Outline
Power system analysis and control

- Power system analysis
  - Power flow
  - Optimal power flow
- Power flow control
  - Primary control
  - Secondary control
  - Tertiary control
  - Voltage control

Control of active and reactive power
Voltage regulation

- Voltage between sender and receiver

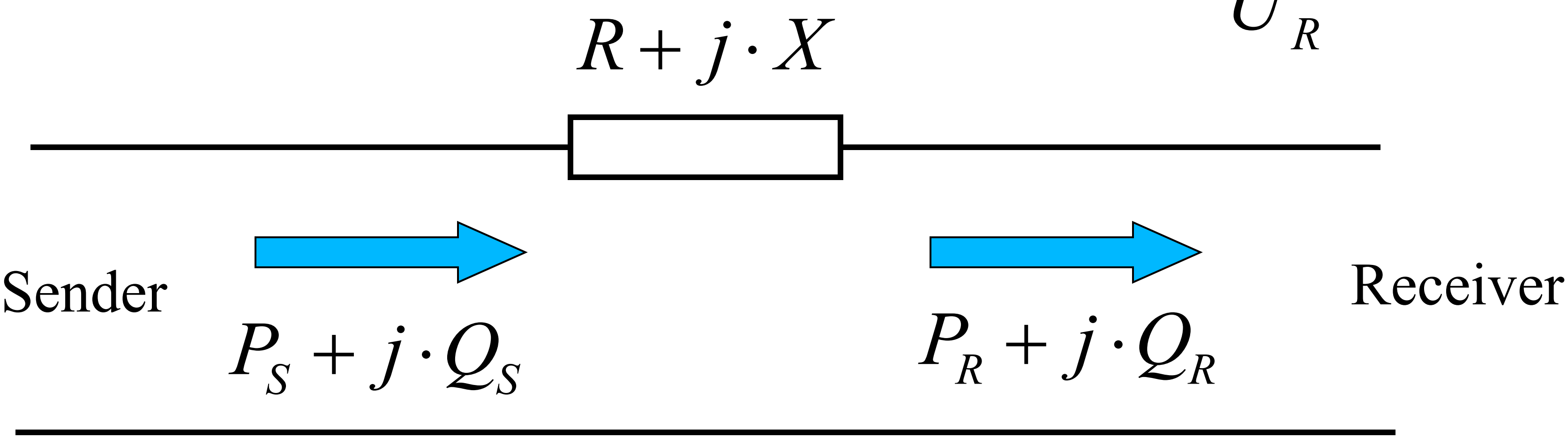
$$\underline{S}_R = \underline{U}_R \cdot \underline{I}^*_R = P_R + j \cdot Q_R$$

- Voltage related to reactive power:

$$\Delta|U| \approx \frac{X}{U_R} \cdot Q_R$$

- Angle related to active power:

$$\delta \approx \frac{X}{U_R^2} \cdot P_R$$

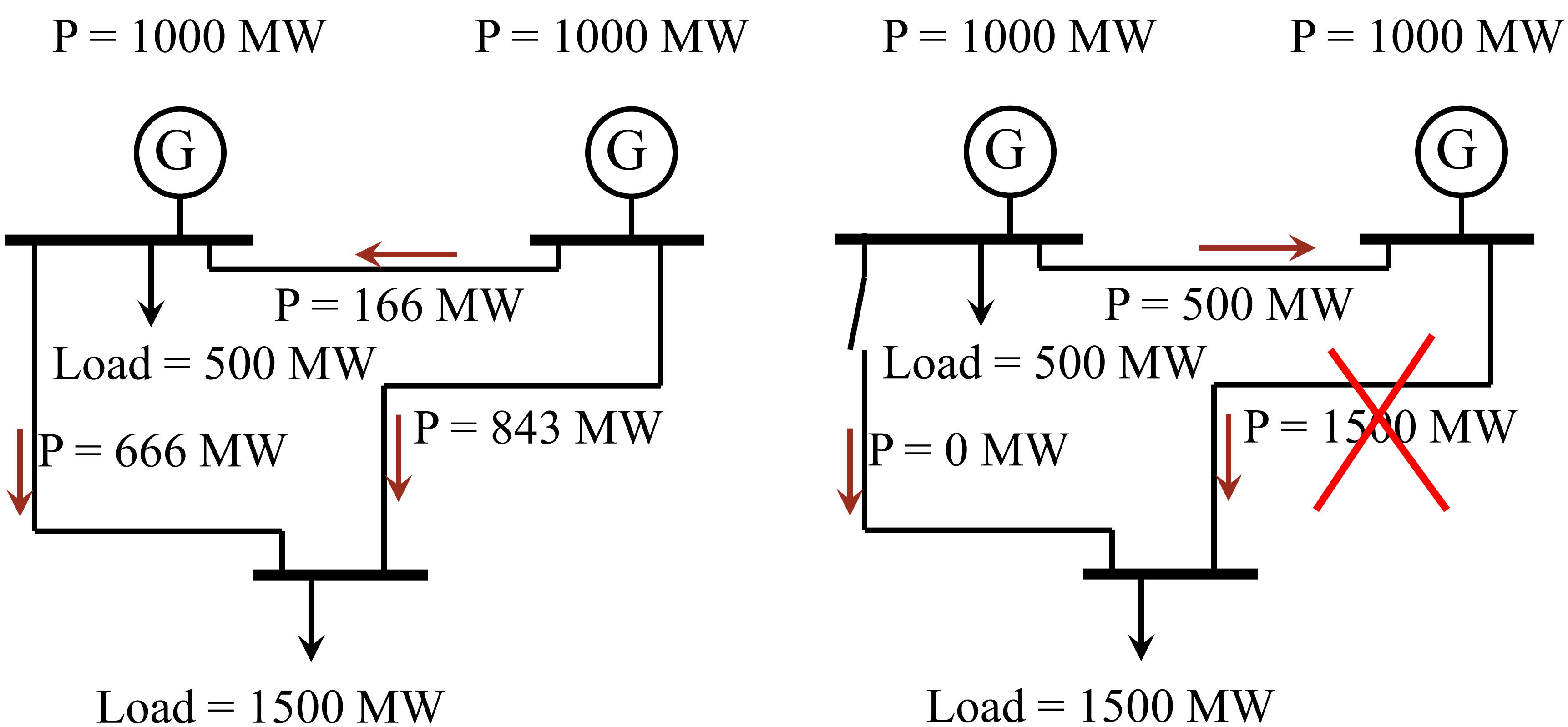


Power flow

- Normal conditions ==> steady state (equilibrium)
- Basis calculations to obtain this state are called Power Flow
  - Also called Load Flow
- Purpose of power flow:
  - Determine steady state situation of the grid
  - Get values for P, Q, U and voltage angle
  - Calculate system losses
  - First step for
    - N-1 contingency study
    - Congestion analysis
    - Need for redispatch
    - System development
    - Stability studies
    - ...

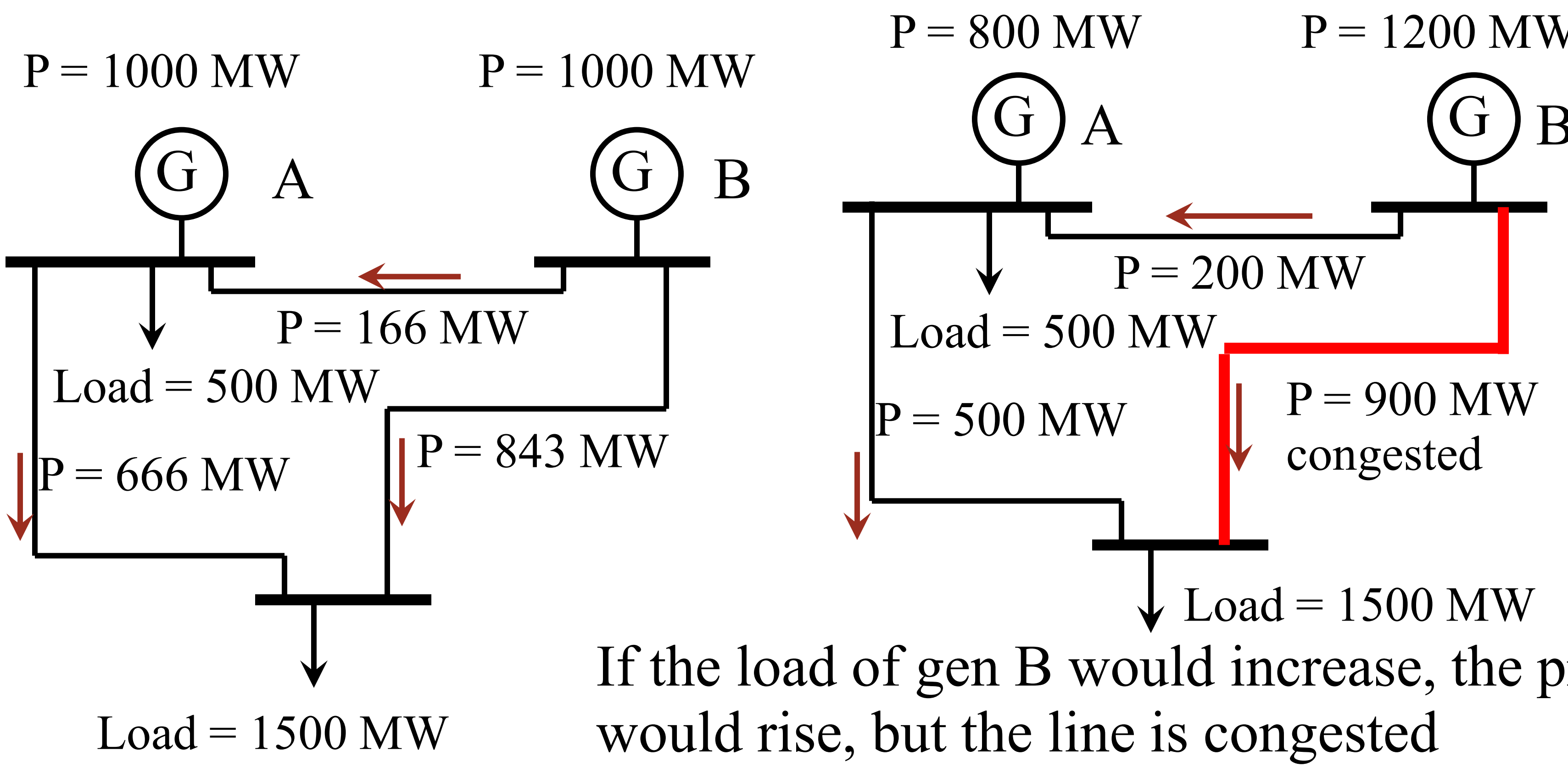
N-1 Example

- Each line has capacity of 900 MW
- Equal, lossless lines between nodes



Congestion and redispatch Example

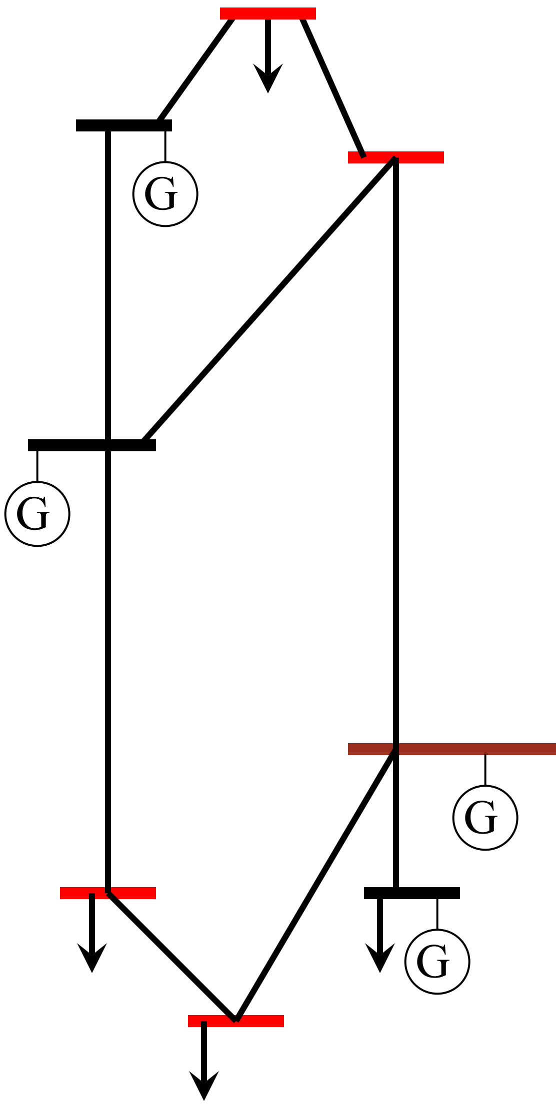
- Each line has capacity of 900 MW
- Equal, lossless lines between nodes
- The right generator is cheaper than the left, both have capacity 1500 MW



If the load of gen B would increase, the profit would rise, but the line is congested

Power flow
Three types of nodes

- Voltage controlled nodes (P-U node)
  - Nodes connected to a generator
  - Voltage is controlled at a fixed value
  - Active power delivered at a known value
- Unregulated voltage node (P-Q node)
  - A certain P and Q is demanded or delivered (non dispatched power plants, e.g. CHP)
  - In practice: mostly nodes representing a pure `load'
- Slack or swing bus (U-δ node)
  - Variable P and Q
  - Node that takes up mismatches

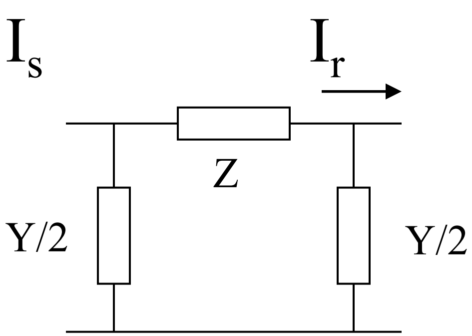


Power flow
Assumptions and representation

- Properties are not influenced by small changes in voltage or frequency
- Linear, localized parameters
- Balanced system

==> Single line representation

- Loads represented by their P and Q values
- Current and power flowing to the node is positive
- Transmission lines and transformers: π-equivalent



$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} 1+\frac{1}{2}YZ & Z \\ Y\left(1+\frac{1}{4}YZ\right) & 1+\frac{1}{2}YZ \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix}$$

Power Flow Equations

- *I=Y.V is a set of (complex) linear equations*
- *But P and Q are needed ==> S=V.I**
  - *Set of non-linear equations*

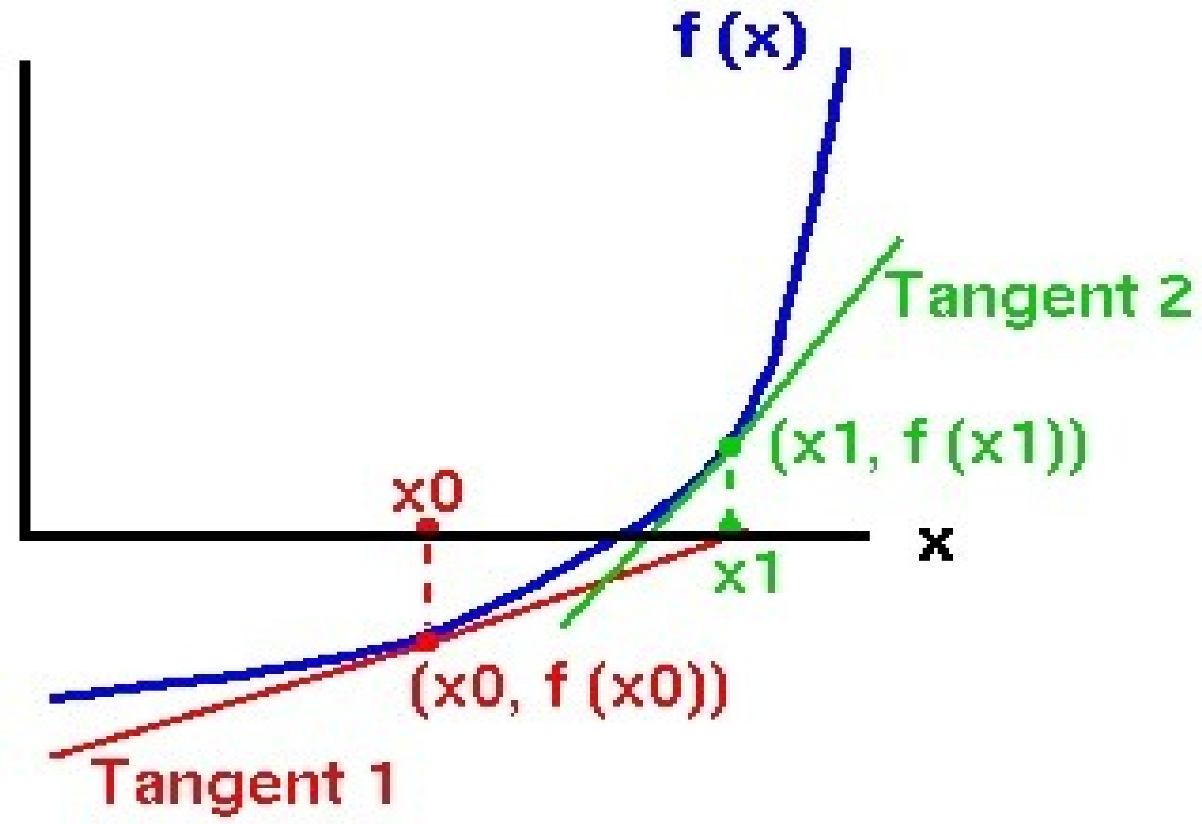
$$\Delta P_k = P_{Gk} - P_{Lk} - \left\{ -V_k^2 G_{kk} + V_k V_m \left[G_{km} \cos\left(\theta_k - \theta_m\right) + B_{km} \sin\left(\theta_k - \theta_m\right) \right] \right\} = 0$$

$$\Delta Q_k = Q_{Gk} - Q_{Lk} - \left\{ -V_k^2 B_{kk} + V_k V_m \left[G_{km} \sin\left(\theta_k - \theta_m\right) - B_{km} \cos\left(\theta_k - \theta_m\right) \right] \right\} = 0$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}^{(i)} = - \underbrace{\begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} V \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} V \end{bmatrix}^{(i)}}_{J\left(K^{(i-1)}\right)} \cdot \begin{bmatrix} \Delta \theta \\ \frac{\Delta V}{V} \end{bmatrix}^{(i)}$$

Power flow
Newton-Raphson

- Newton-Raphson has a quadratic convergence
- Normally +/- 7 iterations needed
- Principle Newton-Raphson iterative method:



Power Flow
Alternative methods

- Gauss-Seidel
  - Old method (solves I=Y.V), not used anymore
  - Linear convergence
- Decoupled Newton-Raphson
  - Strong coupling between Q and V, and between P and δ
  - Weak coupling between P and V, and between Q and δ
  - ==> 2 smaller systems to solve ==> faster (2-3 times faster)

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}^{(i)} = -\begin{bmatrix} \frac{\partial P}{\partial \theta} & 0 \\ 0 & \frac{\partial Q}{\partial V} V \end{bmatrix}^{(i)} \cdot \begin{bmatrix} \Delta \theta \\ \frac{\Delta V}{V} \end{bmatrix}^{(i)}$$

Power Flow
Alternative methods (II)

- Fast decoupled Newton-Raphson
  - Neglects coupling as in decoupled Newton-Raphson
  - Approximation: Jacobian considered constant
- Newton-Raphson with convergence parameter
  - Step in right direction (first order) multiplied by factor
- DC load flow
  - Consider only B (not Y)
  - Single calculation (no iterations needed)
  - Very fast ==> 7-10 times faster than normal Newton-Raphson
  - In high voltage grids: 1 pu
  - Sometimes used as first value for Newton-Raphson iteration (starting value)
  - Economic studies and contingency analysis also use DC load flow

Power flow: Available computer tools

- Available programs:
  - PSS/E (Siemens)
  - DigSILENT (power factory)
  - Eurostag (tractebel)
  - ETAP
  - Powerworld (demo version available for download)
  - Matpower (free download, matlab based)
  - PSAT: power system analysis toolbox (free download, matlab based)
  - ...

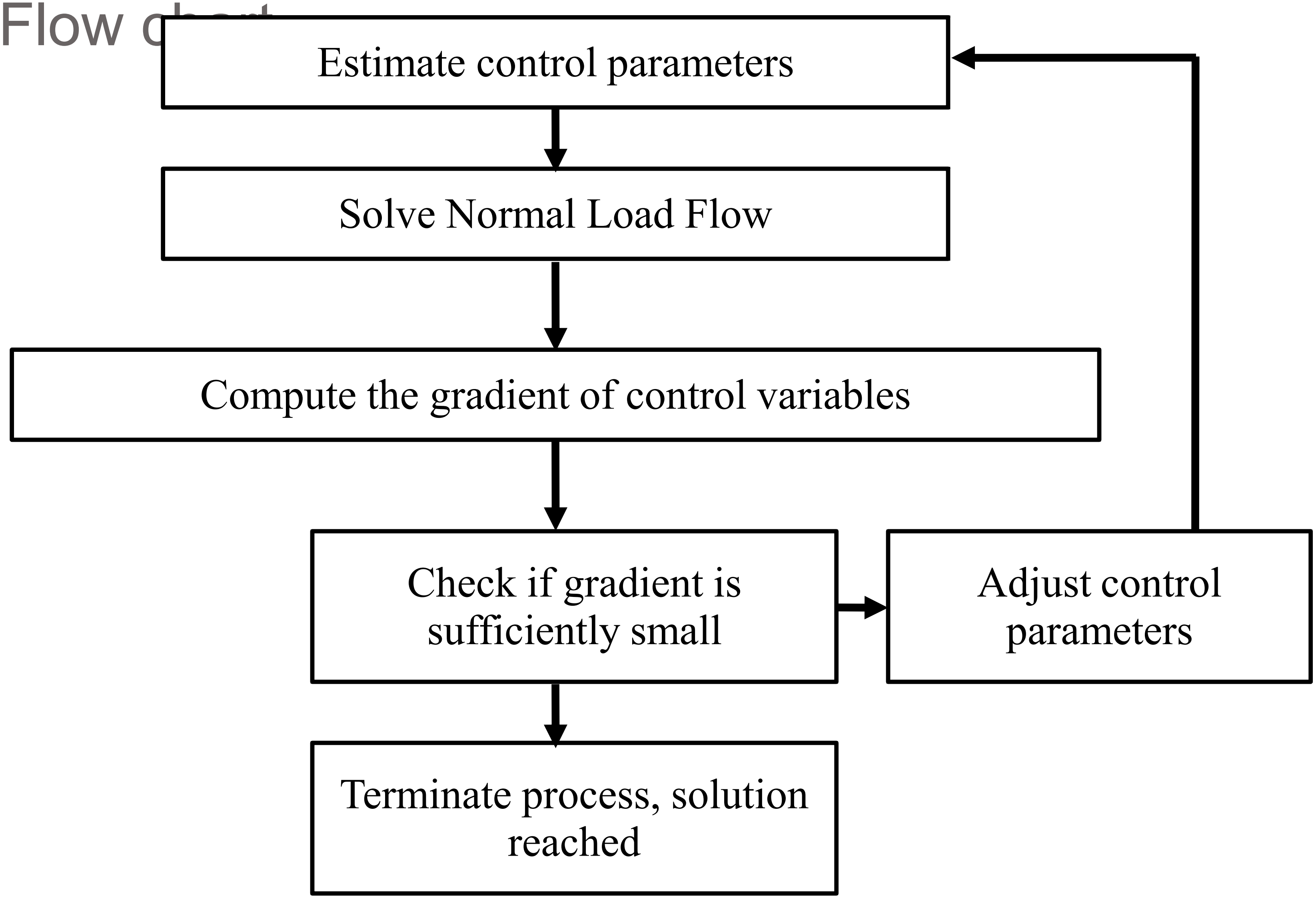
Optimal power flow (OPF)

- Optimal power flow = power flow with a goal
- Optimizing for highest objective
  - Minimum losses
  - Economic dispatch (cheapest generation)
  - ...
- Problem formulation

  minimize $F(x, u, p)$
  Objective function

  subject to $g(x, u, p) = 0$
  Constraints
- *Build the Lagrangian function*
  - $L = F(x, u, p) + \lambda^T g(x, u, p)$
- *Other optimization algorithms can also be used*

Optimal power flow
Flow chart



Optimal power flow Example

Iter	F-count	f(x)	max constraint	Step-size	Directional derivative	First-order optimality
0	1	4570.1	1.63			
1	3	9656.06	0.3196	1	1.35e+004	5.28e+003
2	6	7345.79	0.2431	0.5	506	1.98e+003
3	9	5212.76	0.1449	0.5	1.41e+003	4.32e+004
4	11	5384.17	0.02825	1	367	2.83e+003
5	14	5305.59	0.08544	0.5	-132	696
6	17	5439.61	0.07677	0.5	958	859
7	19	5328.32	0.08351	1	144	1.04e+003
8	22	5267.51	0.1398	0.5	-82.7	730
9	24	5301.72	0.05758	1	63.8	282
10	26	5300.88	0.004961	1	17.3	406
11	28	5295.95	0.003562	1	-0.325	116
12	30	5296.69	4.436e-005	1	1.15	30.8
13	32	5296.69	8.402e-007	1	0.0222	4.99
14	34	5296.69	4.487e-009	1	0.000728	0.431
15	36	5296.69	3.16e-011	1	2.75e-006	0.0113

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Control problem

- Complex MIMO system
  - Thousands of nodes
  - Voltage and angle on each node
  - Power flows through the lines (P and Q)
  - Generated power (P and Q), and voltage
  - OLTC positions
  - ...
  - Not everything is known!
    - Not every flow is known
    - Local or global control
    - Cross-border information
    - Output of power plants
    - Metering equipment is not always available or correct

Control problem
Requirements

- Voltage must remain between its limits
  - 1 p.u. +/- 5 or 10 %
- Power flow through a line is limited
  - Thermal limit depending on section
- Frequency has to remain between strict limits
- Economic optimum

Control problem
Assumptions

- P-f control and Q-U control can be separated
  $$\tau_{Q-V} << \tau_{P-f}$$
- Voltage control is independent for each voltage controlled node
- Global system can be divided in control areas
  - Control area = region of generators that experience the same frequency perturbation

$$\Delta fi$$

Control problem
Separation of the problem

- P-f control

$$\Delta f_i \ \ and \ \ \Delta P_{transfered} \rightarrow \Delta \delta_i = phase \ \ fault$$

- Using feedback:
  - $\Delta \delta_i$ results in $\Delta P_{c,i}$

Q-U control

- Measuring
- Control signal $U \Rightarrow \Delta |V_i|$, generator excitation and static Var compensation (capacitors or power electronics)

$\Delta Q_{c,i}$

Turbine – Generator control