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MEDOW MULTI-TERMINAL DC GRID FOR OFFSHORE WIND

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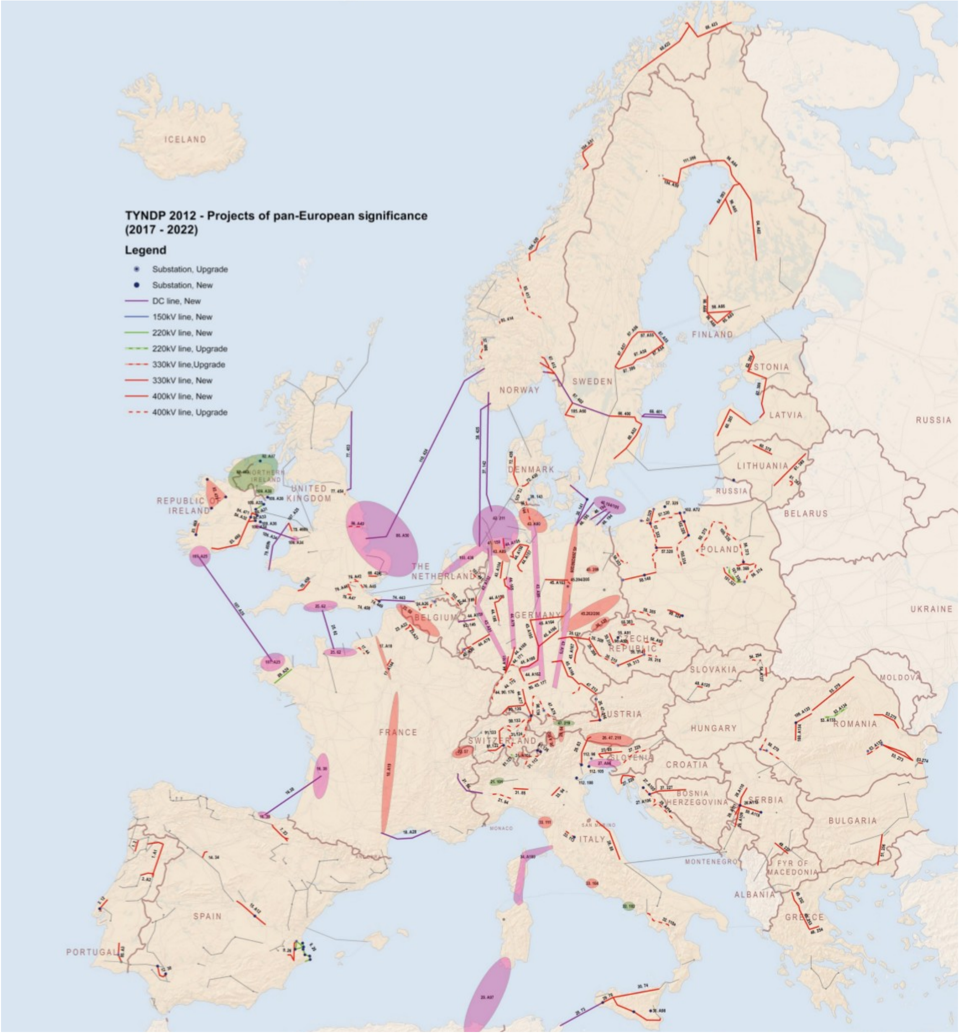
Operation of HVDC Power Systems

Robert H. Renner

Overview

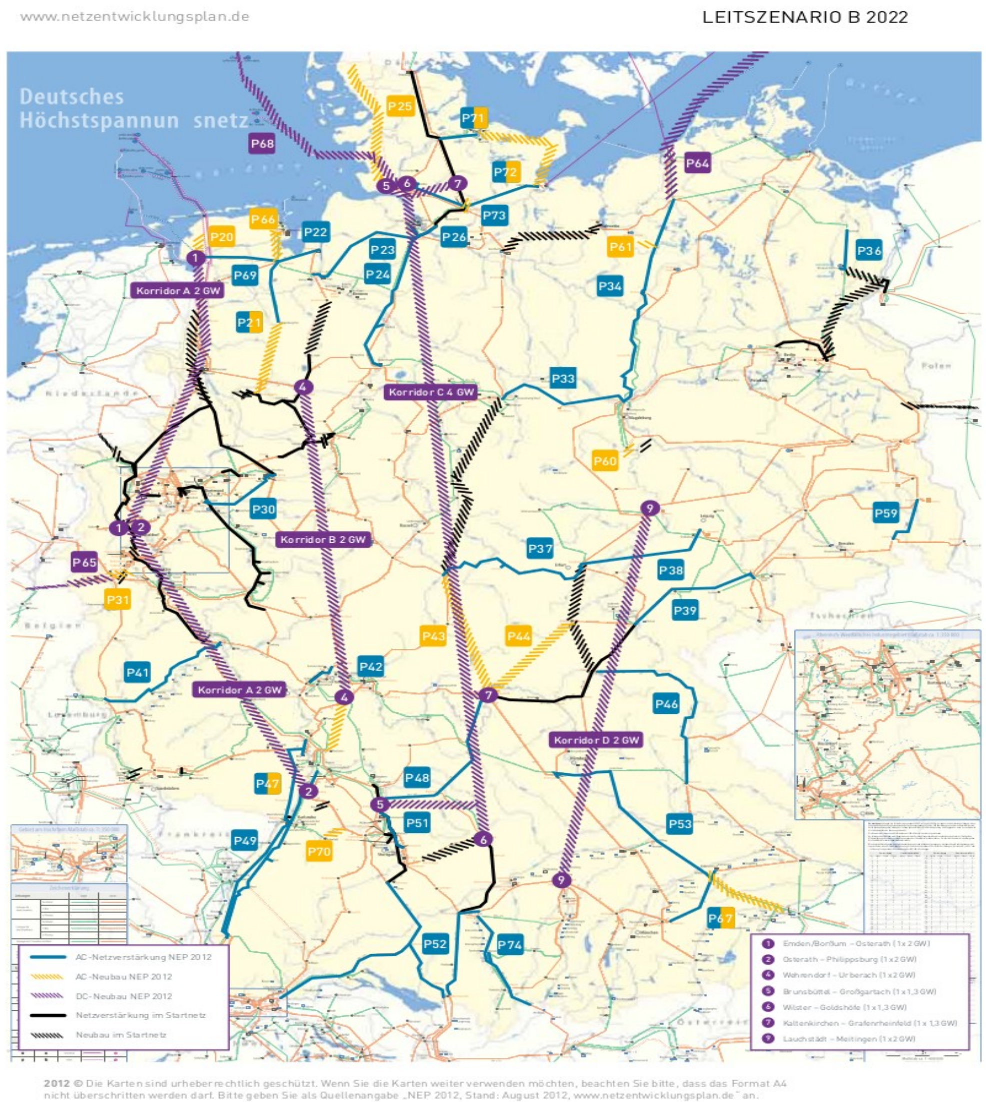
- Introduction
- System operation
  - System balancing
  - DC secondary control
    - Steady state
    - Dynamic
  - Simulation example
- Conclusion



Reference: ENTSOE 10-Year Network Development Plan 2012

Introduction

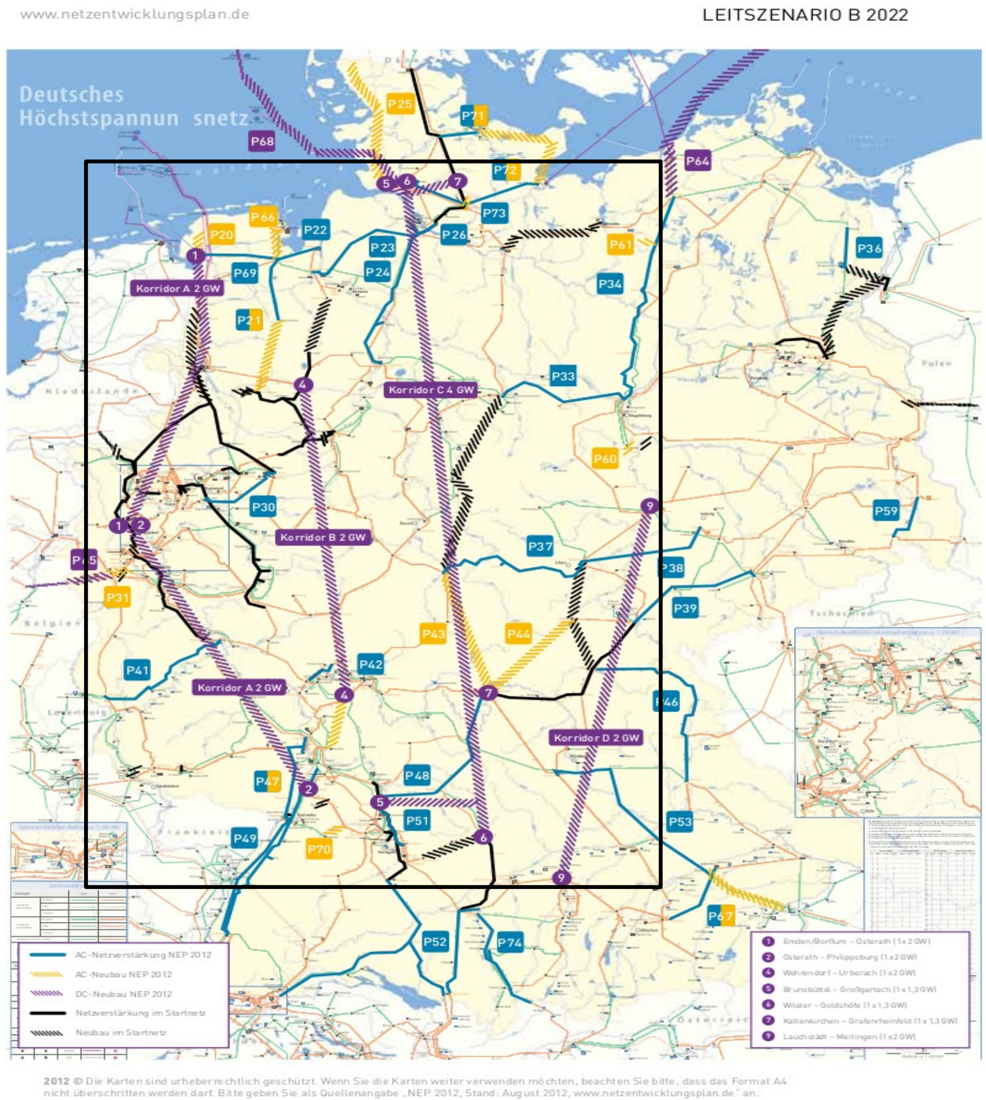
Development plan for 2022



Reference:NEP 2012, Date: August 2012, www.netzentwicklungsplan.de

Introduction

Development plan for 2022



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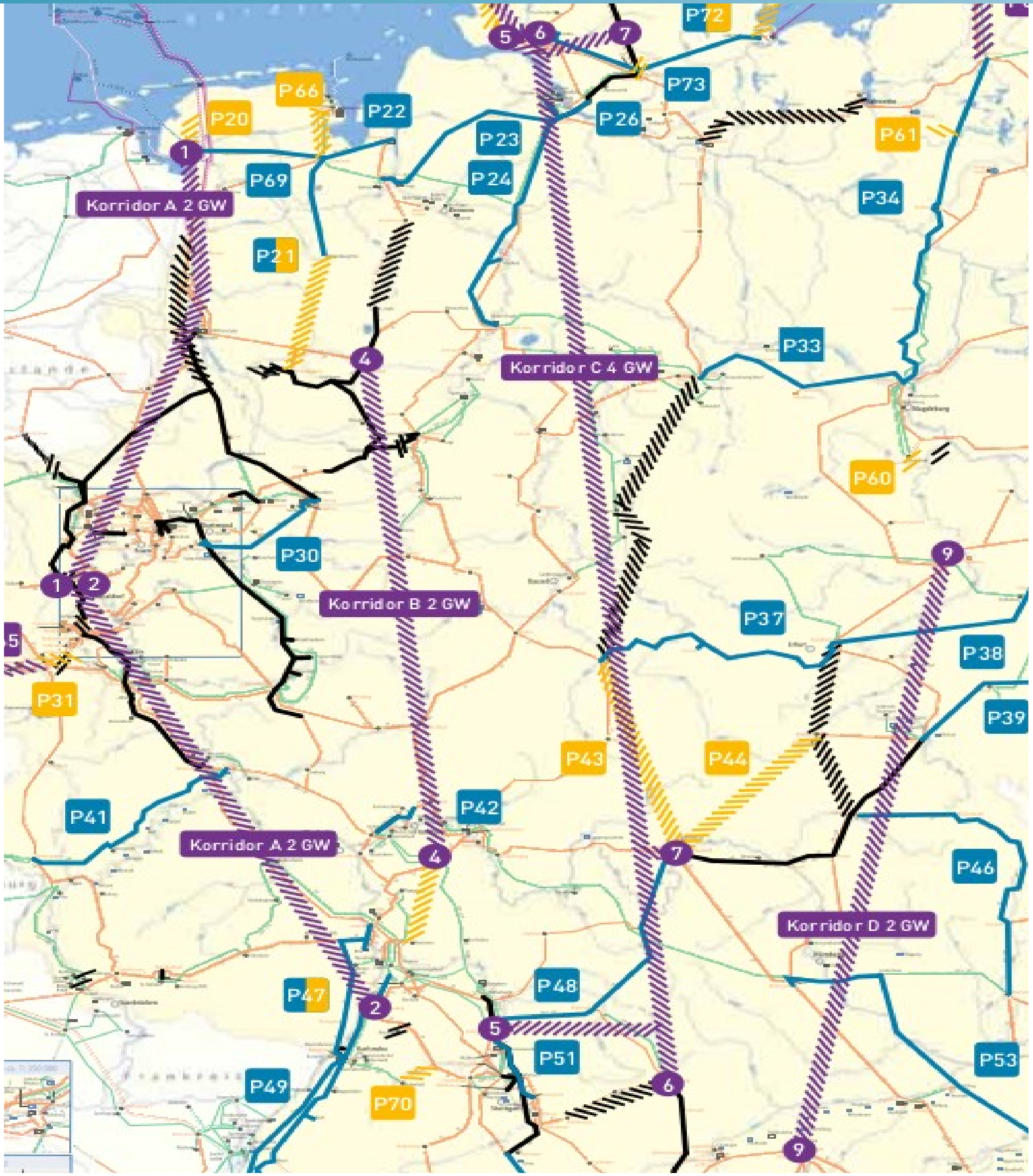
Introduction

Development plan for 2022



Reference:NEP 2012,
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Introduction

Development from 2022 to 2050

1-4 ~160 km

2-4 ~100 km

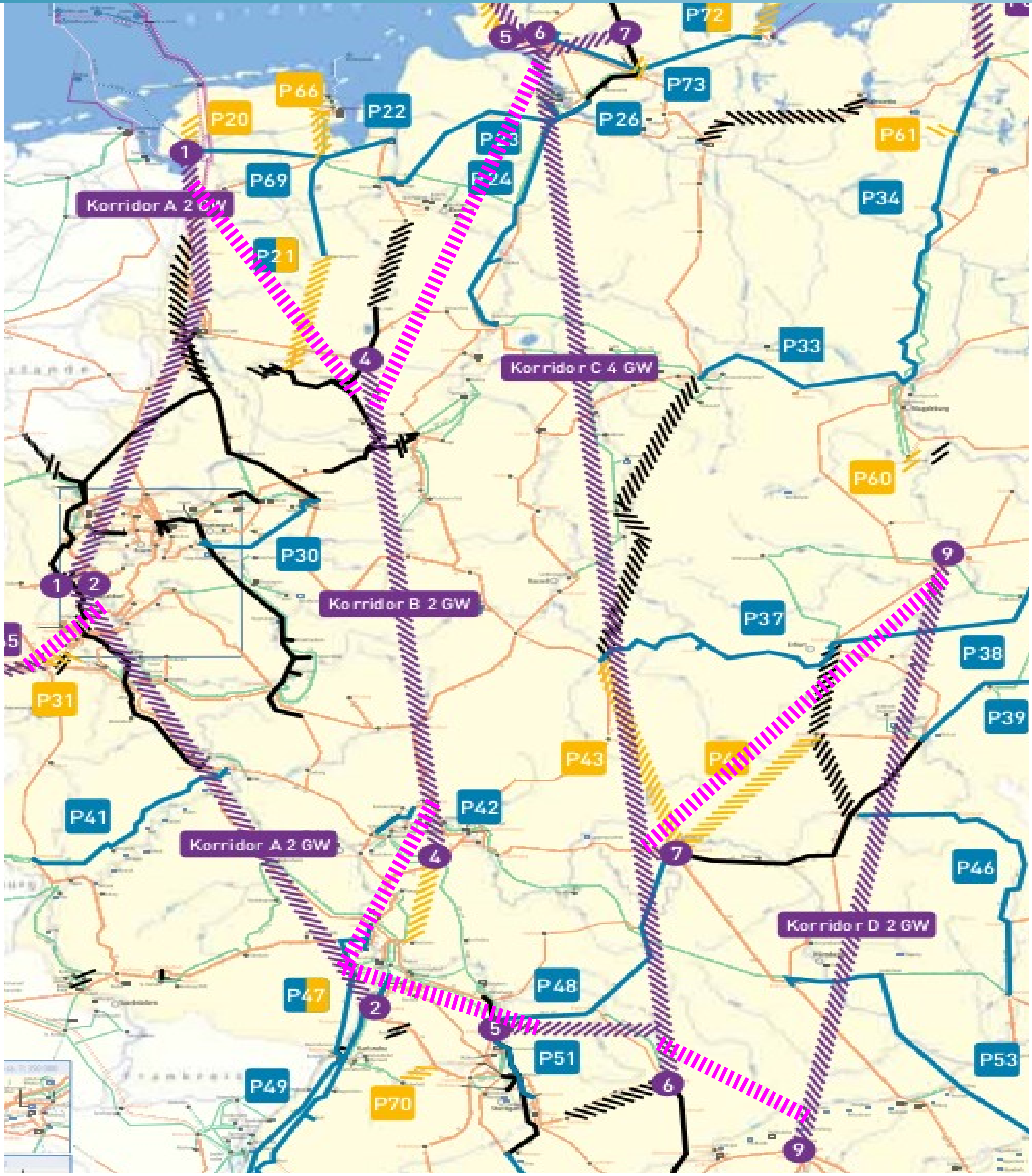
2-A ~60 km

2-5 ~100 km

6-9 ~100 km

4-6 ~250 km

7-9 ~250 km



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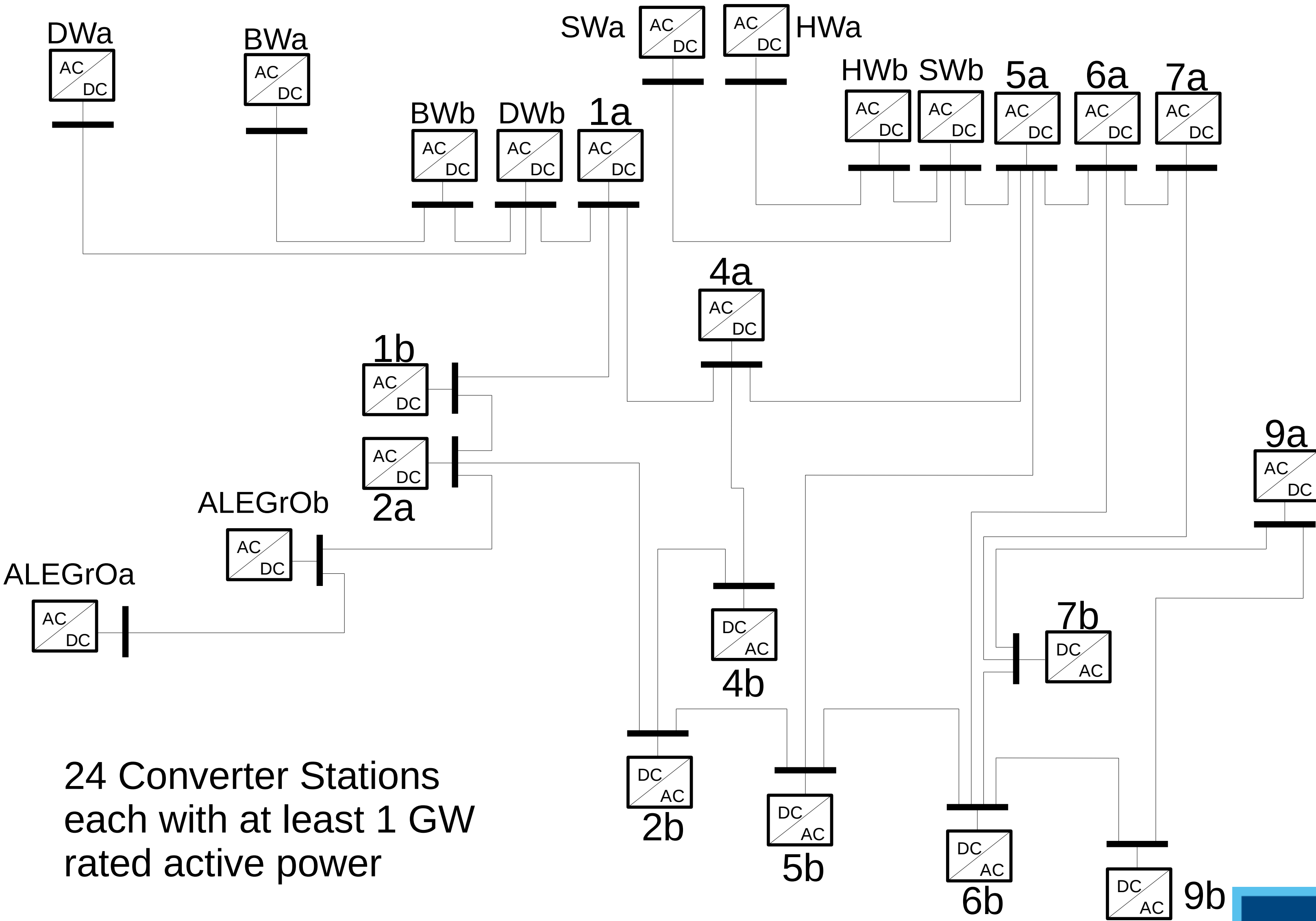
Introduction



24 Converter Stations each with at least 1 GW rated active power

System Operation

Transmission system operator are responsible for the security of supply in a certain geographical area (in AC systems mostly a country)

Operation

- Monitoring and Control of actual grid states (Voltage, Power, Topology, etc.)
- Ensuring security level (e.g. N-1)
- Congestion management
- Loss optimization
- Contingency registration and clearance
- Grid restoration
- Etc.

System balancing

- Schedule verification
- Reserve management
- Wind forecast
- Etc.

Development, Maintenance and Protection

- Planning
- Coordinating
- Supervising

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System balancing

- AC systems
  - Generation = Load
  - Imbalance is buffered by the energy stored in the rotating mass, thus change in frequency = power imbalance
- Three step reserve
  - Frequency Containment Reserve (FCR) or Primary Reserve
  - Frequency Restoration Reserve (FRR) or Secondary Reserve
  - Replacement Reserve (RR) or Tertiary Reserve

- DC systems
  - In-feed = withdraw
  - Imbalance is buffered by the energy stored in the capacitance, thus change in voltage = power imbalance
- Multi step reserve ?

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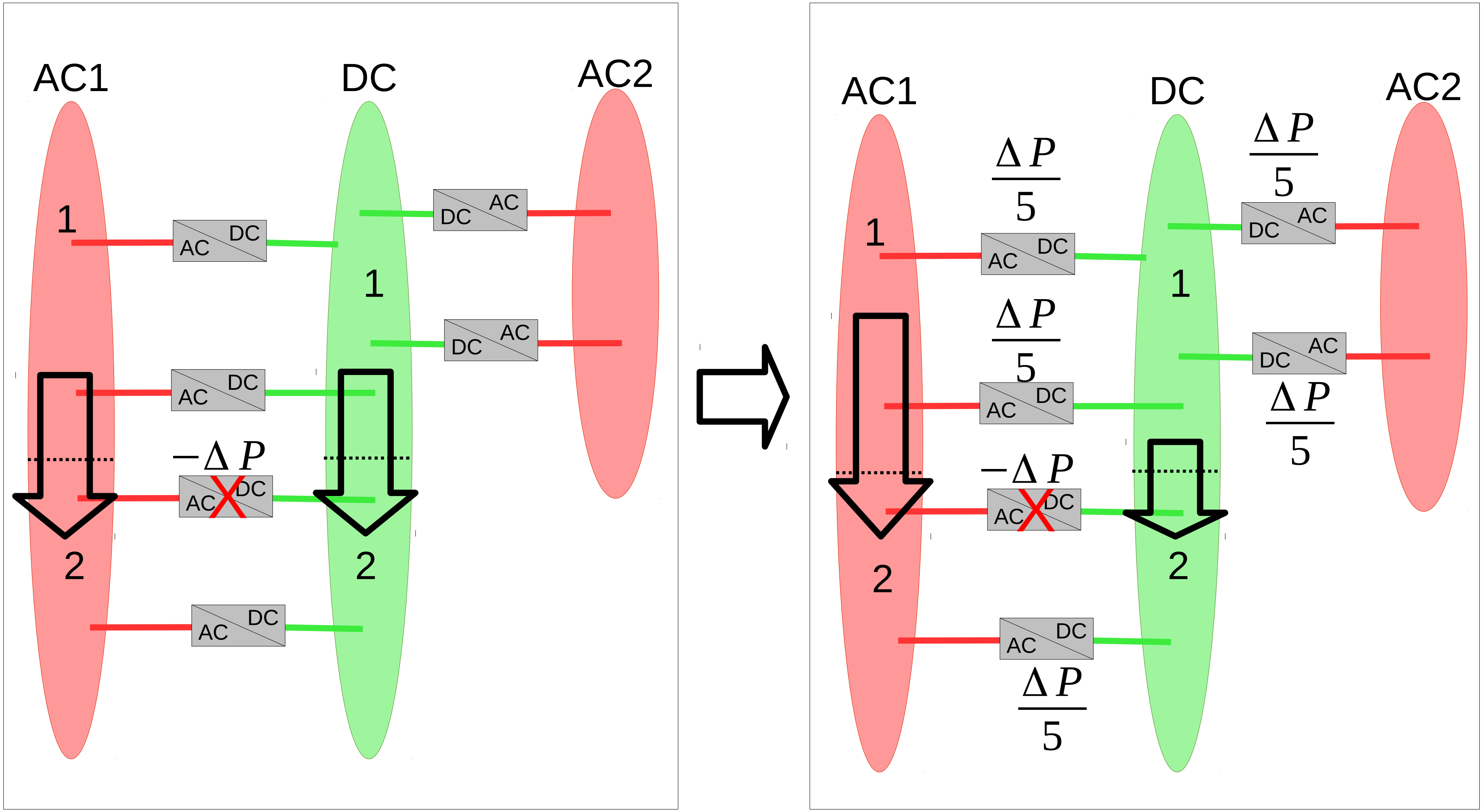
DC Secondary Control

Secondary Reserve

Outage of a Converter
- Replacement of primary reserve
- Re-establish scheduled power exchange

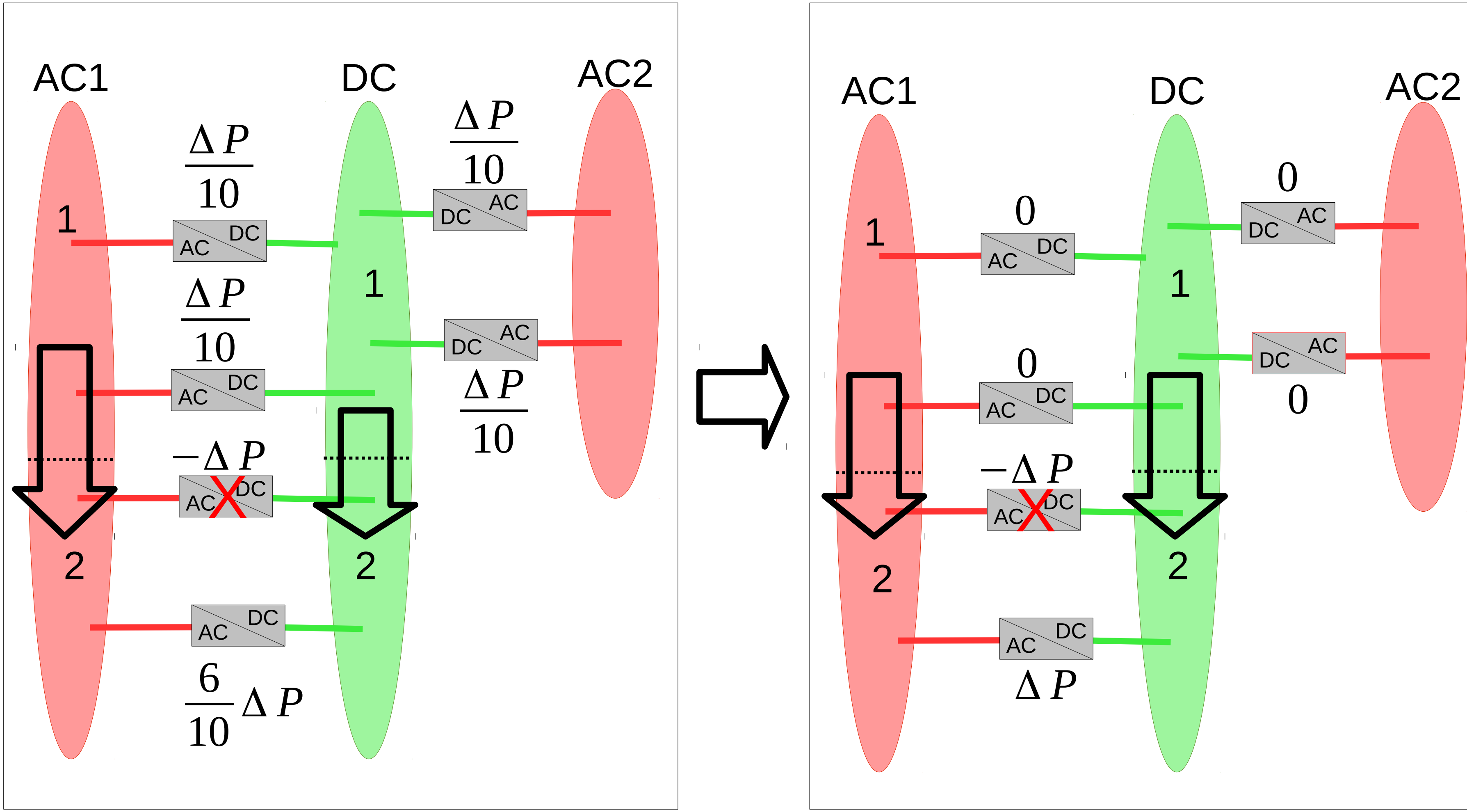
While normal operation, compensate deviations from power set-points
- Measurement errors
- Forecast errors
- Unsynchronised set-point change
- Etc.

System balancing



First reserve step guarantee the stability of the whole power system after a major disturbance

System balancing



Second reserve step brings the system back to the scheduled power exchanges

System balancing

Thus, a three step reserve for DC power systems is beneficial

DC Voltage Droop Control

DC Voltage Containment Reserve (DCVCR)
or Primary Reserve (automatic activation)
Decentralised P-controller

DC Power-Voltage control

DC Voltage Restoration Reserve (DCVRR)
or DC Secondary Reserve (automatic activation)
Centralised PI-controller

Manual set-point change

DC Replacement Reserve (DCRR)
or DC Tertiary Reserve (manual activation)

DC Secondary Control

- Secondary Control
  - Central Control, Power Sum + Energy Deviation
    - Loss Optimisation
    - Defined Power Change speed (Ramps)
    - Defined Power exchange between control areas

$$G=\Delta X\cdot k_{System}+\sum_{i=1}^{n} P_{iSet}-\sum_{i=1}^{n} P_{iMeas}$$

$$with\ \ X=Energy\ \ balance\ \ indicator$$

DC Secondary Control

Secondary Reserve

Outage of a Converter

- Replacement of primary reserve
- Re-establish scheduled power exchange

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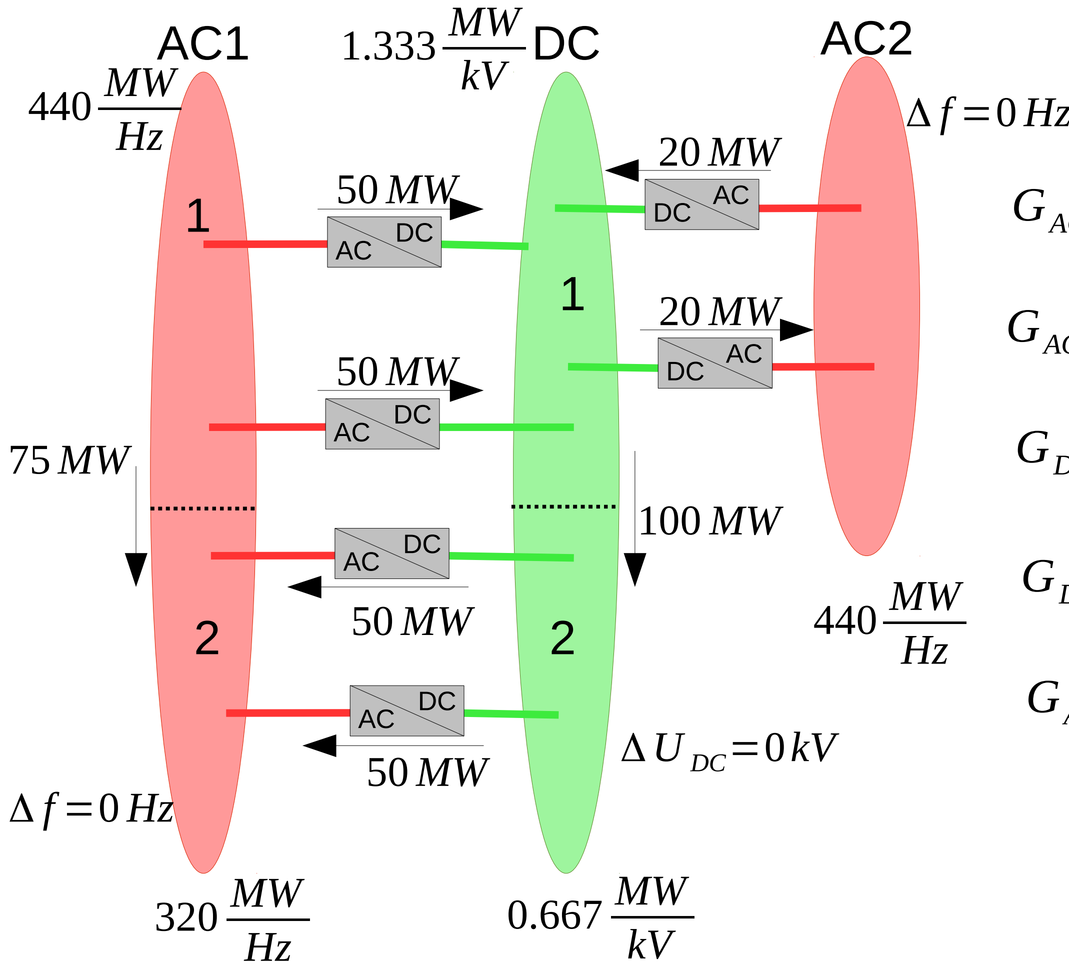
System balancing



$$G_{AC1.1}=\Delta f_{AC1}\cdot k_{AC1}+\sum_{i=1}^{n}P_{iSetTie}-\sum_{i=1}^{n}P_{iMeasTie}$$

$$G_{AC1.2}=\Delta f_{AC1}\cdot k_{AC2}+\sum_{i=1}^{n}P_{iSetTie}-\sum_{i=1}^{n}P_{iMeasTie}$$

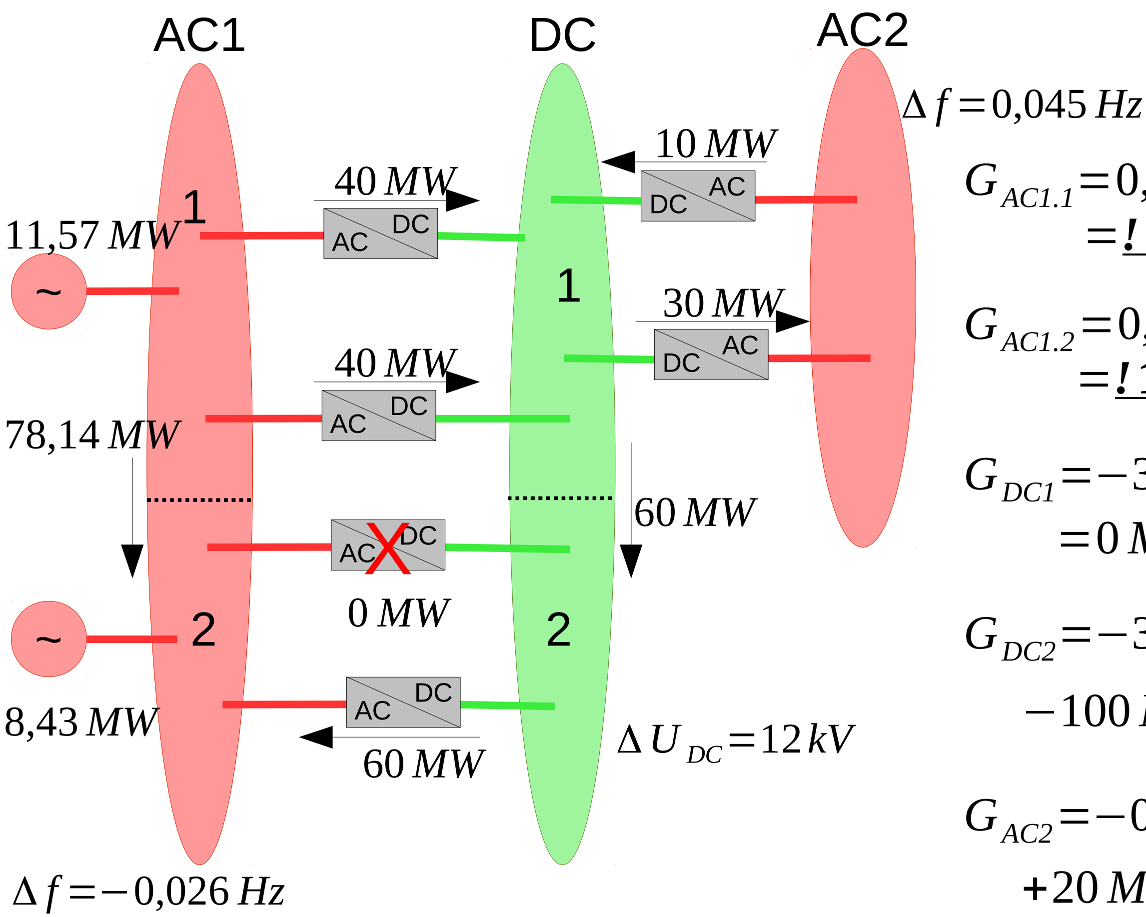
$$G_{DC1}=\Delta U_{DC}\cdot k_{DC1}+\sum_{i=1}^{n}P_{iSetTie}-\sum_{i=1}^{n}P_{iMeasTie}$$

$$G_{DC2}=\Delta U_{DC}\cdot k_{DC2}+\sum_{i=1}^{n}P_{iSetTie}-\sum_{i=1}^{n}P_{iMeasTie}$$

$$G_{AC2}=\Delta f_{AC2}\cdot k_{AC2}+\sum_{i=1}^{n}P_{iSetCon}-\sum_{i=1}^{n}P_{iMeasCon}$$

First reserve step guarantee the stability of the whole power system after a major disturbance

System balancing



$$G_{AC1.1} = 0{,}026\,Hz \cdot 440\,\frac{MW}{Hz} + 75\,MW - 78{,}14\,MW$$
$$= \underline{\mathbf{!\,8{,}43\,MW\,!}}$$

$$G_{AC1.2} = 0{,}026\,Hz \cdot 320\,\frac{MW}{Hz} - 75\,MW + 78{,}14\,MW$$
$$= \underline{\mathbf{!\,11{,}57\,MW\,!}}$$

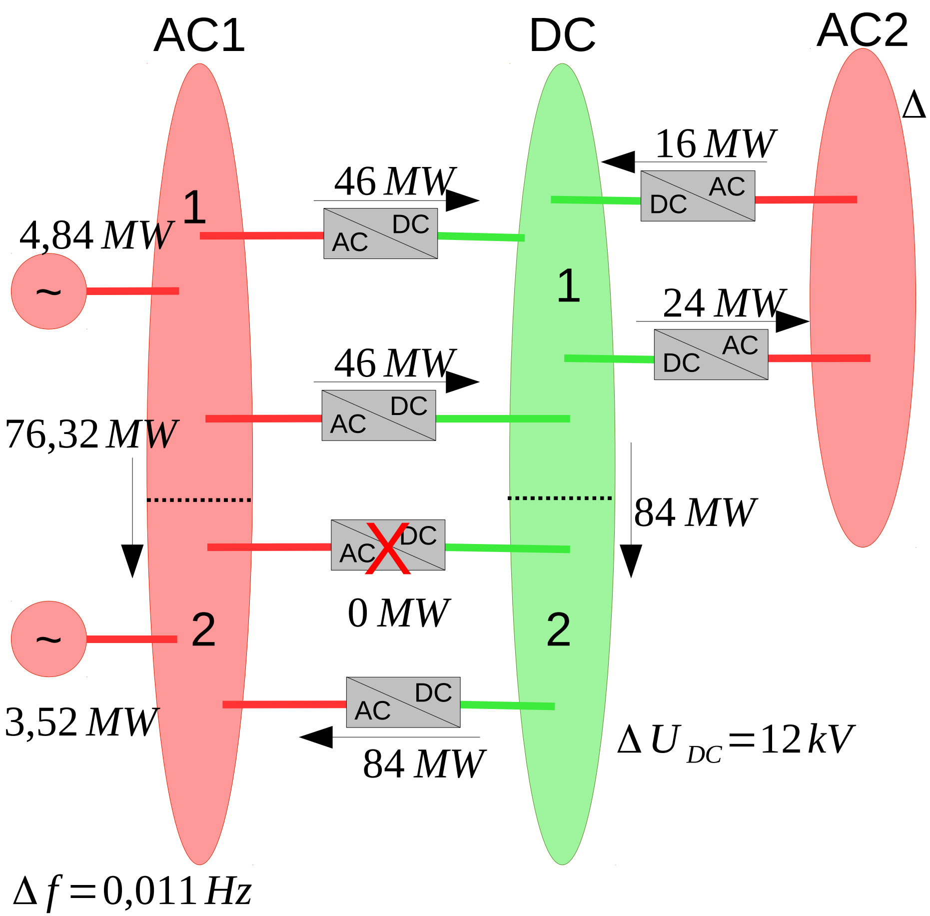
$$G_{DC1} = -30\,kV \cdot 1{,}333\,\frac{MW}{kV} + 100\,MW - 60\,MW$$
$$= 0\,MW$$

$$G_{DC2} = -30\,kV \cdot 0{,}333\,\frac{MW}{kV}$$
$$-100\,MW + 60\,MW = -50\,MW$$

$$G_{AC2} = -0{,}045\,Hz \cdot 440\,\frac{MW}{Hz}$$
$$+20\,MW - 20\,MW - 10\,MW + 30\,MW = 0\,MW$$

Second reserve step brings the system back to the scheduled power exchanges

System balancing



$$G_{AC1.1} = 0{,}011\ Hz \cdot 440\ \frac{MW}{Hz} + 75\ MW - 76{,}32\ MW$$
$$= \underline{\mathbf{!\ 3{,}52\ MW\ !}}$$

$$G_{AC1.2} = 0{,}011\ Hz \cdot 320\ \frac{MW}{Hz} - 75\ MW + 76{,}32\ MW$$
$$= \underline{\mathbf{!\ 4{,}84\ MW\ !}}$$

$$G_{DC1} = -12\ kV \cdot 1{,}333\ \frac{MW}{kV} + 100\ MW - 84\ MW$$
$$= 0\ MW$$

$$G_{DC2} = -12\ kV \cdot 0{,}333\ \frac{MW}{kV}$$
$$-100\ MW + 84\ MW = -20\ MW$$

$$G_{AC2} = -0{,}018\ Hz \cdot 440\ \frac{MW}{Hz}$$
$$+20\ MW - 20\ MW - 16\ MW + 24\ MW = 0\ MW$$

Second reserve step brings the system back to the scheduled power exchanges

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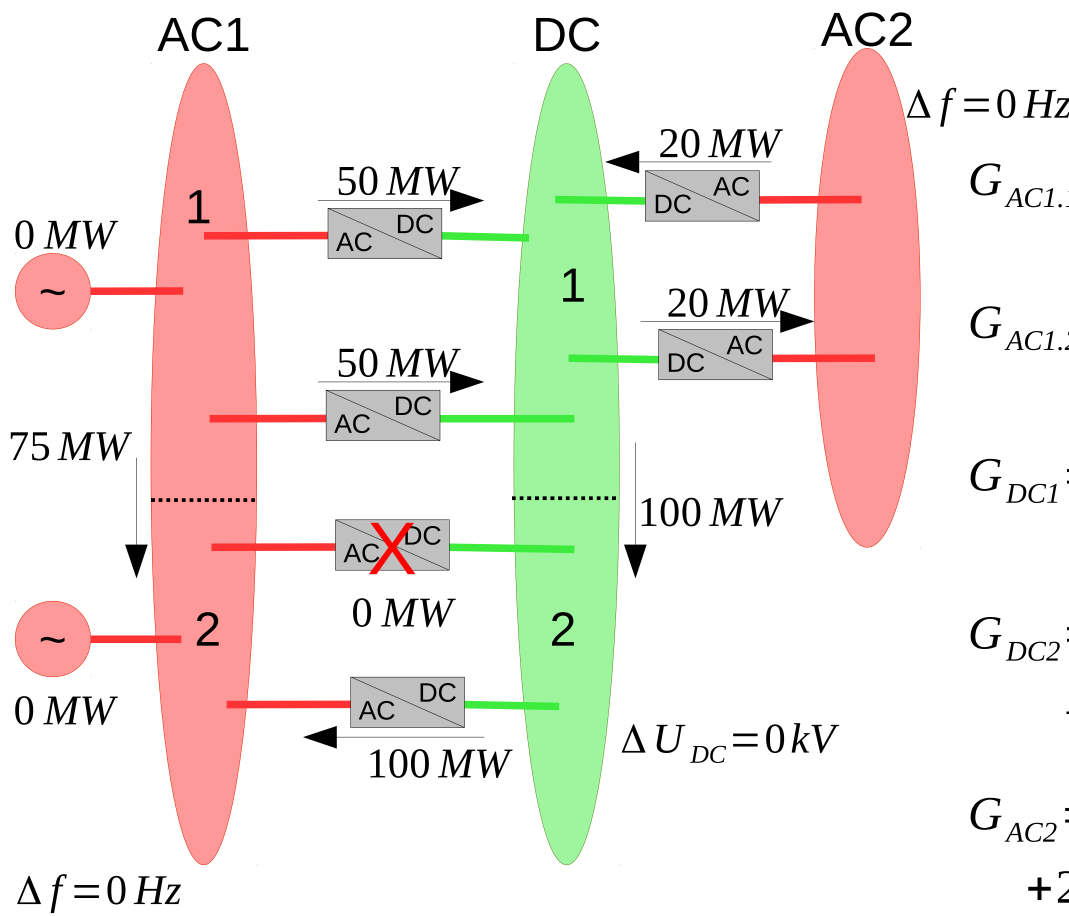
System balancing



$$G_{AC1.1} = 0\,Hz \cdot 440\,\frac{MW}{Hz} + 75\,MW - 75\,MW = 0\,MW$$

$$G_{AC1.2} = 0\,Hz \cdot 320\,\frac{MW}{Hz} - 75\,MW + 75\,MW = 0$$

$$G_{DC1} = 0\,kV \cdot 1{,}333\,\frac{MW}{kV} + 100\,MW - 100\,MW = 0\,MW$$

$$G_{DC2} = 0\,kV \cdot 0{,}333\,\frac{MW}{kV} - 100\,MW + 100\,MW = 0\,MW$$

$$G_{AC2} = 0\,Hz \cdot 440\,\frac{MW}{Hz} + 20\,MW - 20\,MW - 20\,MW + 20\,MW = 0\,MW$$

Second reserve step brings the system back to the scheduled power exchanges

DC Secondary Control

Secondary Reserve

While normal operation, compensate deviations from power set-points

- Measurement errors
- Forecast errors
- Unsynchronised set-point change
- Etc.

DC Secondary Control

Energy equations

$$P(t)_{Cap} = i(t)\cdot v(t) = \left(C\cdot\frac{dv(t)}{dt}\right)\cdot v(t)$$

$$P(t)_{Rot} = M(t)\cdot\omega(t) = \left(J\cdot\frac{d\omega(t)}{dt}\right)\cdot\omega(t)$$

$$\text{with } E = \int_{t_1}^{t_2} P(t)\,dt$$

$$\Rightarrow \int_{t_1}^{t_2} P(t)_{Cap}\,dt = \int_{t_1}^{t_2}\left(C\cdot\frac{dv(t)}{dt}\right)v(t)\,dt$$

$$\Rightarrow \int_{t_1}^{t_2} P(t)_{Rot}\,dt = \int_{t_1}^{t_2}\left(J\cdot\frac{d\omega(t)}{dt}\right)\cdot\omega(t)\,dt$$

$$P = const.$$

$$P_{Cap}\cdot t_2 - P_{Cap}\cdot t_1 = C\cdot\frac{1}{2}\cdot\left(v(t_2)^2 - v(t_1)^2\right)$$

$$P_{Rot}\cdot t_2 - P_{Rot}\cdot t_1 = J\cdot\frac{1}{2}\cdot\left(\omega(t_2)^2 - \omega(t_1)^2\right)$$

$$t_1 = 0$$

$$P_{Cap}\cdot t = C\cdot\frac{1}{2}\cdot\left(v(t)^2 - v(0)^2\right)$$

$$P_{Rot}\cdot t = J\cdot\frac{1}{2}\cdot\left(\omega(t)^2 - \omega(0)^2\right)$$

DC Secondary Control

Buffer energy related to τ respectively H

$$P_{Cap} \cdot t = C \cdot \frac{1}{2} \cdot \left(v(t)^2 - v(0)^2\right)$$

$$\text{with } v(0) = V_N \wedge t = \tau \wedge P = P_r$$

$$\Rightarrow P_r \cdot \tau = C \cdot \frac{1}{2} \cdot \left(\left(V_N \cdot e^{(-1)}\right)^2 - V_N^2\right)$$

$$\Rightarrow C = \frac{2 \cdot P_r \cdot \tau}{\left(\left(V_N \cdot e^{(-1)}\right)^2 - V_N^2\right)} = \frac{2 \cdot P_r \cdot \tau}{V_N^2 \left(e^{(-2)} - 1\right)}$$

$$\Delta E_{Cap} = \frac{P_r \cdot \tau}{V_N^2 \left(e^{(-2)} - 1\right)} \cdot \left(v(t_2)^2 - v(t_1)^2\right)$$

$$P_{Rot} \cdot t = J \cdot \frac{1}{2} \cdot \left(\omega(t)^2 - \omega(0)^2\right)$$

$$\text{with } \omega(0) = \omega_N \wedge t = H \wedge P = S_r$$

$$\Rightarrow S_r \cdot H = J \cdot \frac{1}{2} \cdot \omega_N^2$$

$$\Rightarrow J = \frac{2 \cdot S_r \cdot H}{\omega_N^2}$$

$$\Delta E_{Rot} = \frac{H \cdot S_r}{\omega_N^2} \cdot \left(\omega(t_2)^2 - \omega(t_1)^2\right)$$

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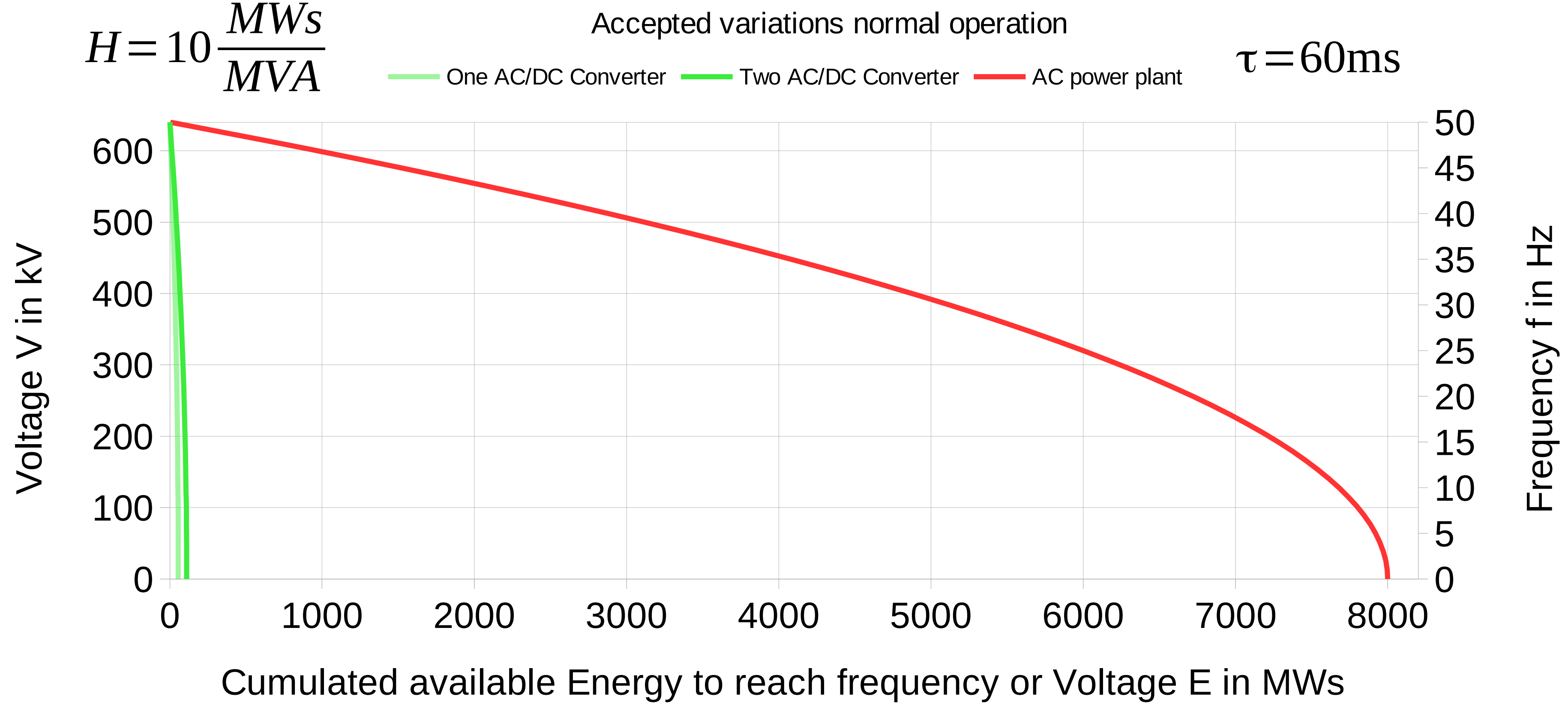
DC Secondary Control

Total energy in rotating mass compared with energy in capacitors

$\omega_N = 2\cdot\pi\cdot 50\text{Hz}$ $P_r = 800\text{MW}$ $S_r = 800\text{MVA}$ $V_N = \pm 320\,kV$

$H = 10\frac{MWs}{MVA}$ $\tau = 60\text{ms}$

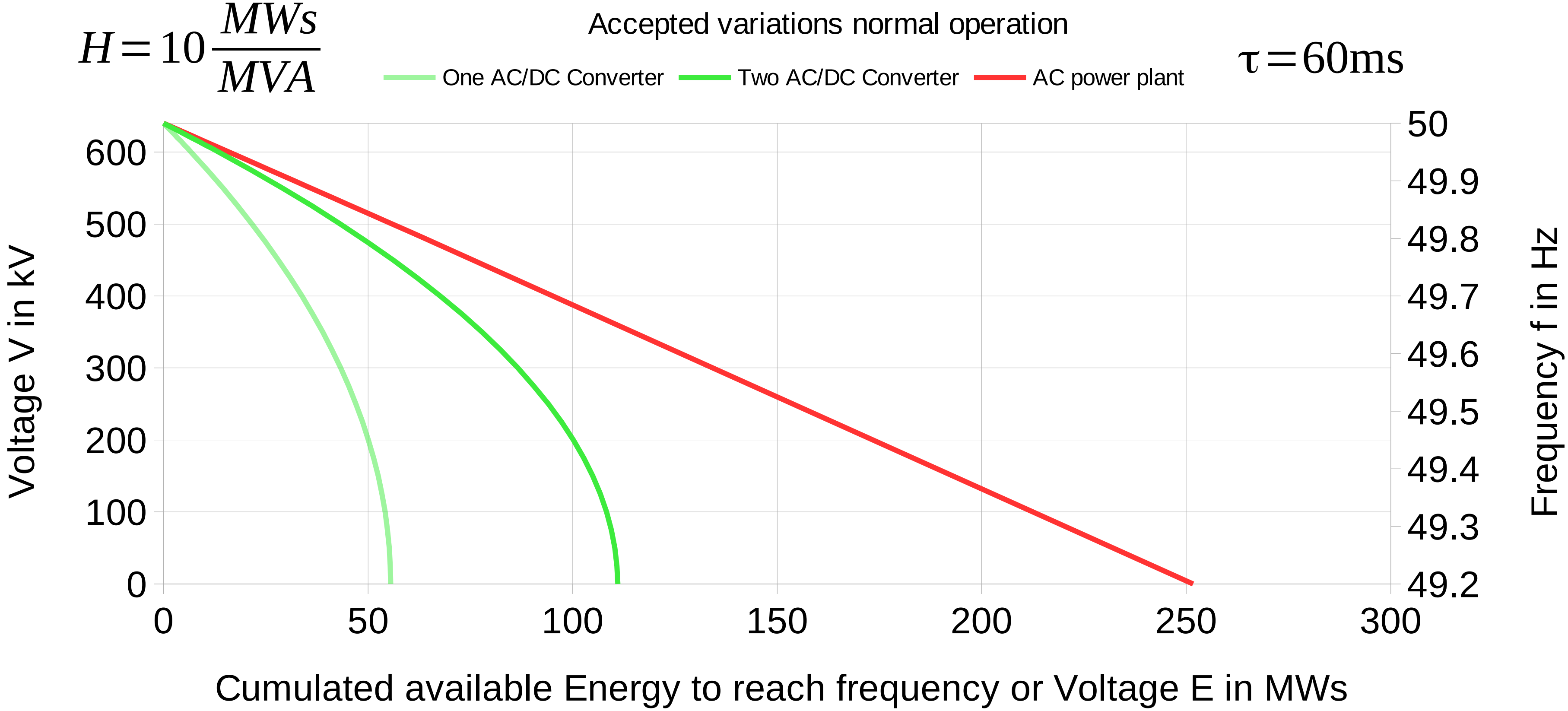


DC Secondary Control

Used energy from rotating mass after a disturbance compared with total energy in capacitors

$\omega_N = 2\cdot\pi\cdot 50\text{Hz}$ $P_r = 800\text{MW}$ $S_r = 800\text{MVA}$ $V_N = \pm 320\,kV$

$H = 10\,\frac{MWs}{MVA}$ $\tau = 60\text{ms}$

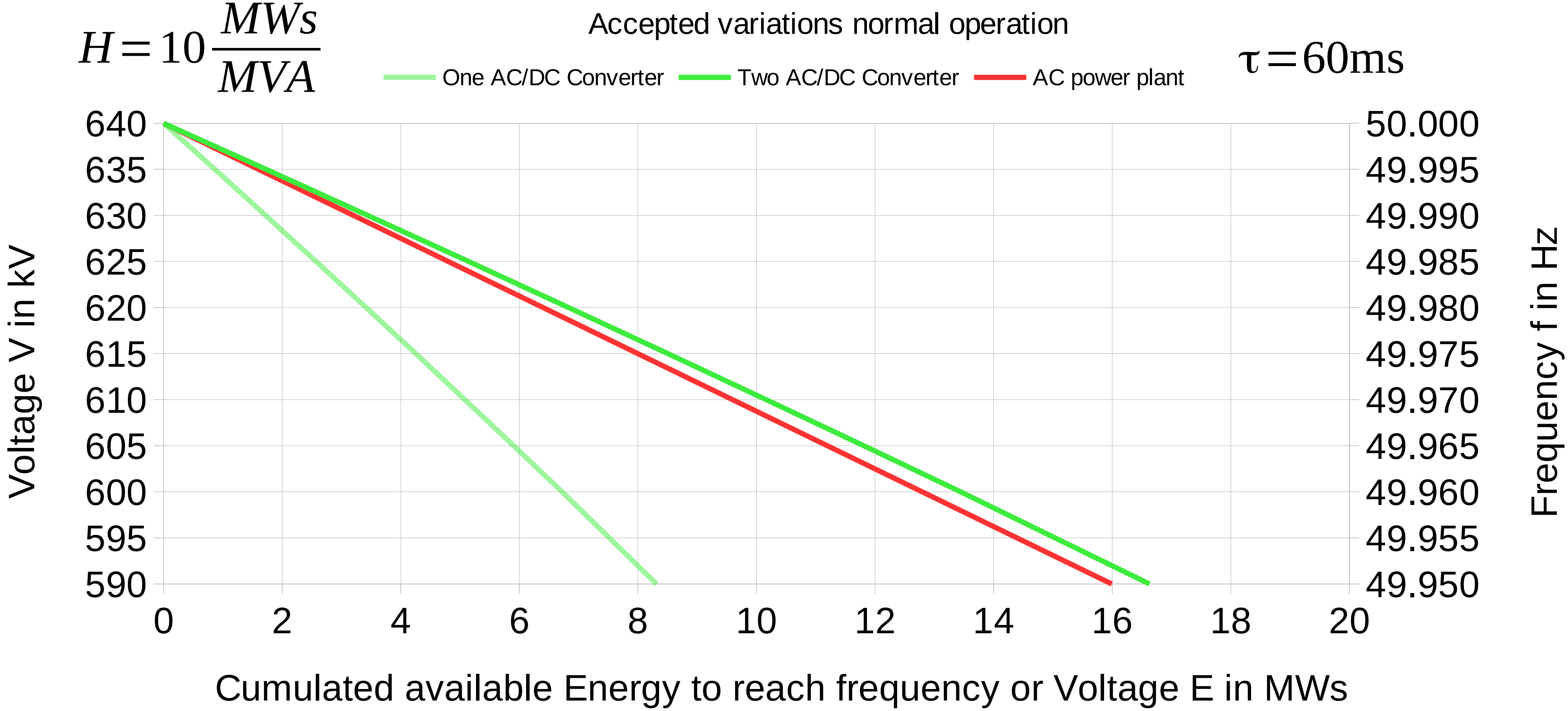


DC Secondary Control

Energy used as buffer while normal operation in rotating mass compared with capacitors

$\omega_N = 2 \cdot \pi \cdot 50\mathrm{Hz}$ $\quad P_r = 800\mathrm{MW}$ $\quad S_r = 800\mathrm{MVA}$ $\quad V_N = \pm 320\,kV$

$H = 10 \dfrac{MWs}{MVA}$ $\quad \tau = 60\mathrm{ms}$



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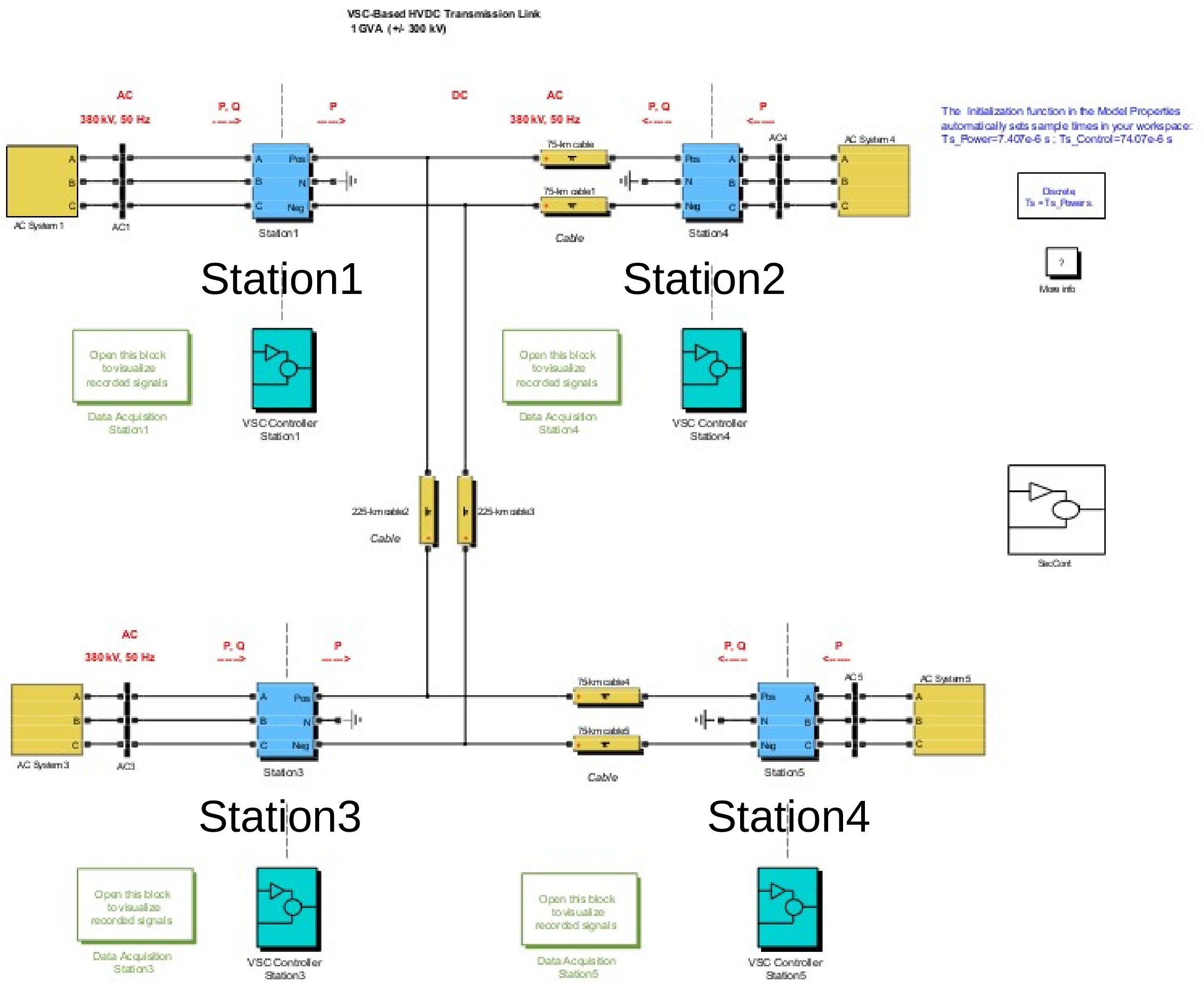
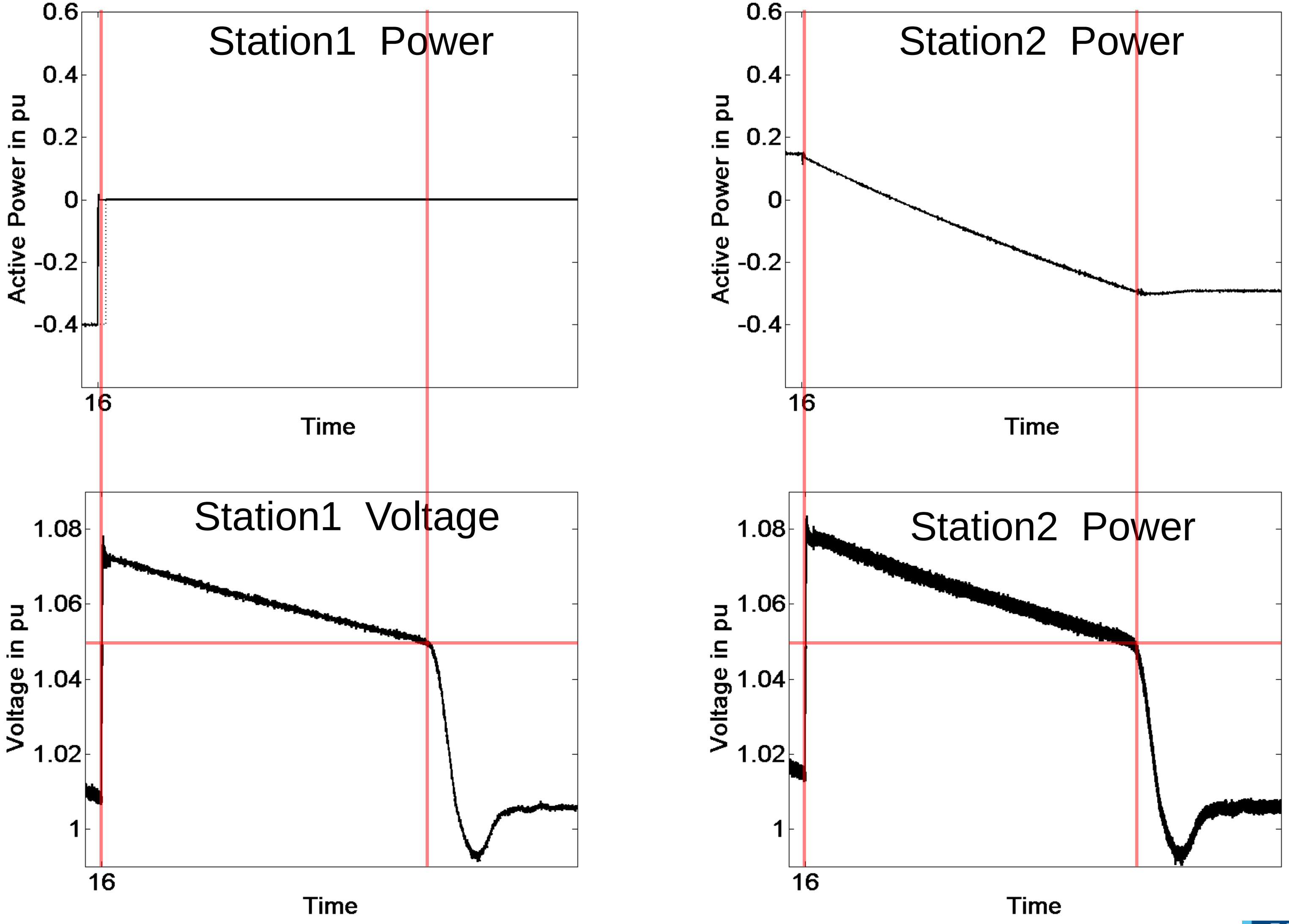
Example System



Simulation Results



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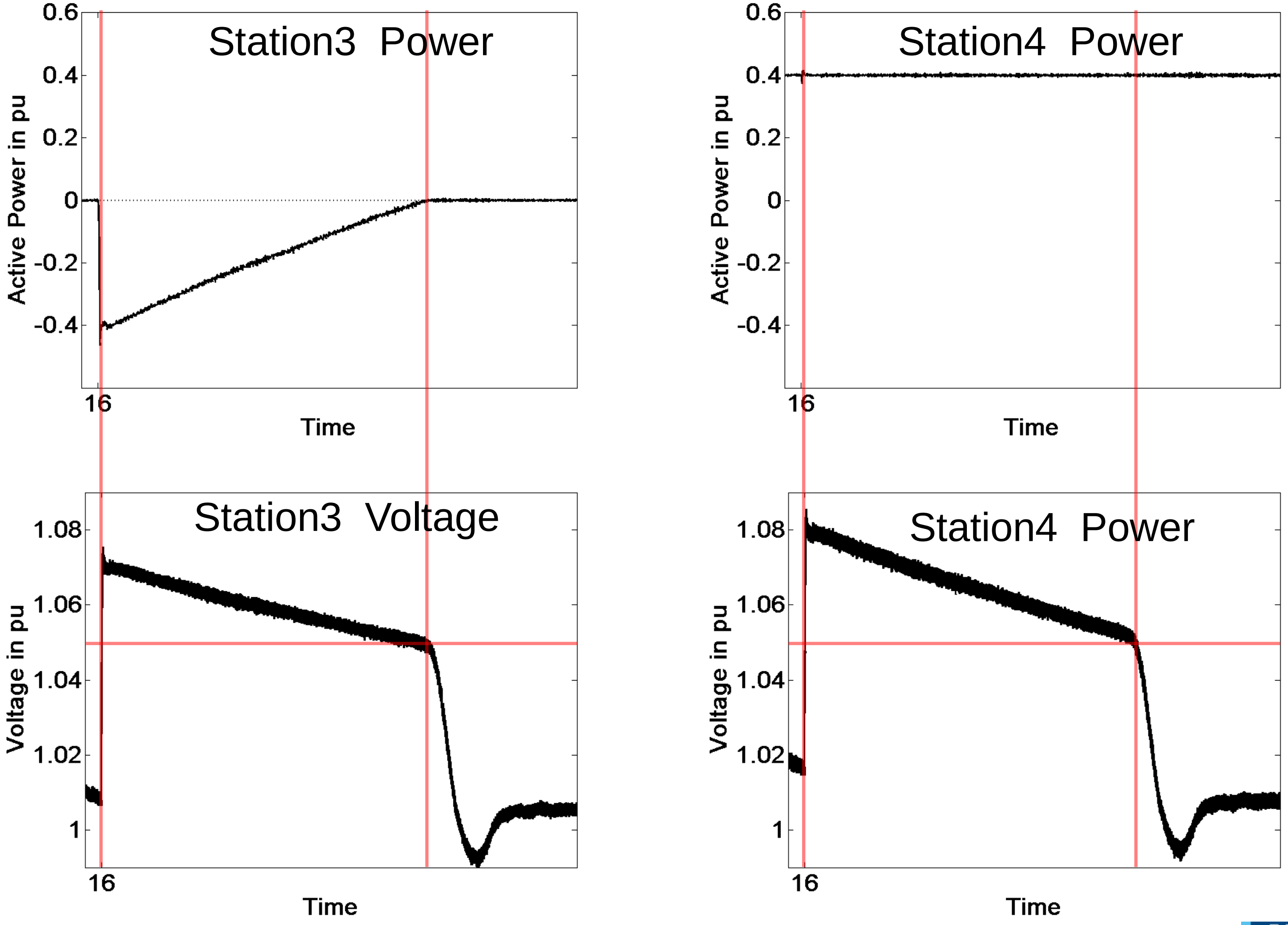
Simulation Results



Conclusion

- Conclusion
  - If DC power systems will arise by connecting point to point connections, they have to be operated similar to AC power systems
  - Problems with the area control error if several AC systems are connected
  - A DC secondary reserve similar to AC secondary reserve will be possible if the DC voltage band is accepted to be ±5% to ±10%
  - Then, is the available buffer energy for two converter stations similar to the buffer energy in the rotating mass of a power plant with the same rated power

Thank you for your Attention!

DC Secondary Control

- Size of the DC power system to use AC power system pre qualification for secondary reserve providing power plants
  - Ireland peak load around 5 GW with 2.5 GW installed wind generation
  - UK peak load around 57 GW with 10 GW installed wind generation
  - If DC power systems arise, the behaviour without crucial disturbances will be similar to Ireland and UK transmission systems if the accepted DC voltage band is in the range of ±5% to ±10%
  - With an increase of the system, the dynamic of voltage change will decrease as the total capacitance will increase
  - If the voltage band is not expectable, the DC system could use the AC system as a buffer, this could be a new ancillary service