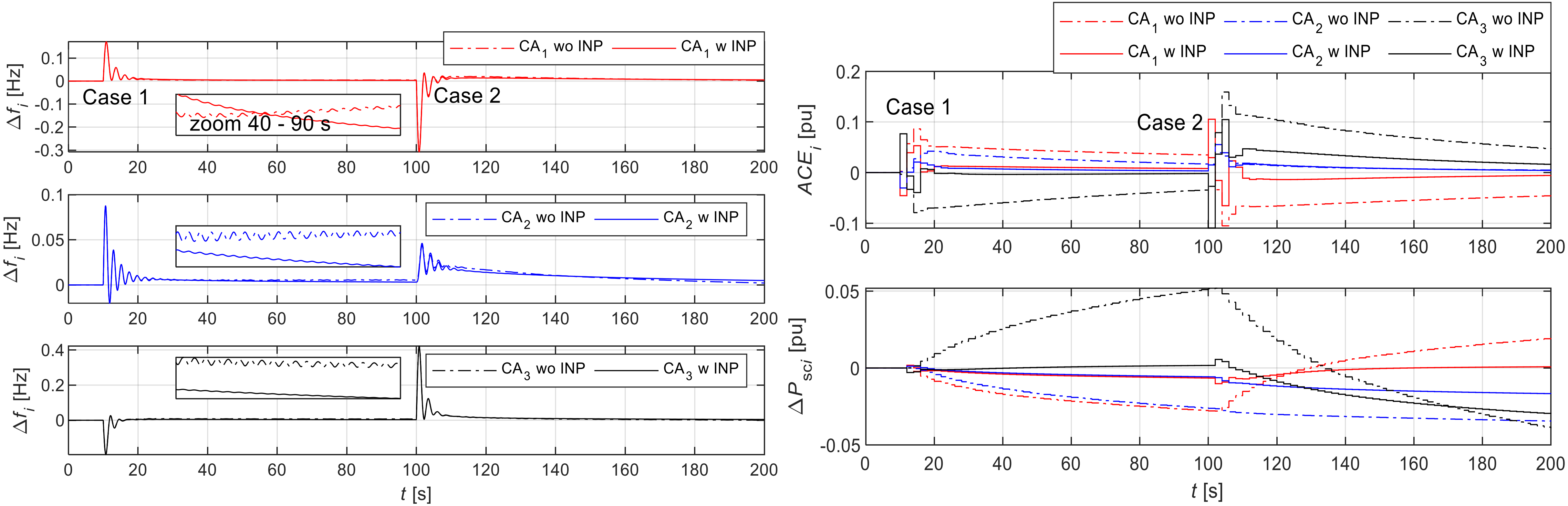


Figure 9: Time response of Δf_i, ACE_i and ΔP_{sci} for a three CA testing system, where ”wo” is without INP and ”w” is with INP.

- Electrical control power ΔP_{ei}, interchange power variation ΔP_i, demand power P_{di} and correction power P_{cori}
  - Reduced ΔP_{ei}, increased ΔP_i with INP
  - Opposite sign of P_{di} and P_{cori}

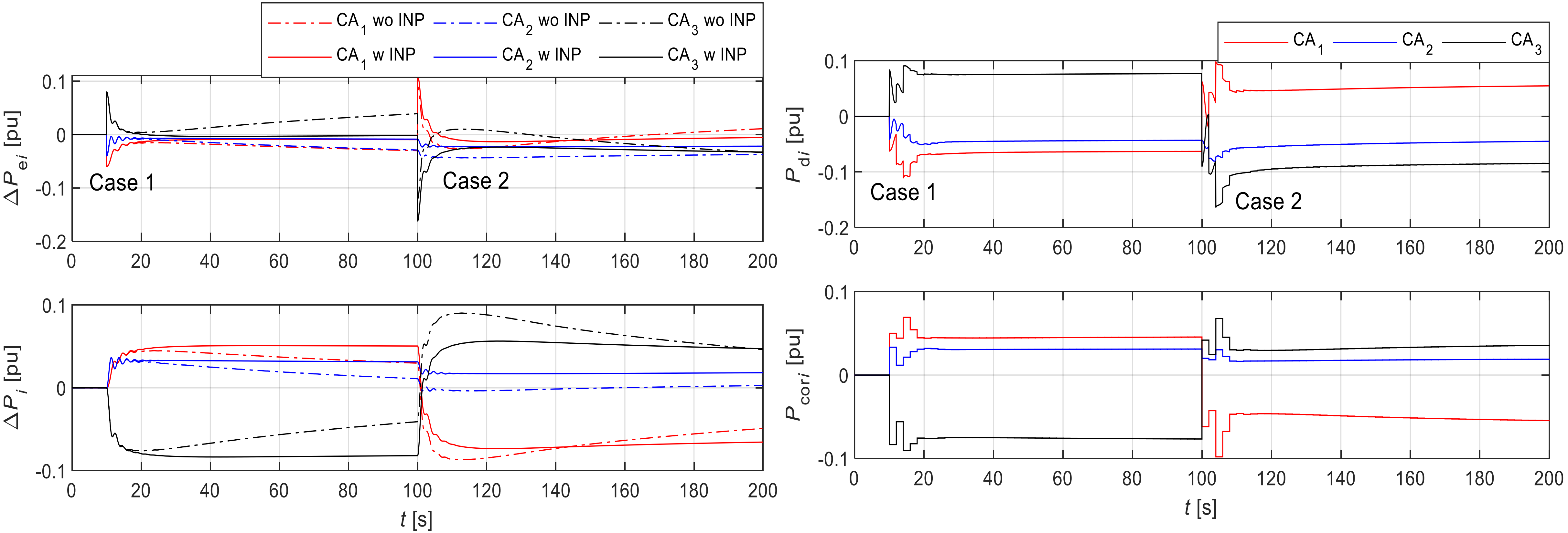


Figure 10: Time response of ΔP_{ei}, ΔP_i, P_{di} and P_{cori} for a three CA testing system, where "wo" is without INP and "w" is with INP.

RESULTS TO STEP CHANGES OF LOADS WITH aFRP

- Frequency deviation Δf_i, area control error ACE_i and scheduled control power ΔP_{sci}
  - Reduced Δf_i with INP
  - Increased ACE_1 and ACE_2, reduced ACE_3
  - Increased ΔP_{sc1} and ΔP_{sc2}, reduced ΔP_{sc3}

CA_3 activated:

- $0.7P_{corj}^*$ in CA_1
- $0.3P_{corj}^*$ in CA_2

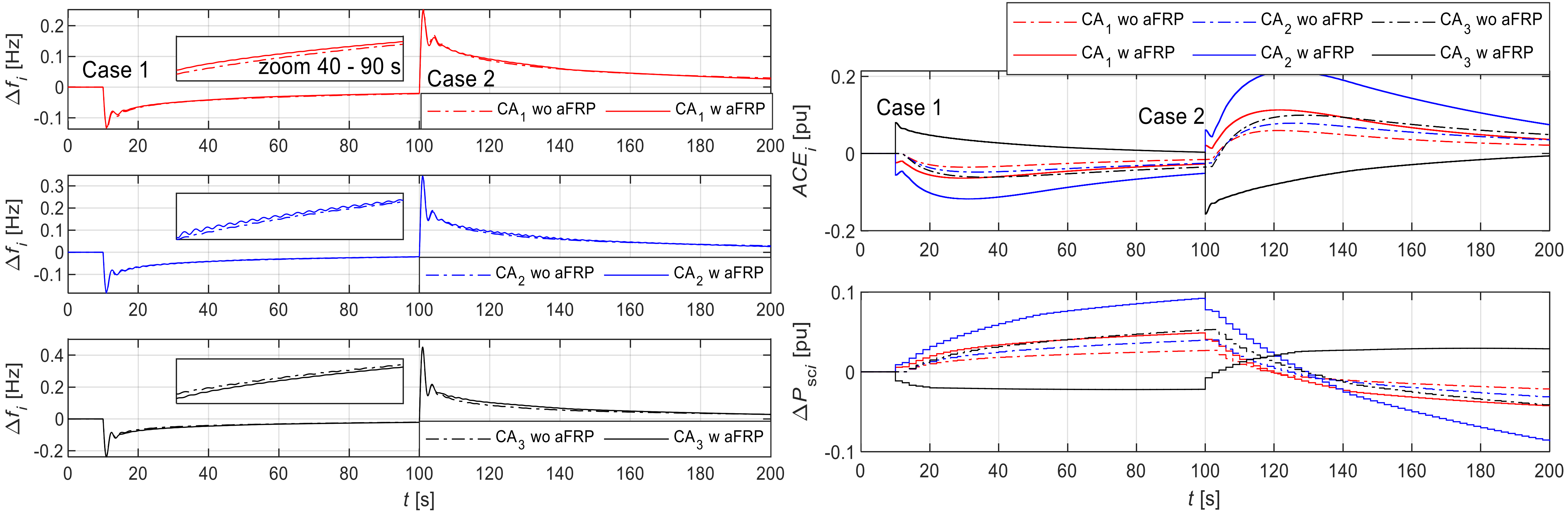


Figure 11: Time response of Δf_i, ACE_i and ΔP_{sci} for a three CA testing system, where ”wo” is without INP and ”w” is with INP.

- Area control error ACE_i and scheduled control Power ΔP_{sci}
- Simulation time 900 s
- Steady-state value

CA_3 activated:
- $0.7P_{corj}^*$ in CA_1
- $0.3P_{corj}^*$ in CA_2

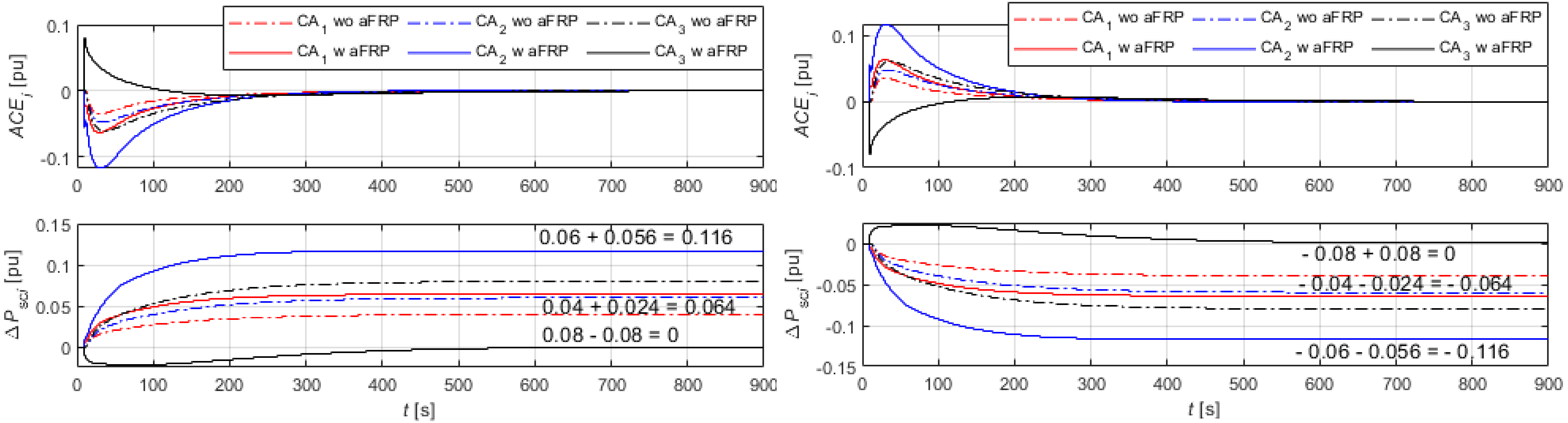


Figure 12: Time response of ACE_i and ΔP_{sci} for a three CA testing system, where ”wo” is without INP and ”w” is with INP.

- Electrical control power ΔP_{ei}, interchange power variation ΔP_{i}, demand power P_{di} and correction power P_{cori}
- Increased ΔP_{e1} and ΔP_{e2}, reduced ΔP_{e3}, increased ΔP_{i} with aFRP
- Opposite sign of P_{di} and P_{cori}

CA_3 activated:

- $0.7P_{corj}^{*}$ in CA_1
- $0.3P_{corj}^{*}$ in CA_2

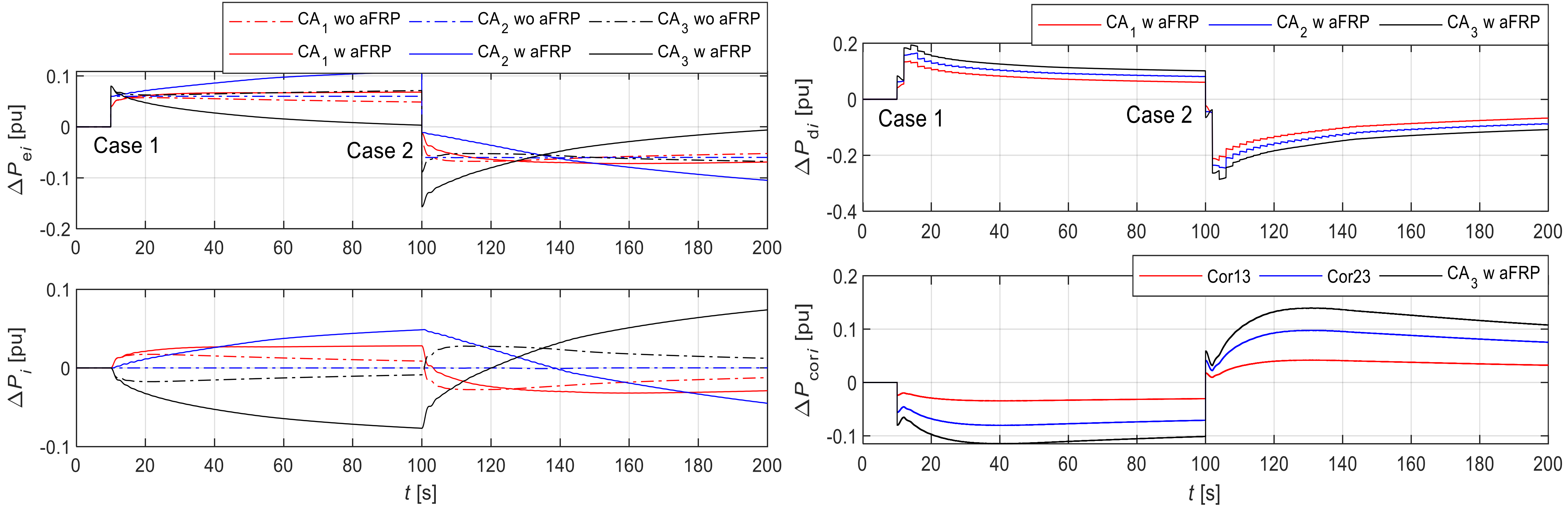
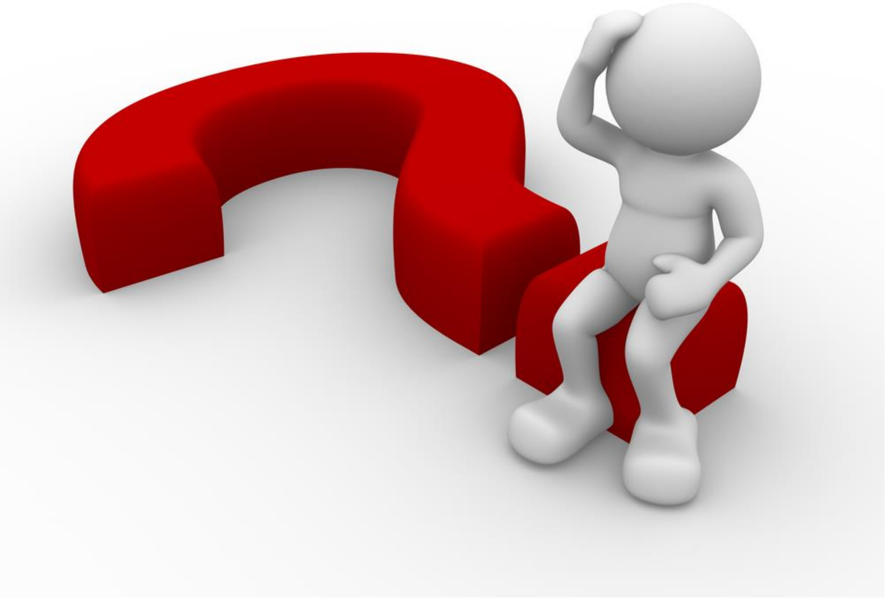


Figure 13: Time response of ΔP_{ei}, ΔP_{i}, P_{di} and P_{cori} for a three CA testing system, where ”wo” is without INP and ”w” is with INP.

CONCLUSION

- INP and cross-border activation of aFRP **reduce** frequency deviation.
- Cases of frequency quality **deterioration** can occur.
- Area control error, scheduled control power and electrical control power are:
  - **Reduced** with INP.
  - **Reduced** with cross-border activation of aFRP, when CA activates the secondary control reserve in neigbouring CAs.
- **Smaller** activation of secondary control reserve.
- INP and cross-border activation of aFRP:
  - **Release** regulating reserve.
  - **Reduce** balancing energy.
- **Future work** should focus on the dynamic dimensioning of regulating reserve with respect to INP and cross-border activation of aFRP.
- Possible **over dimension** of regulating reserve could be **decreased**.

QUESTIONS AND DISCUSSION



Thank you for your attention!

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