Problem Statements

Feasible electrical flows

Dynamic models

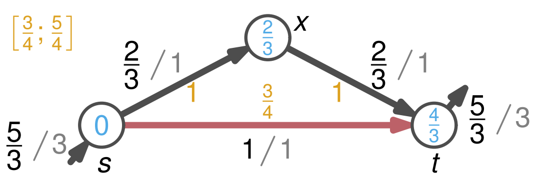
Static models

Alternating Current (AC) model

Direct Current (DC) model

Placement of control units

$b(s,t) \in \left[\frac{3}{4}; \frac{5}{4}\right]$



Discrete control decision

[Grastien, Rutter, Wagner, W., and Wolf, 2018]

Continuous control decision

[Leibfried, Mchedlidze, Meyer-Hübner, Nöllenburg, Rutter, Sanders, Wagner, and **W.**, 2015]

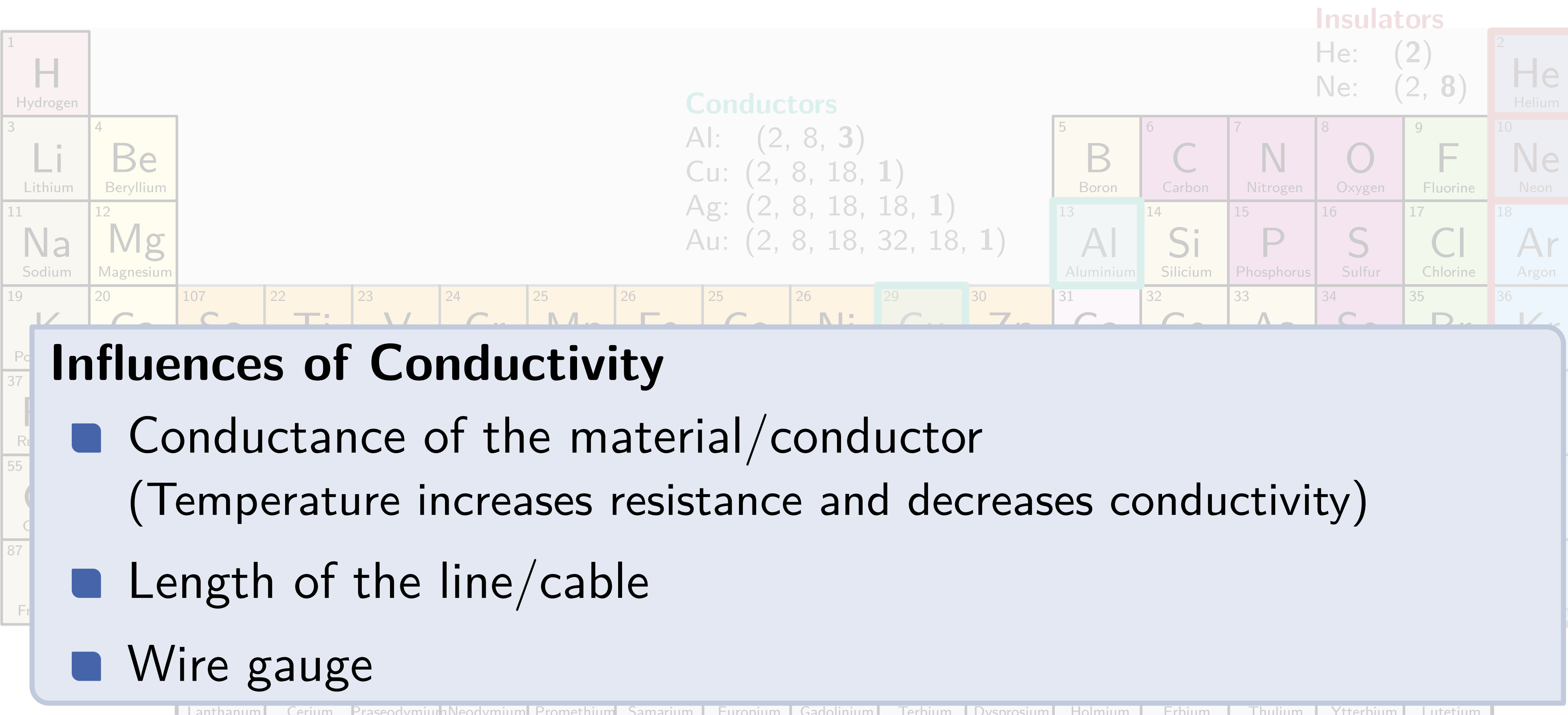
[Mchedlidze, Nöllenburg, Rutter, Wagner, and **W.**, 2015]

Cable layout

Wind farm cabling with multiple cable types

[Lehmann, Rutter, Wagner, and W., 2017]

Influence of Conductivity

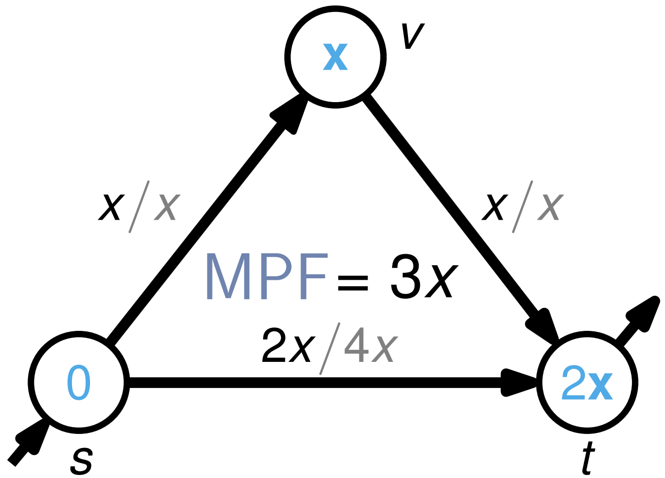


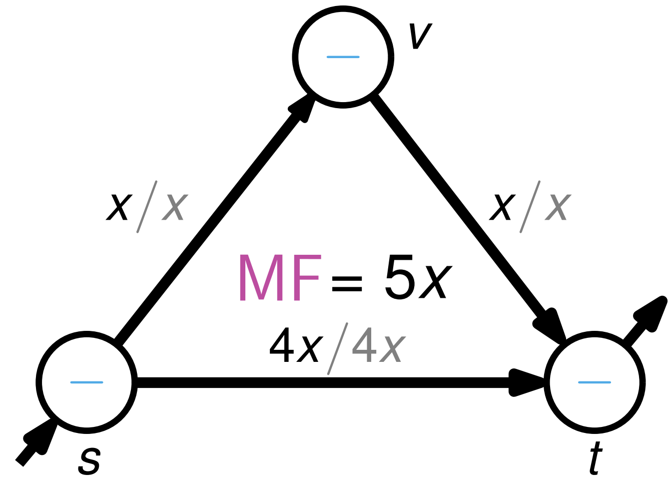
Influences of Conductivity

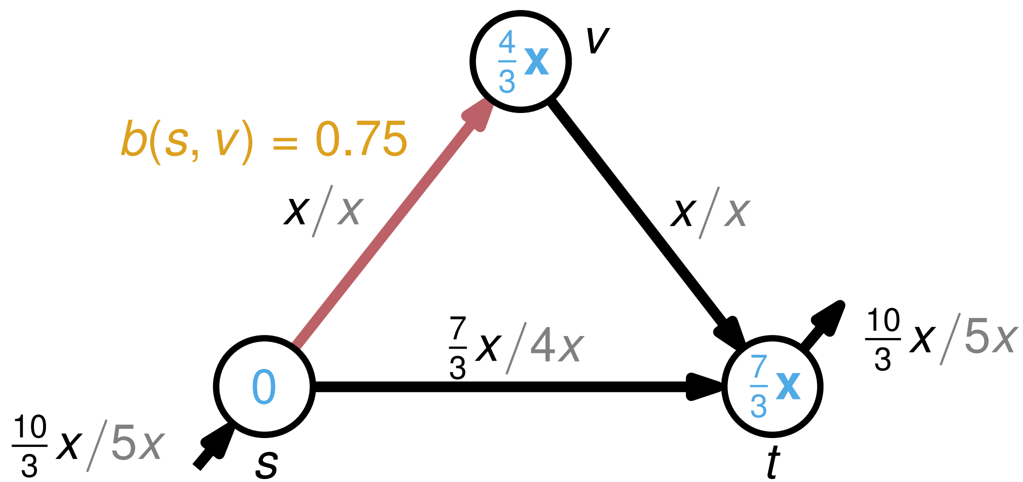
- Conductance of the material/conductor
  (Temperature increases resistance and decreases conductivity)
- Length of the line/cable
- Wire gauge

In the linear AC-Model the conductivity can be changed by the susceptance $b(u, v) \in \mathbb{R}$. To change the susceptance we use FACTS.

The Maximum FACTS Flow (MFF) Problem



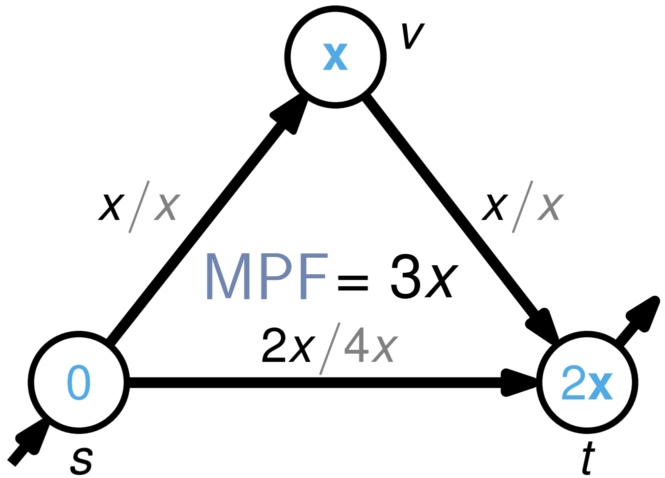


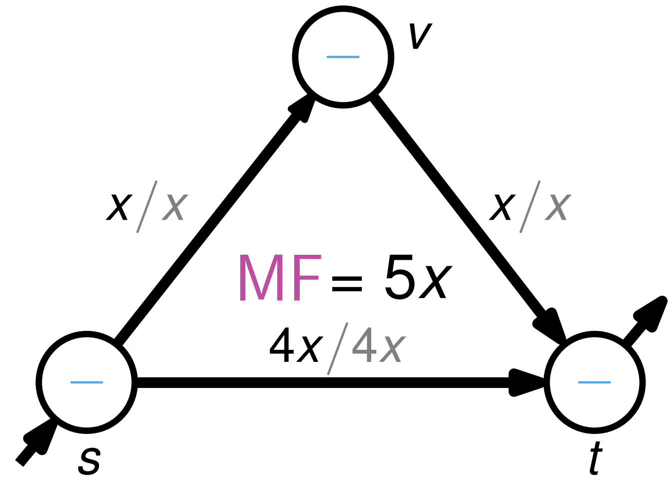


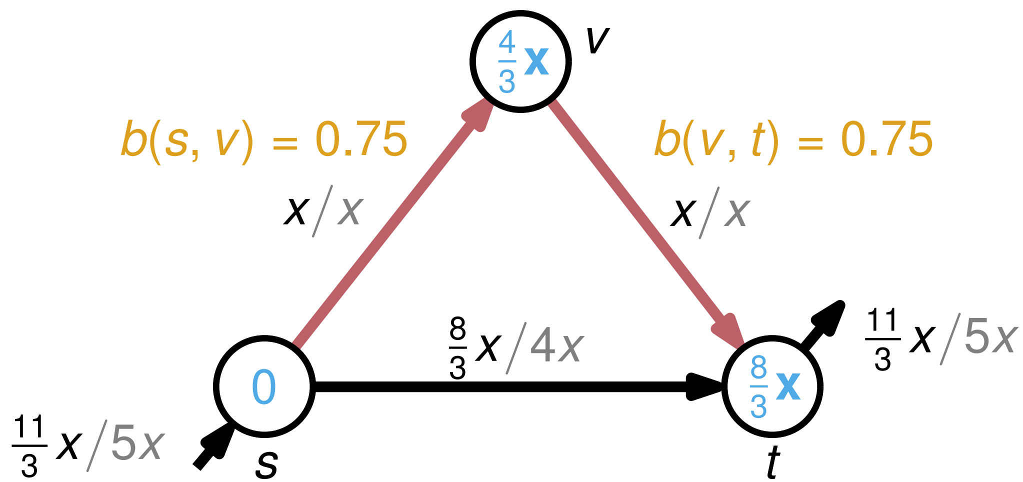
$b(i, j) := [0.75; 1.25]$
$\forall (i, j) \in E$

$$\forall (u, v) \in E \colon\ f(u, v) = b(u, v)\big(\theta(v) - \theta(u)\big)$$

The Maximum FACTS Flow (MFF) Problem







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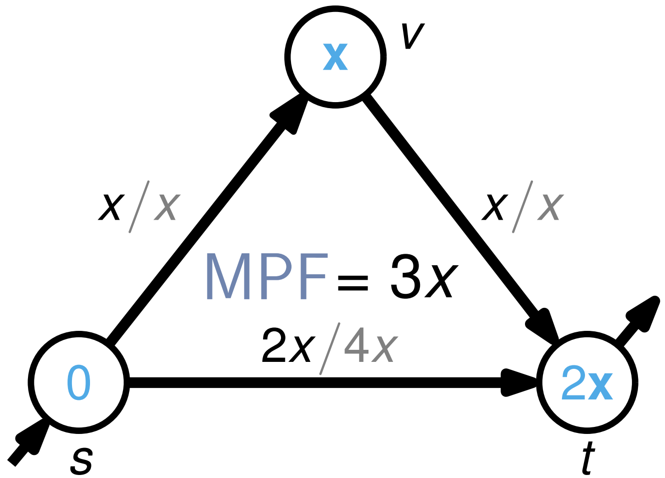

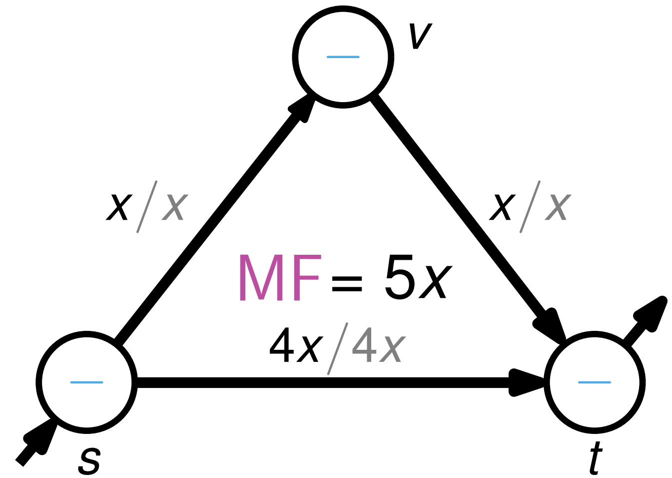

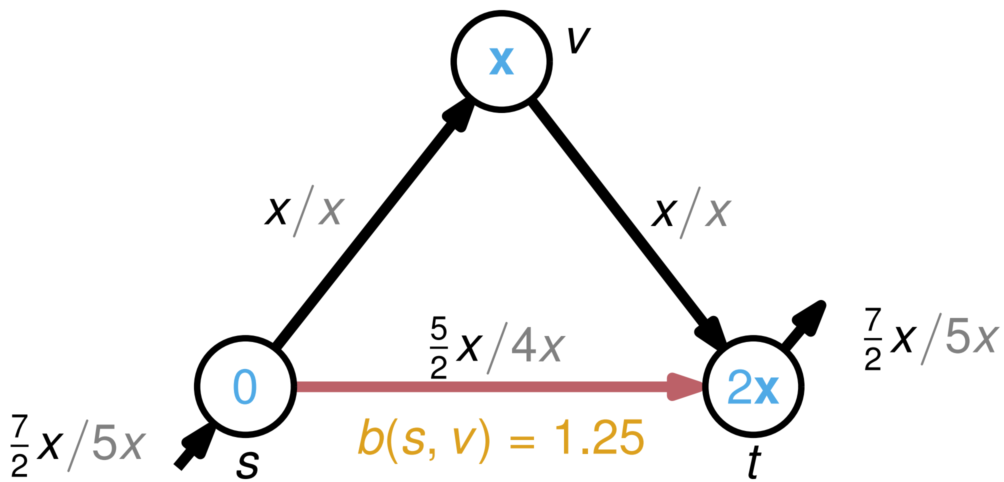

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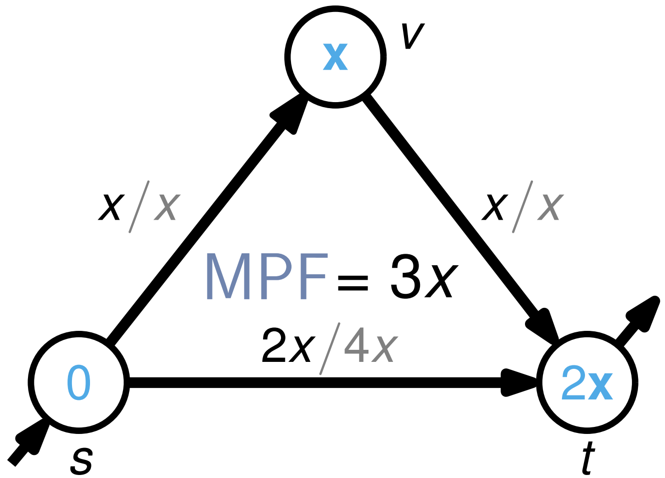

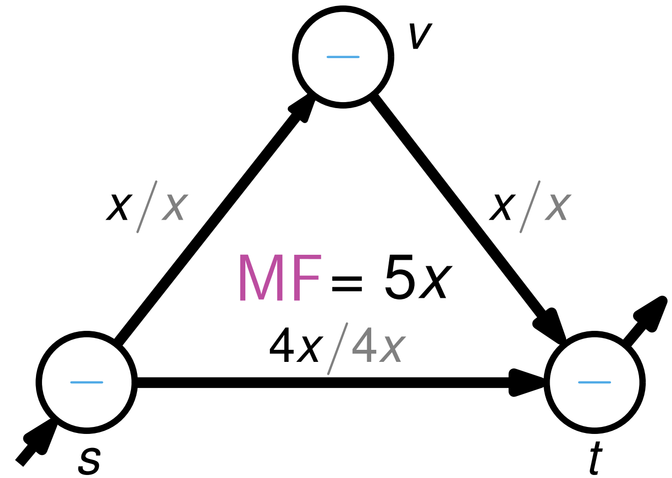

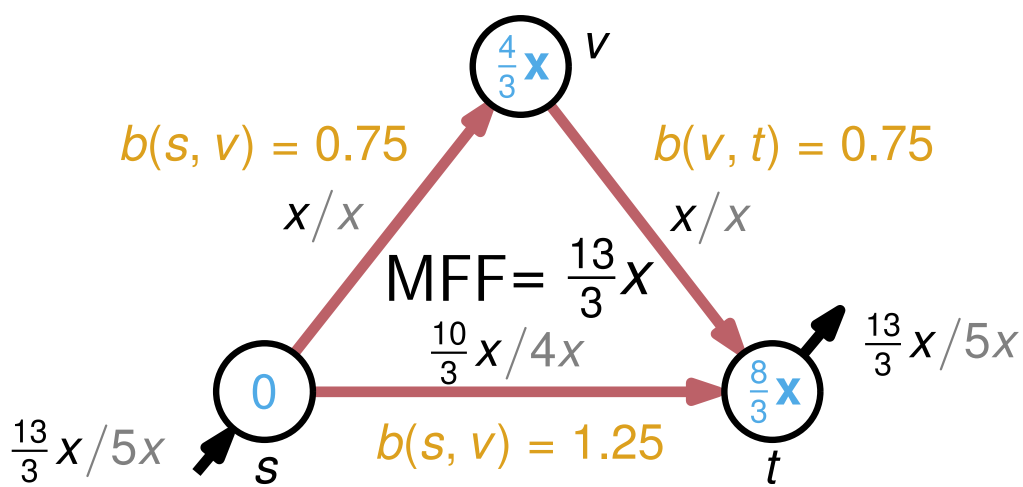

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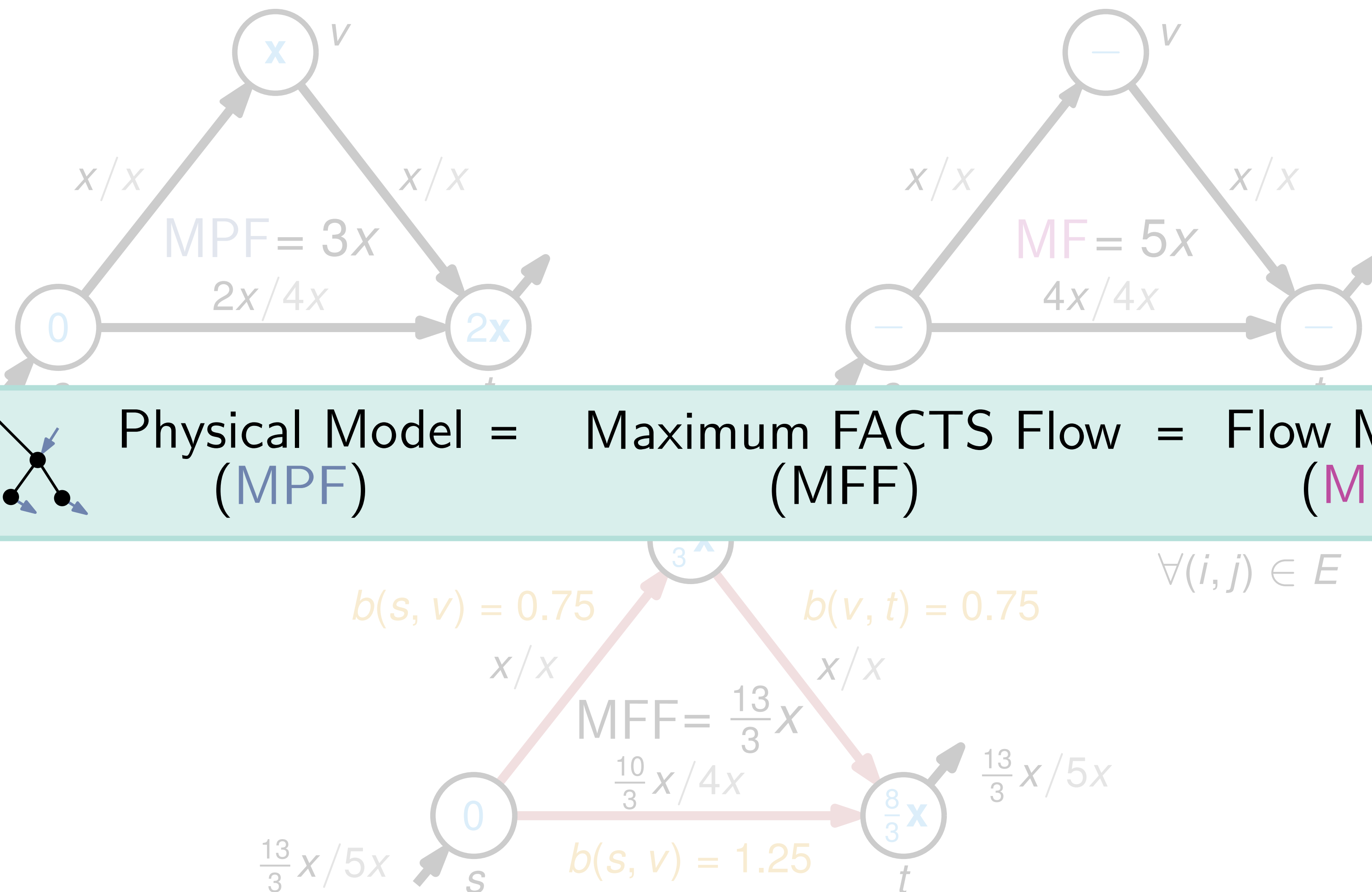
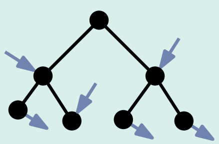
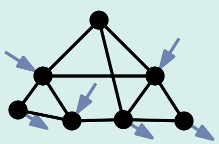




Physical Model (MPF) = Maximum FACTS Flow (MFF) = Flow Model (MF)

$\forall (u,v) \in E\colon f(u,v) = b(u,v)\big(\theta(v) - \theta(u)\big)$

The Maximum FACTS Flow (MFF) Problem



Physical Model (MPF)	$\leq$	Maximum FACTS Flow (MFF)	$\leq$	Flow Model (MF)

$\forall (i,j) \in E$

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The Maximum FACTS Flow (MFF) Problem

[Lehmann et al., 2015]

- The value of the Maximum Flexible AC Transmission Switching Flow (MFF) is defined as

$$\mathrm{MFF}(\mathcal{N}, k) := \max_{E' \subseteq E, b} \mathrm{MPF}(\mathcal{N}) \qquad |E'| \leq k$$

with f being a feasible power flow meaning

$$f_{\mathrm{net}}(u) = 0 \qquad \forall u \in V \setminus (V_G \cup V_D)$$

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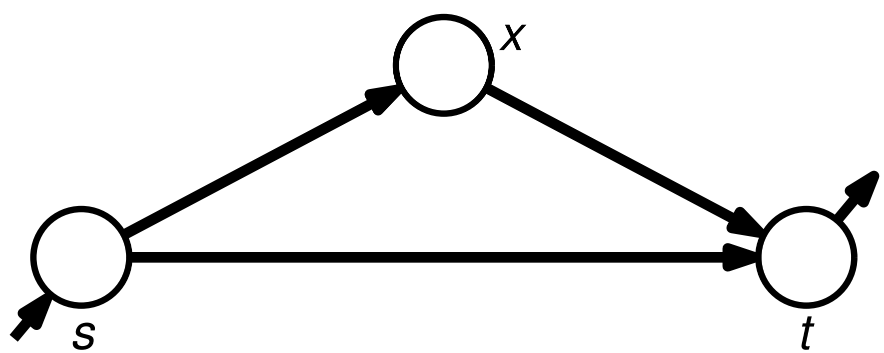
$k = 1$



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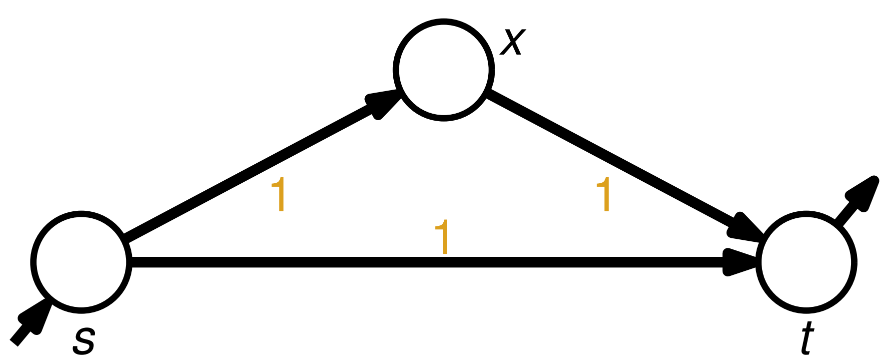

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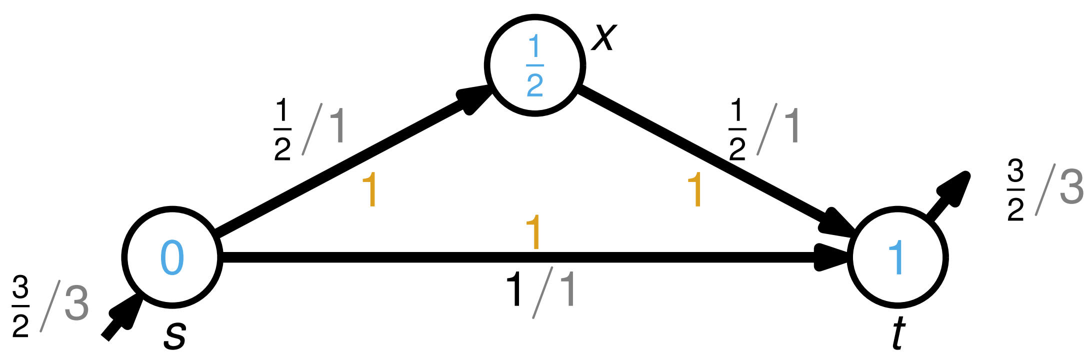

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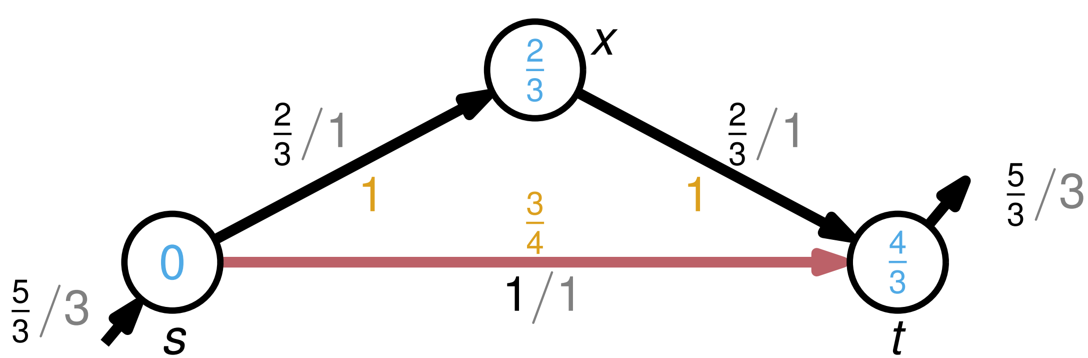

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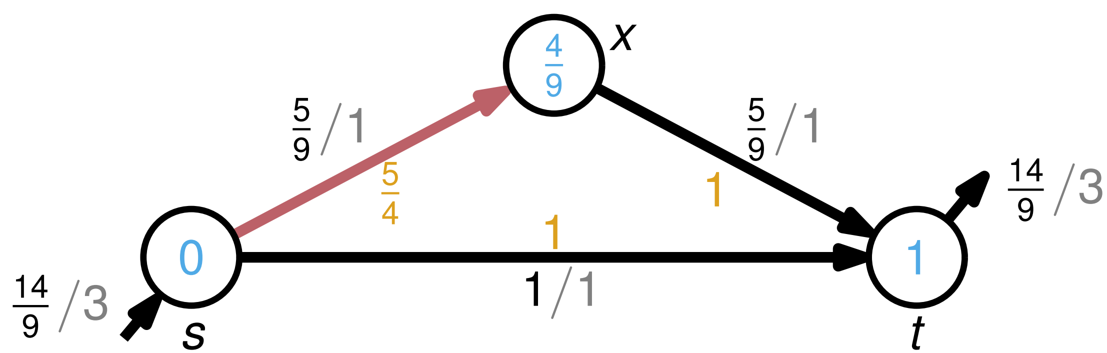

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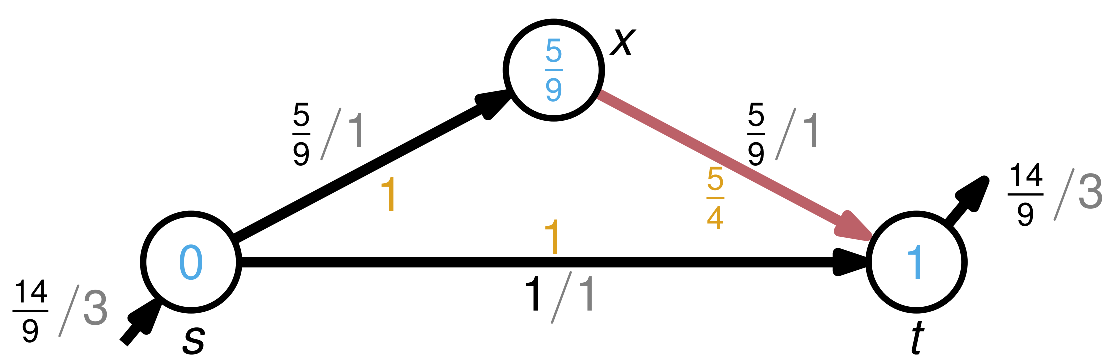


The Maximum FACTS Flow (MFF) Problem

[Lehmann et al., 2015]

Optimization Problem MFF

Instance: A power grid $\mathcal{N}$.

Objective: Find a set $E' \subseteq E$ of edges with FACTS and a susceptance configuration $b(e)$ with $e \in E'$ such that MPF($\mathcal{N}$) is maximum among all choices of FACTS placements and susceptance configurations while complying with $|E'| \leq k$.

The Optimal FACTS Flow (OFF) Problem

- The value of the OPTIMAL POWER FLOW (OPF) is defined as

$$\mathrm{OPF}(\mathcal{N}) = \min \gamma(\mathcal{N}, f)$$

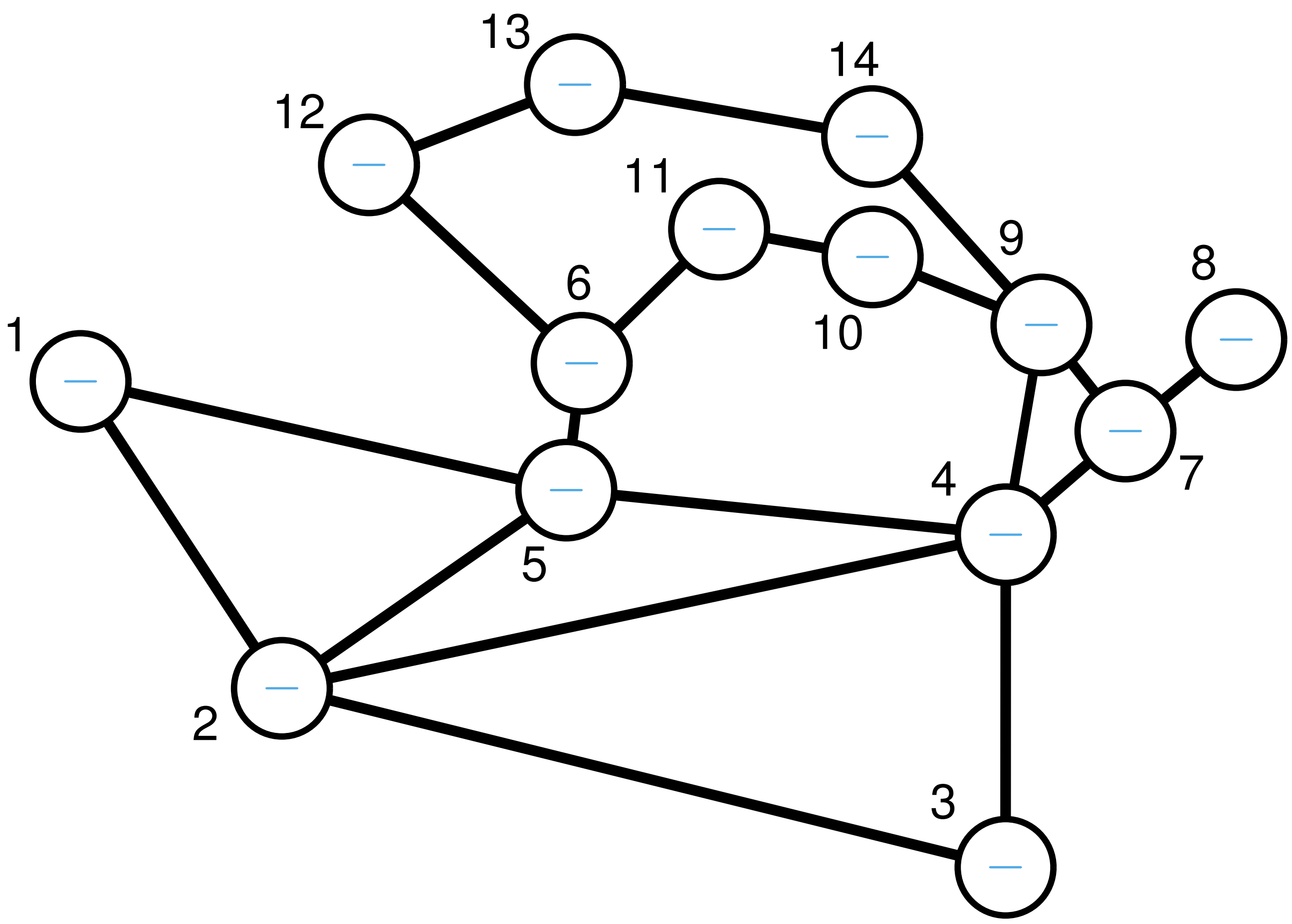
with f being a feasible power flow and the generator cost function γ.

Optimization Problem OFF

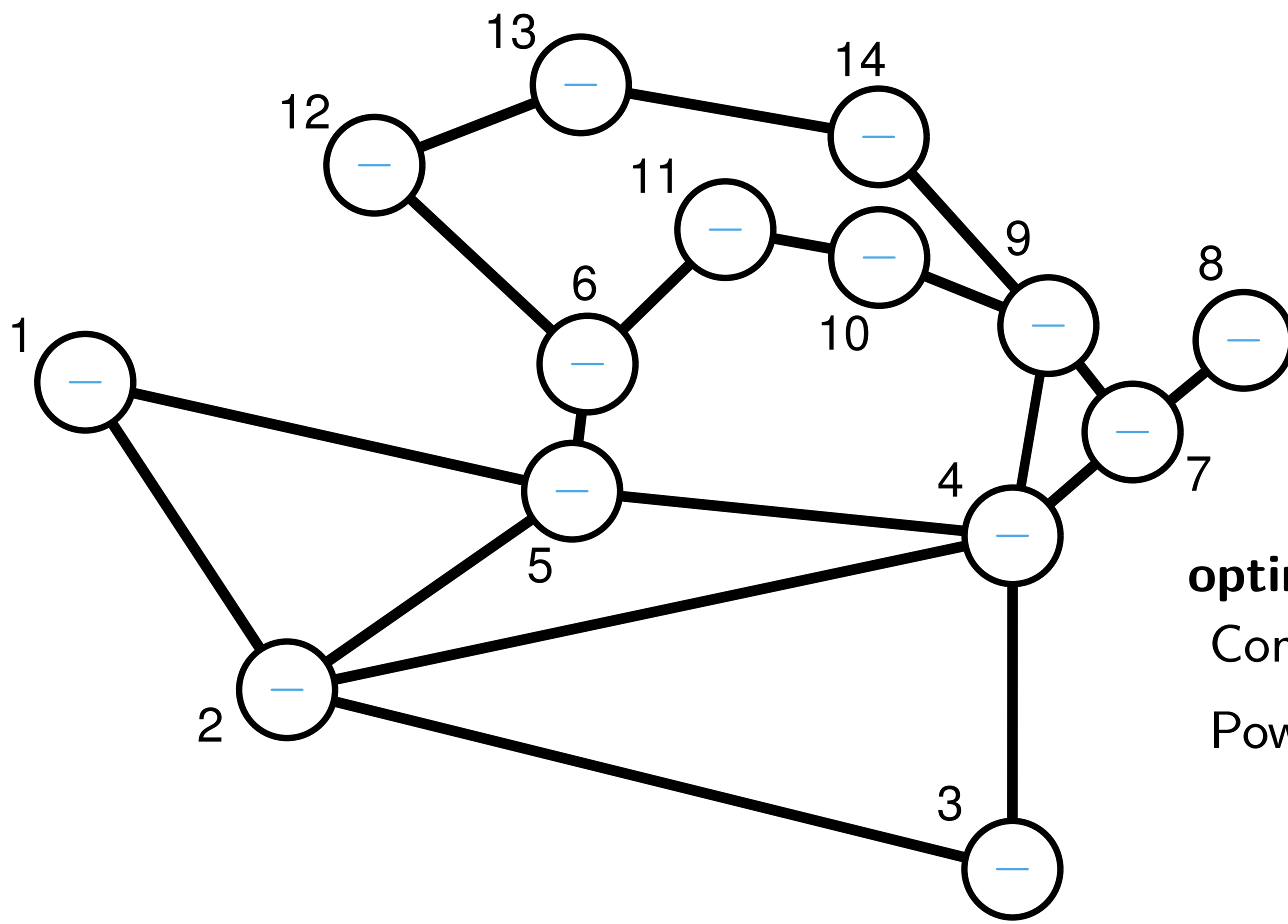
Instance: A power grid $\mathcal{N}$.

Objective: Find a set $E' \subseteq E$ of edges with FACTS and a susceptance configuration $b(e)$ with $e \in E'$ such that $\mathrm{OPF}(\mathcal{N})$ is minimum among all choices of FACTS placements and susceptance configurations while complying with $|E'| \leq k$.

Optimal FACTS Flow (OFF)



Optimal FACTS Flow (OFF)

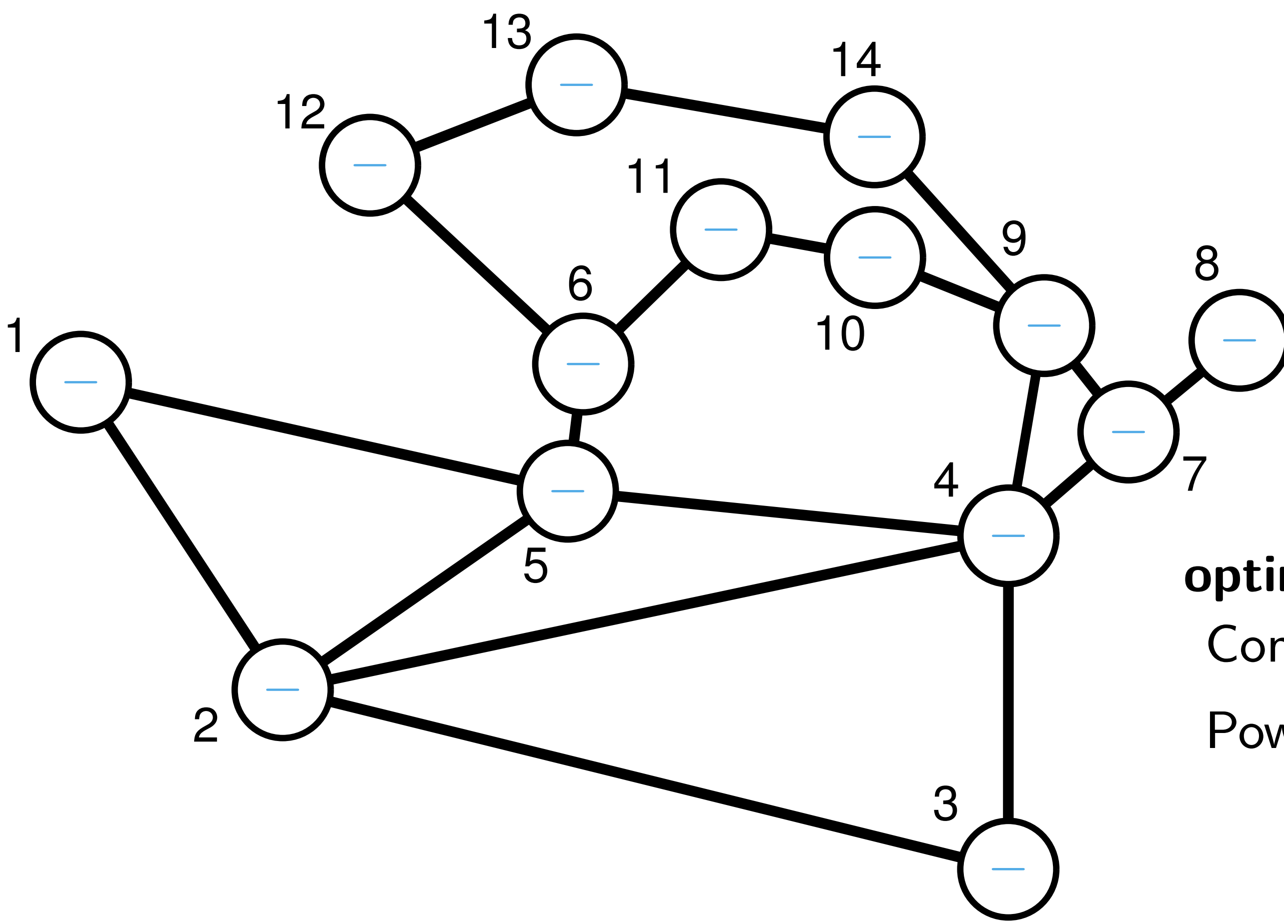


optimize with regards to:

Conservation of Flow

Power Flow Constraint

Optimal FACTS Flow (OFF)



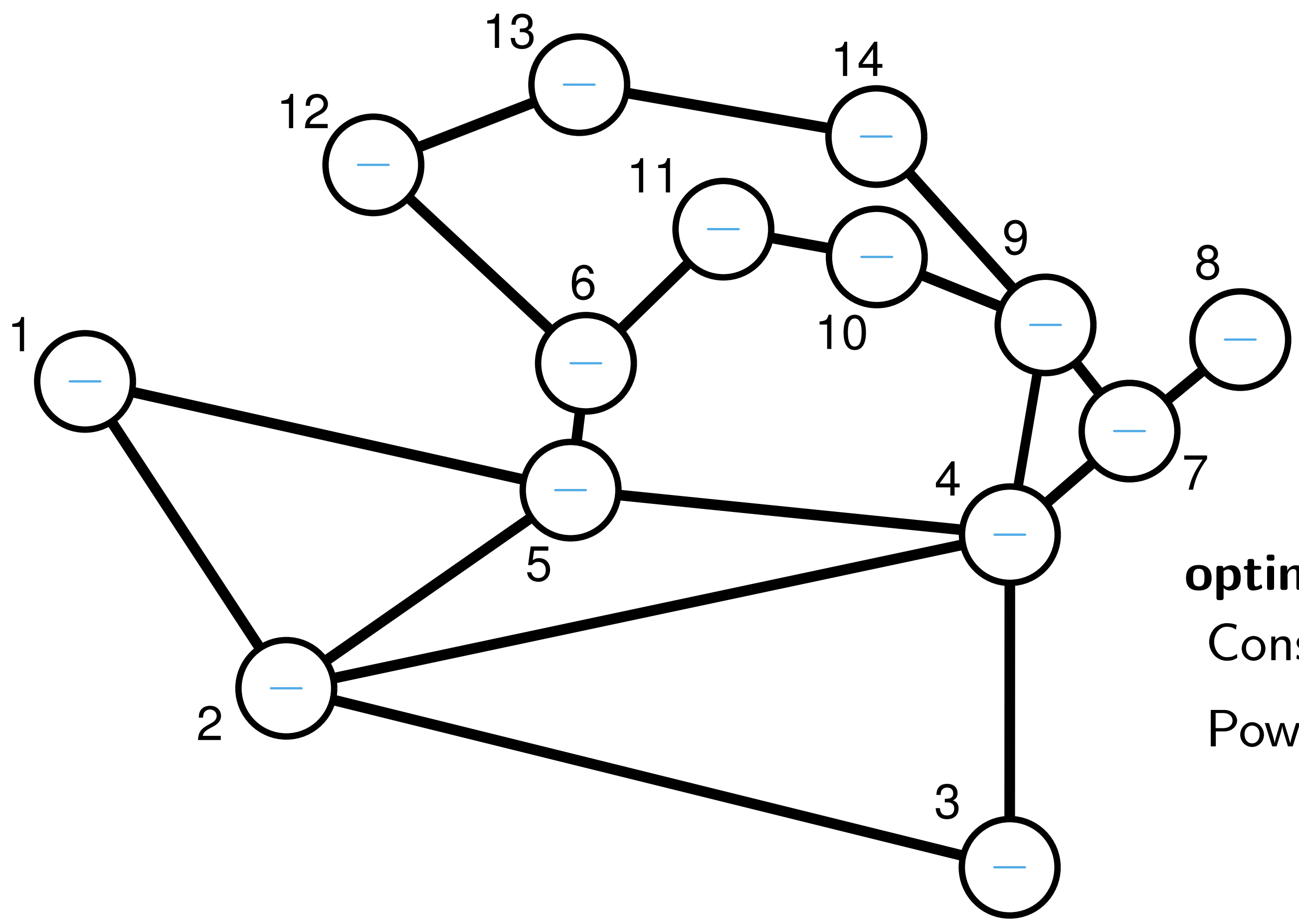
optimize with regards to:

Conservation of Flow

Power Flow Constraint

minimize Costs

Optimal FACTS Flow (OFF)

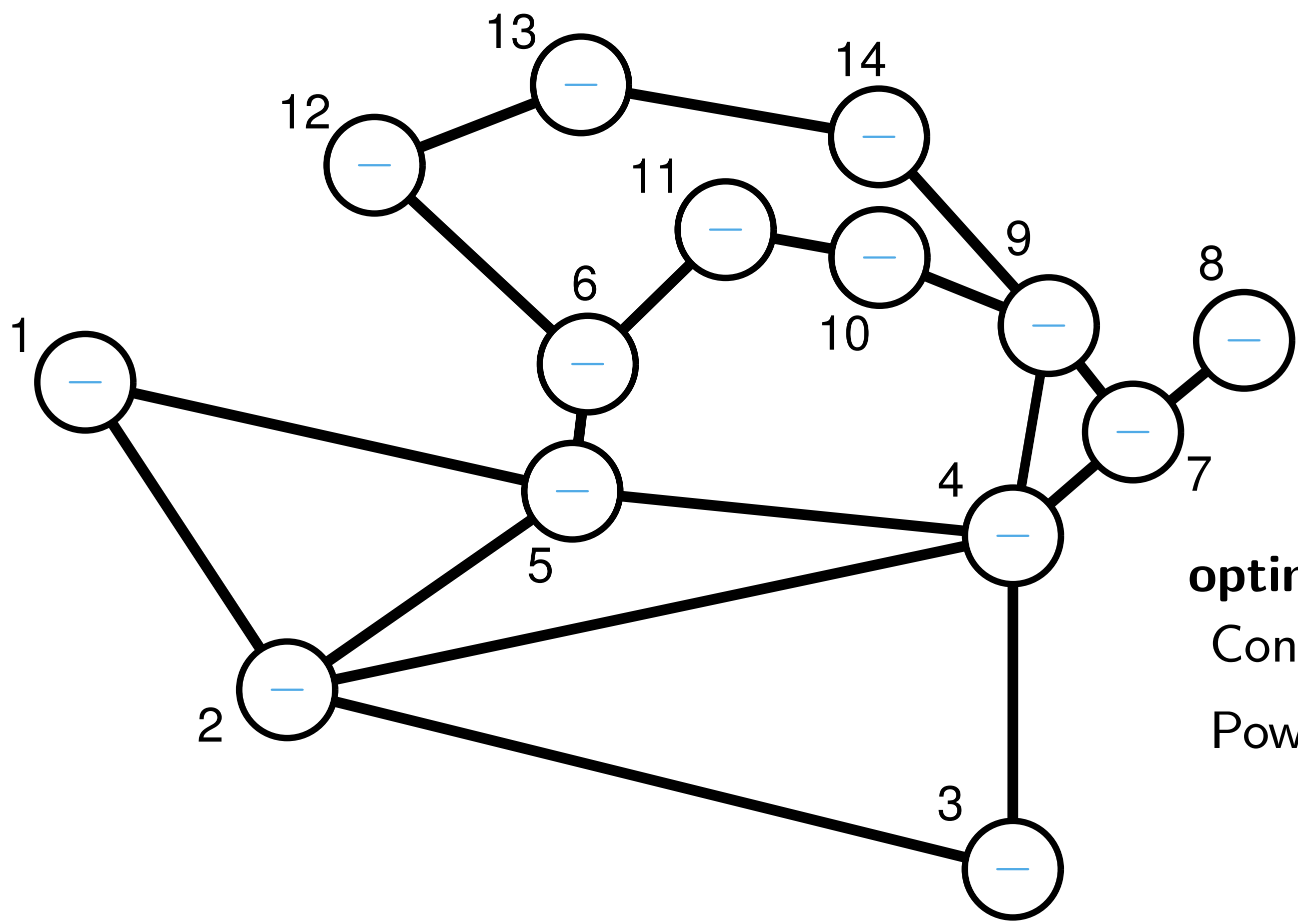


optimize with regards to:
Conservation of Flow ✓
Power Flow Constraint ✓

Physical Model

minimize Costs

Optimal FACTS Flow (OFF)



optimize with regards to:

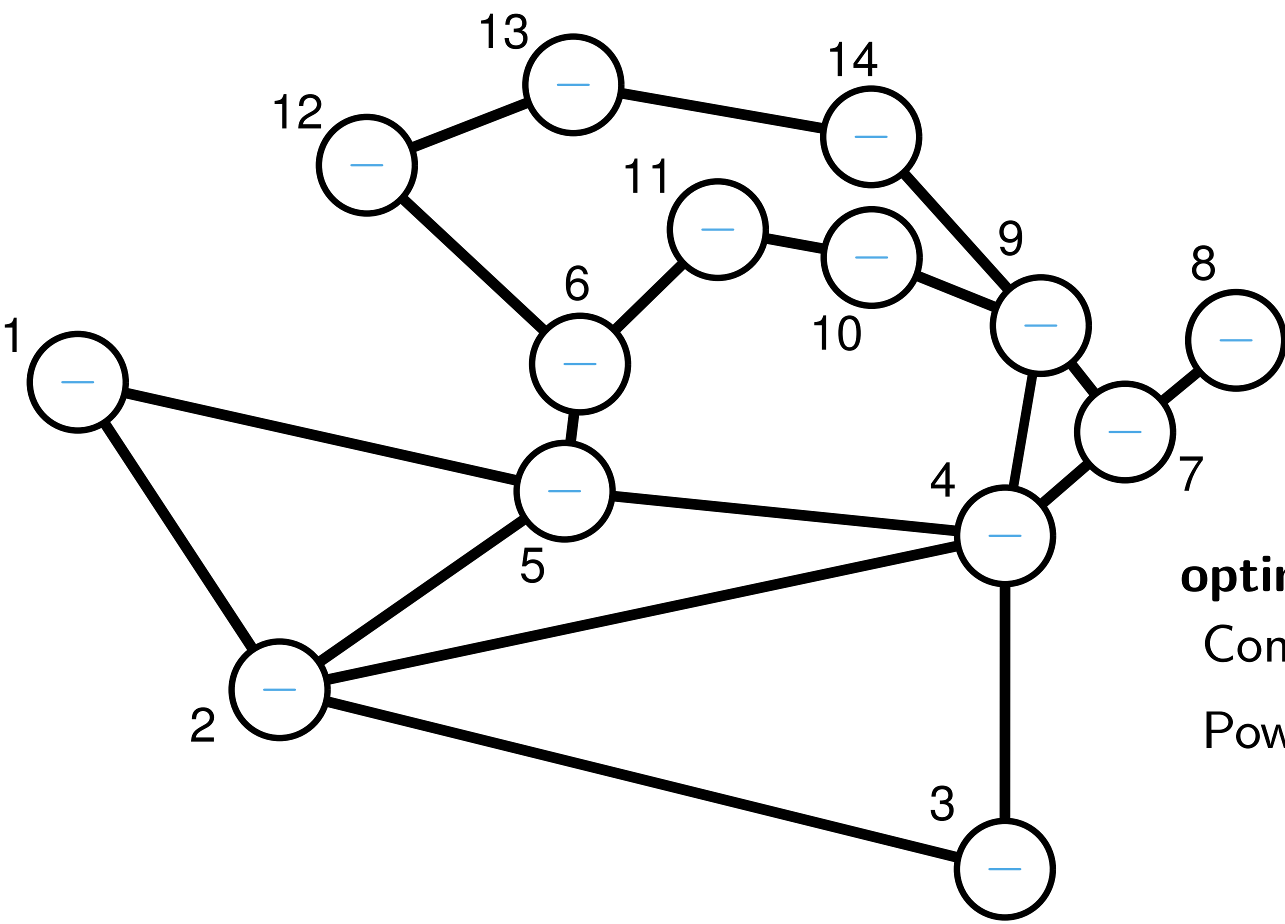
	Physical Model	Flow Model
Conservation of Flow	✓	✓
Power Flow Constraint	✓	✗

Physical Model

minimize Costs

Flow Model

Optimal FACTS Flow (OFF)



optimize with regards to:

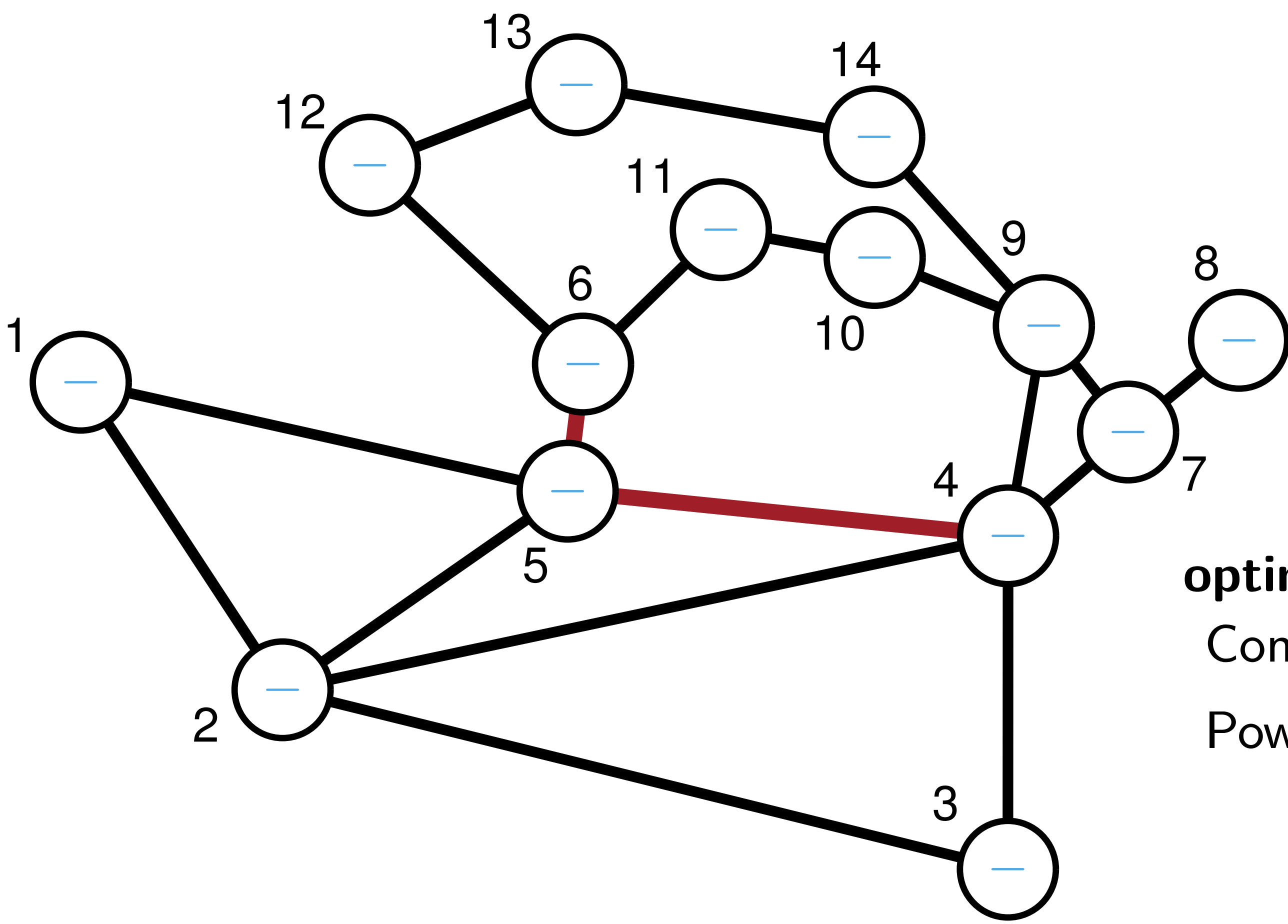
Conservation of Flow	✓	✓
Power Flow Constraint	✓	✗

minimize Costs

Flow Model
lower bound

Physical Model
upper bound

Optimal FACTS Flow (OFF)



FACTS

optimize with regards to:

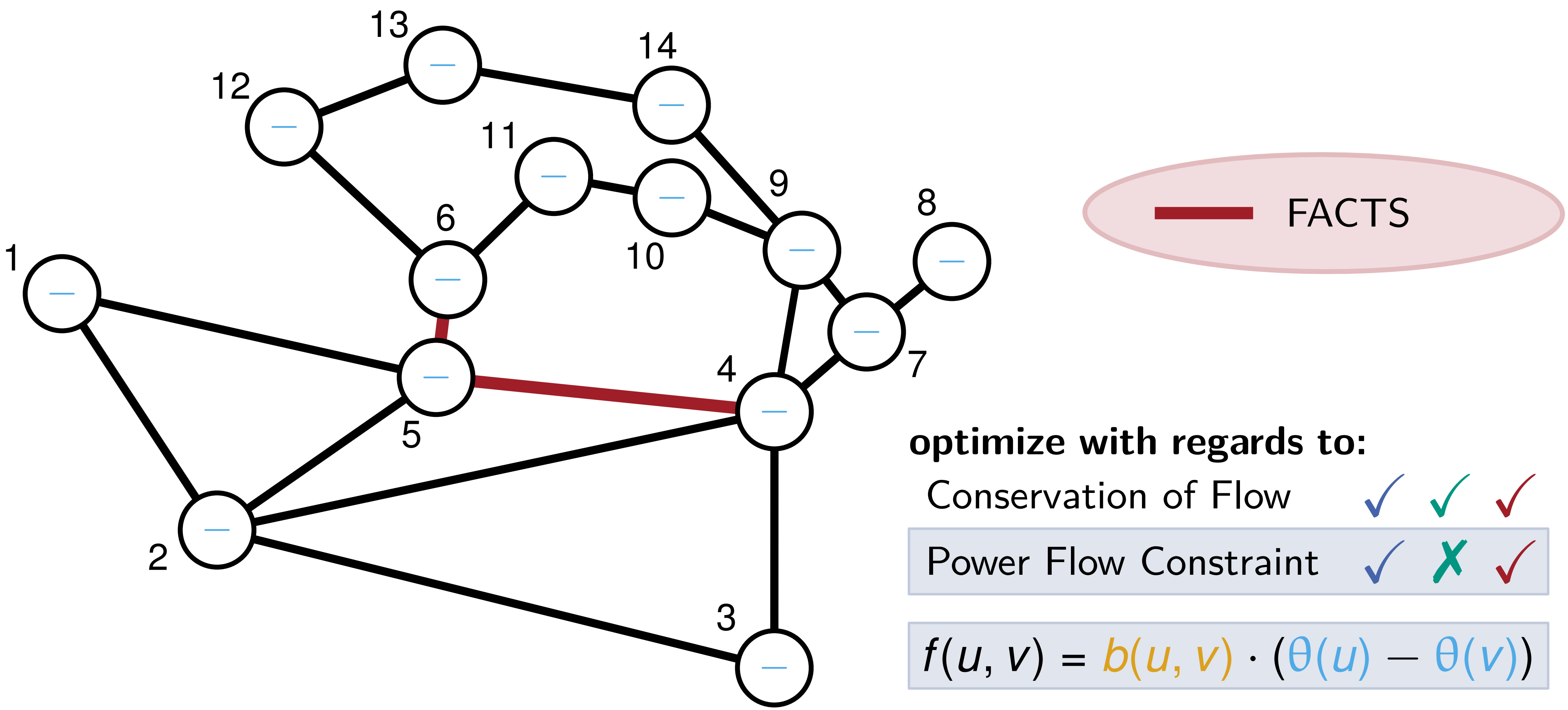
Conservation of Flow	✓	✓	✓
Power Flow Constraint	✓	✗	✓

Flow Model
lower bound

minimize Costs

Physical Model
upper bound

Optimal FACTS Flow (OFF)



optimize with regards to:

Conservation of Flow	✓	✓	✓
Power Flow Constraint	✓	✗	✓

$$f(u, v) = b(u, v) \cdot (\theta(u) - \theta(v))$$

Flow Model lower bound

minimize Costs

Physical Model upper bound

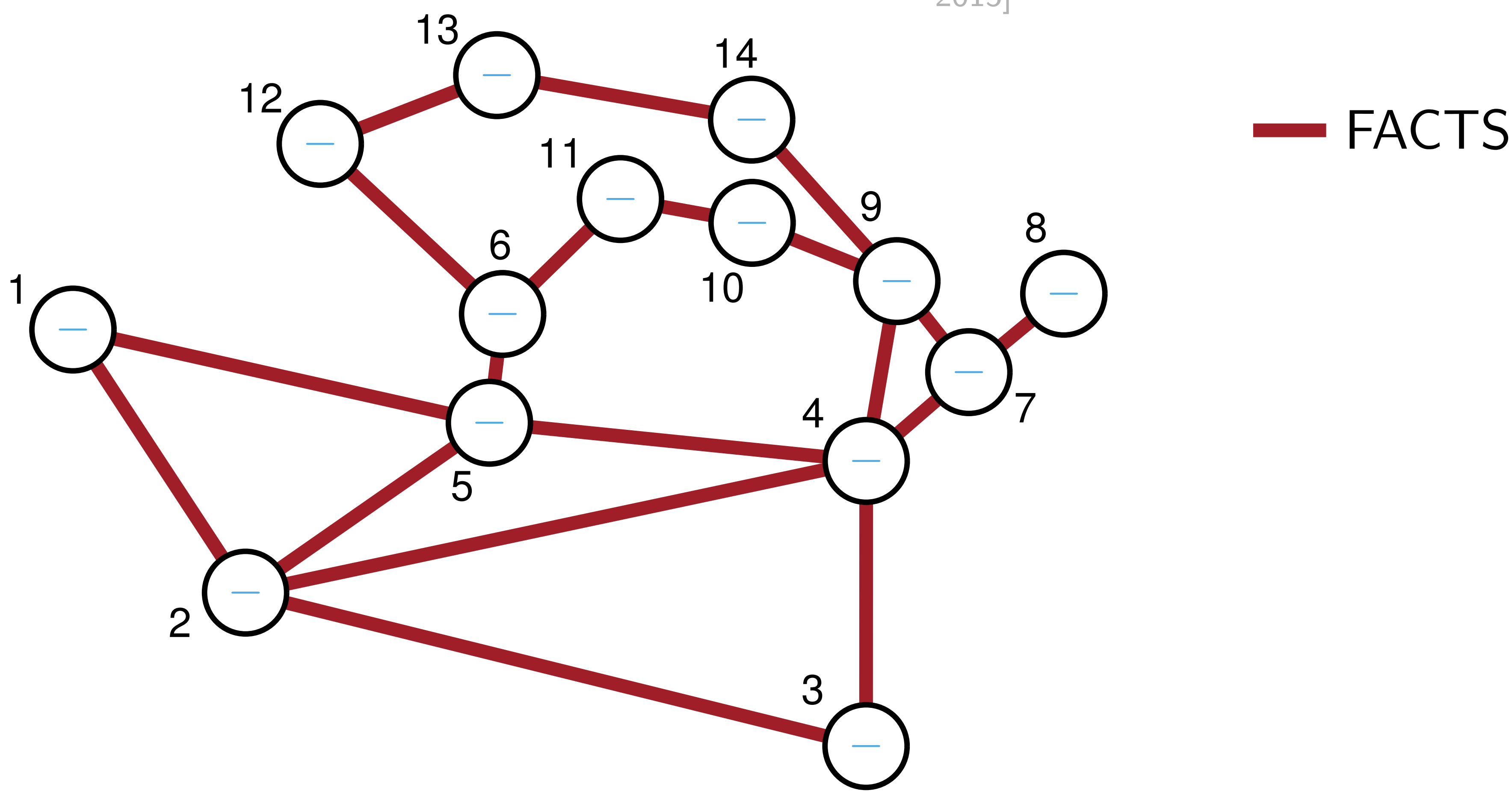
Matching the Flow Model [Leibfried et al.& Mchedlidze et al., 2015]

FACTS are expensive – how many do we need?

1. How many FACTS are necessary for globally optimal power flows? Which edges need to have a FACTS?
2. For a given number of available FACTS, is there a positive effect on flow costs and operability when approaching grid capacity limits?

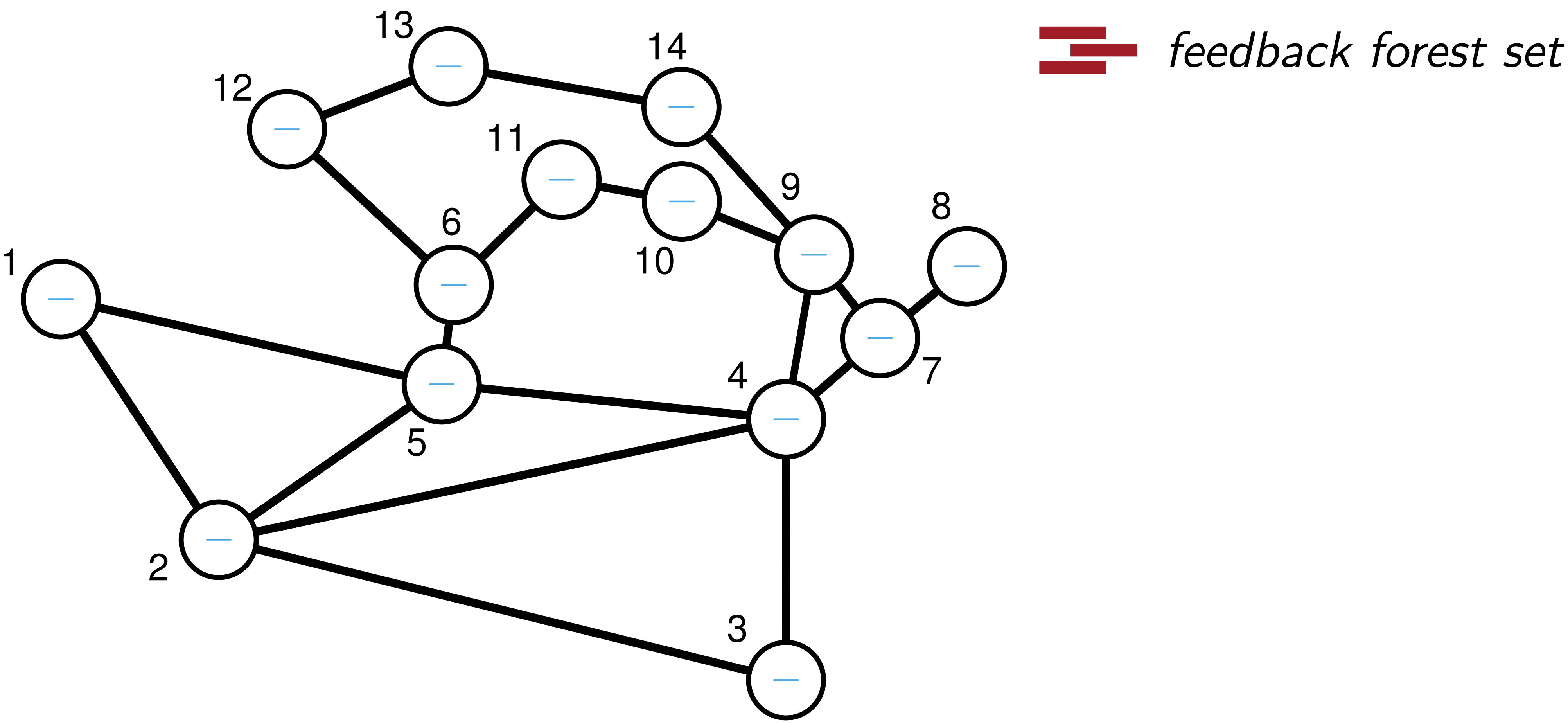
Left Figure:
[2] http://www.lichtenwald-mentaltraining.de/files/bild_licht_im_wal

Globally Optimal Power Flows [Leibfried et al.& Mchedlidze et al., 2015]



Can we become as good as the Flow Model with fewer FACTS?

Feedback Forest Set [Leibfried et al.& Mchedlidze et al., 2015]



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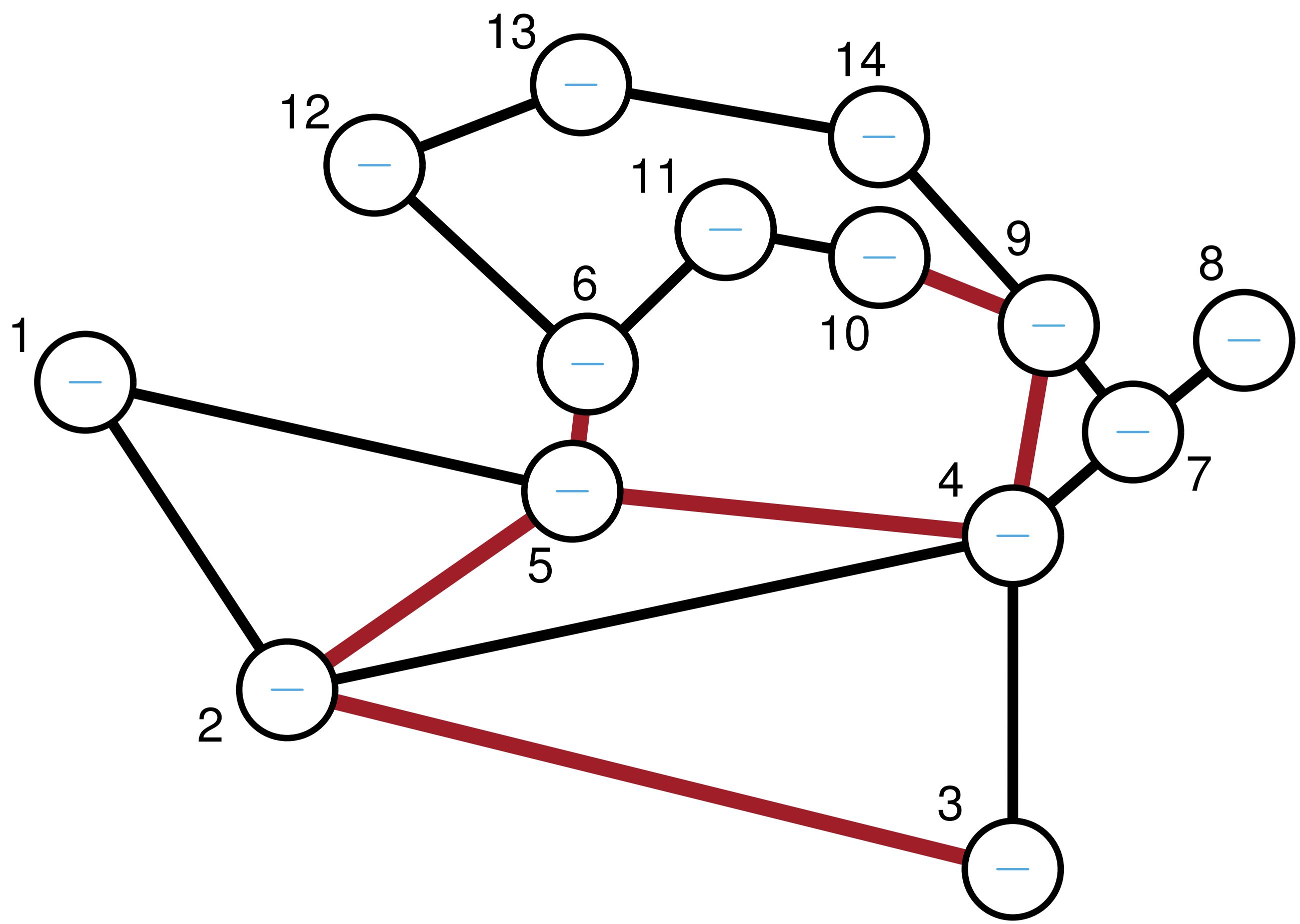
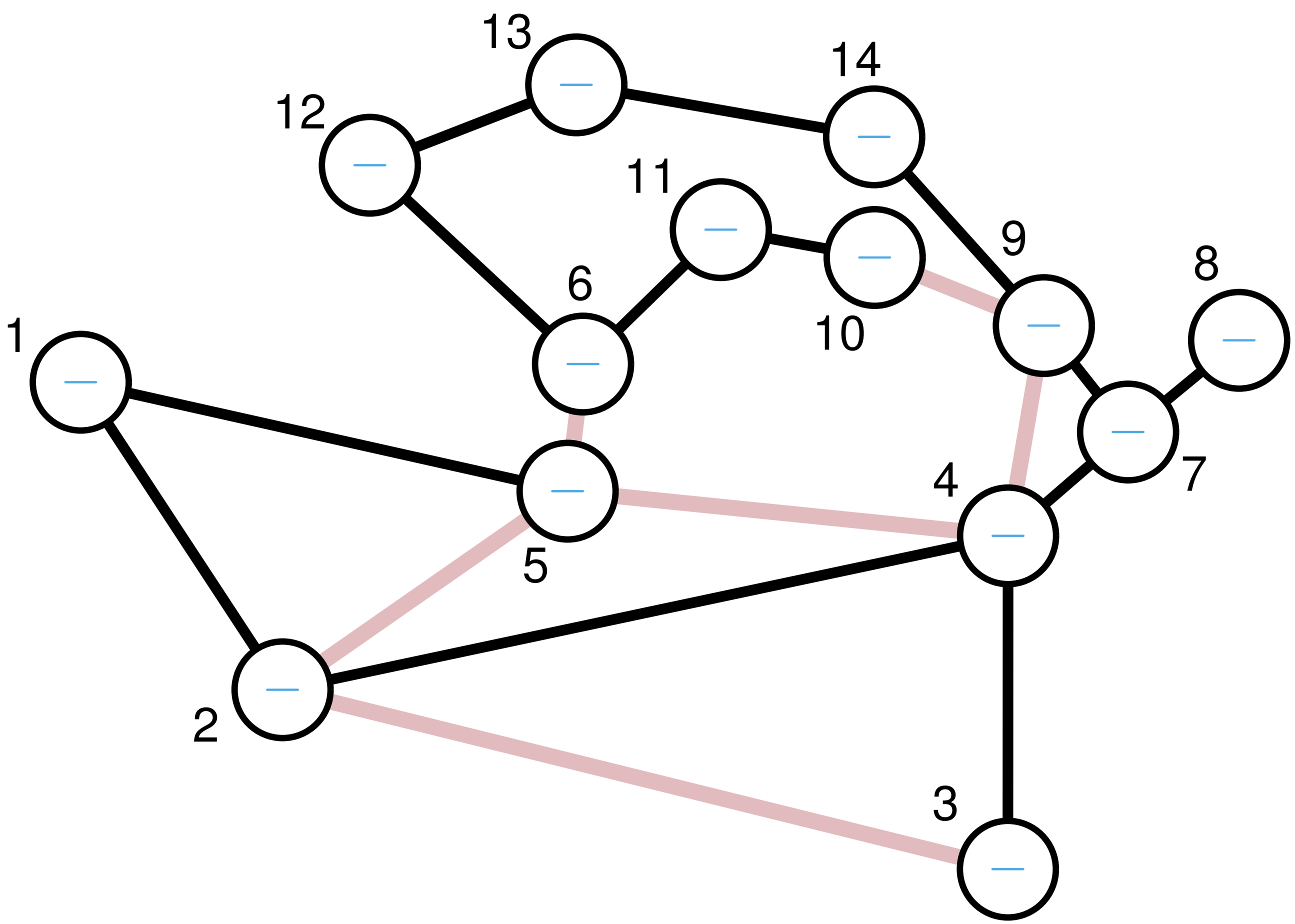


feedback forest set

A set of trees (*forest*) remains!

Feedback Forest Set [Leibfried et al.& Mchedlidze et al., 2015]



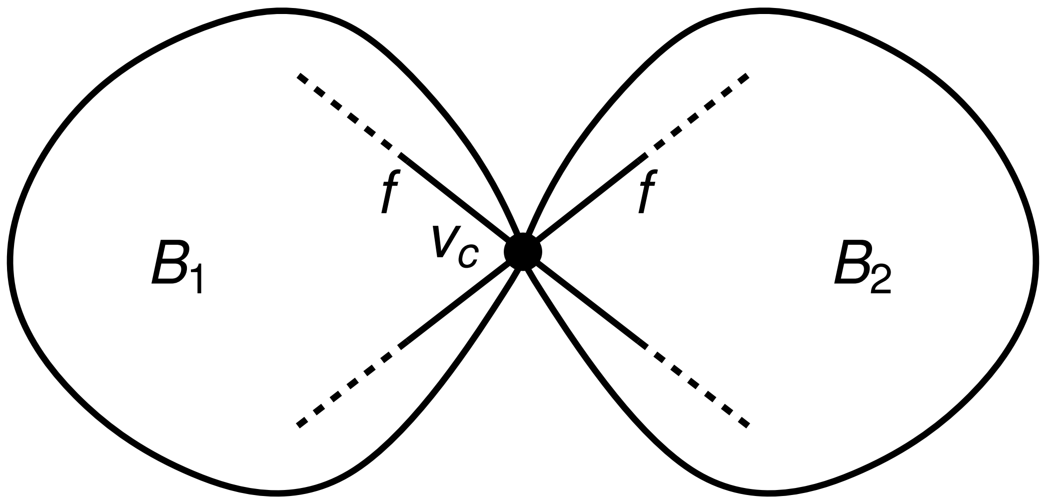
feedback forest set

$\Downarrow$

A set of trees (*forest*) remains!

If the graph without FACTS represents a forest all flows represent feasible power flows.

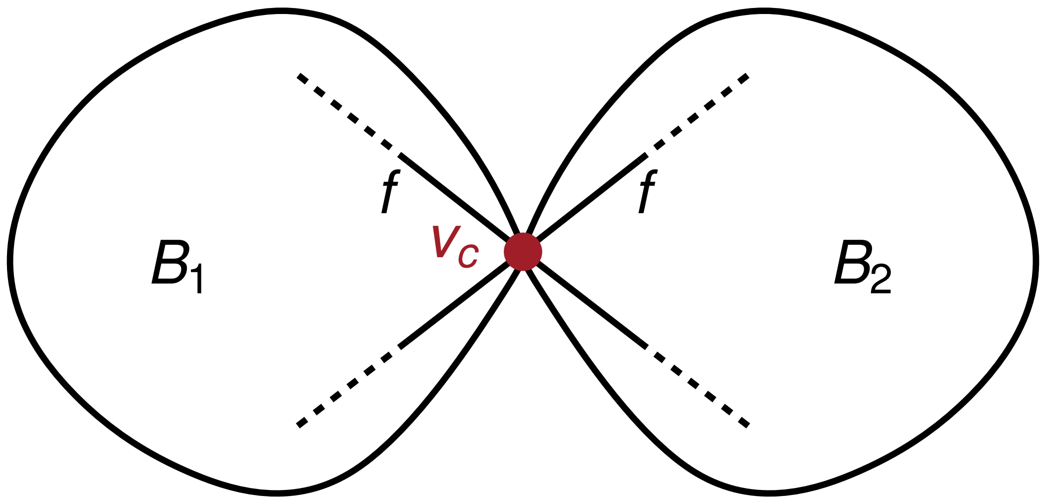
Generalized Algorithmic Idea [Leibfried et al.& Mchedlidze et al., 2015]



Idea

- Decompose the graph G at the cut-vertex v_c into subgraphs B_i
- The feasible power flows f does not change for the subgraphs B_i
- If we have a feasible power flows for each block B_i and combine the subgraphs at v_c this leads to a feasible power flows again

Generalized Algorithmic Idea [Leibfried et al.& Mchedlidze et al., 2015]



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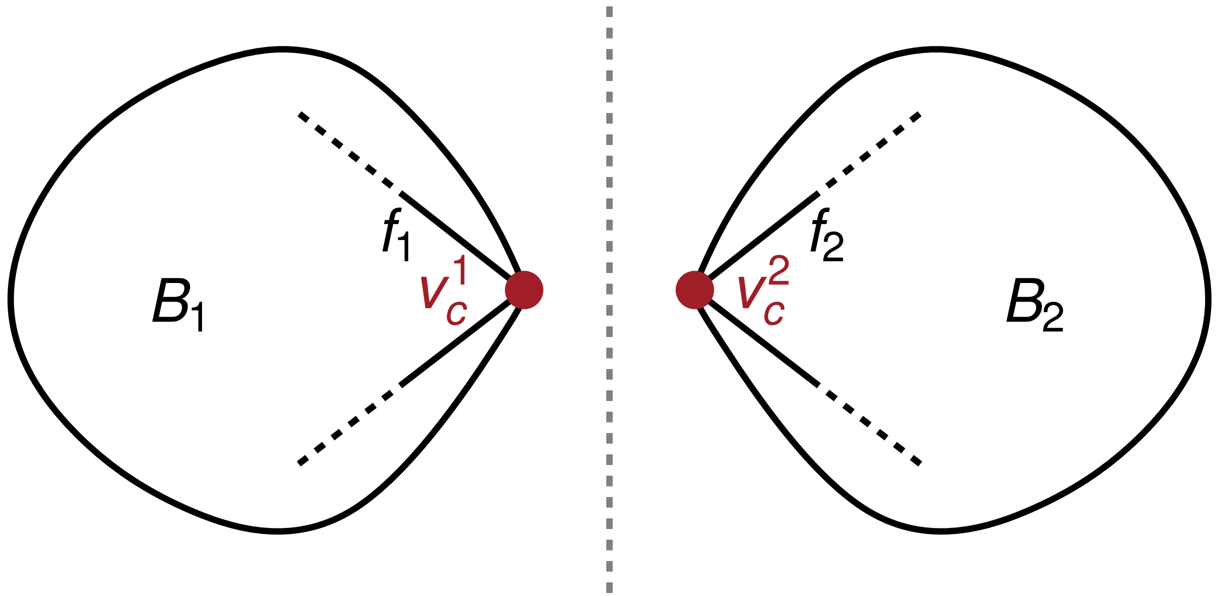

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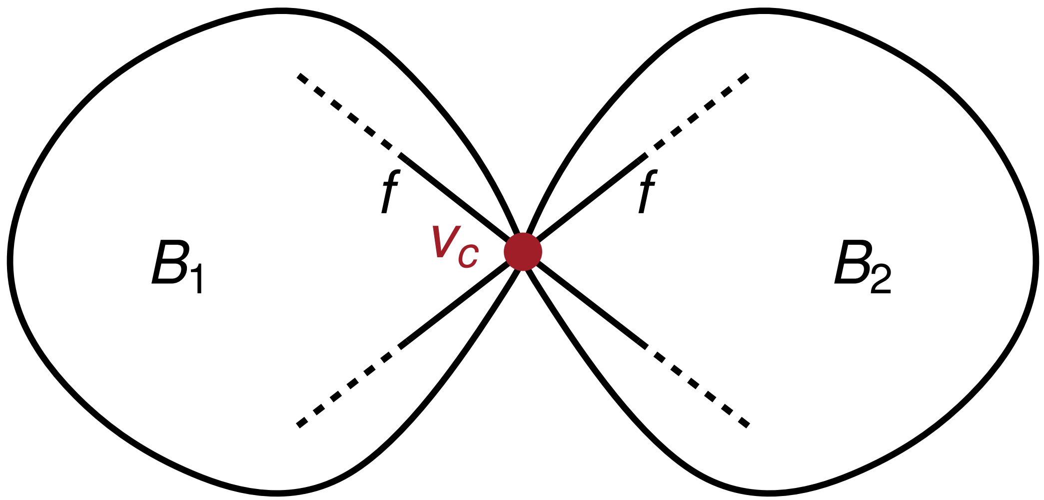

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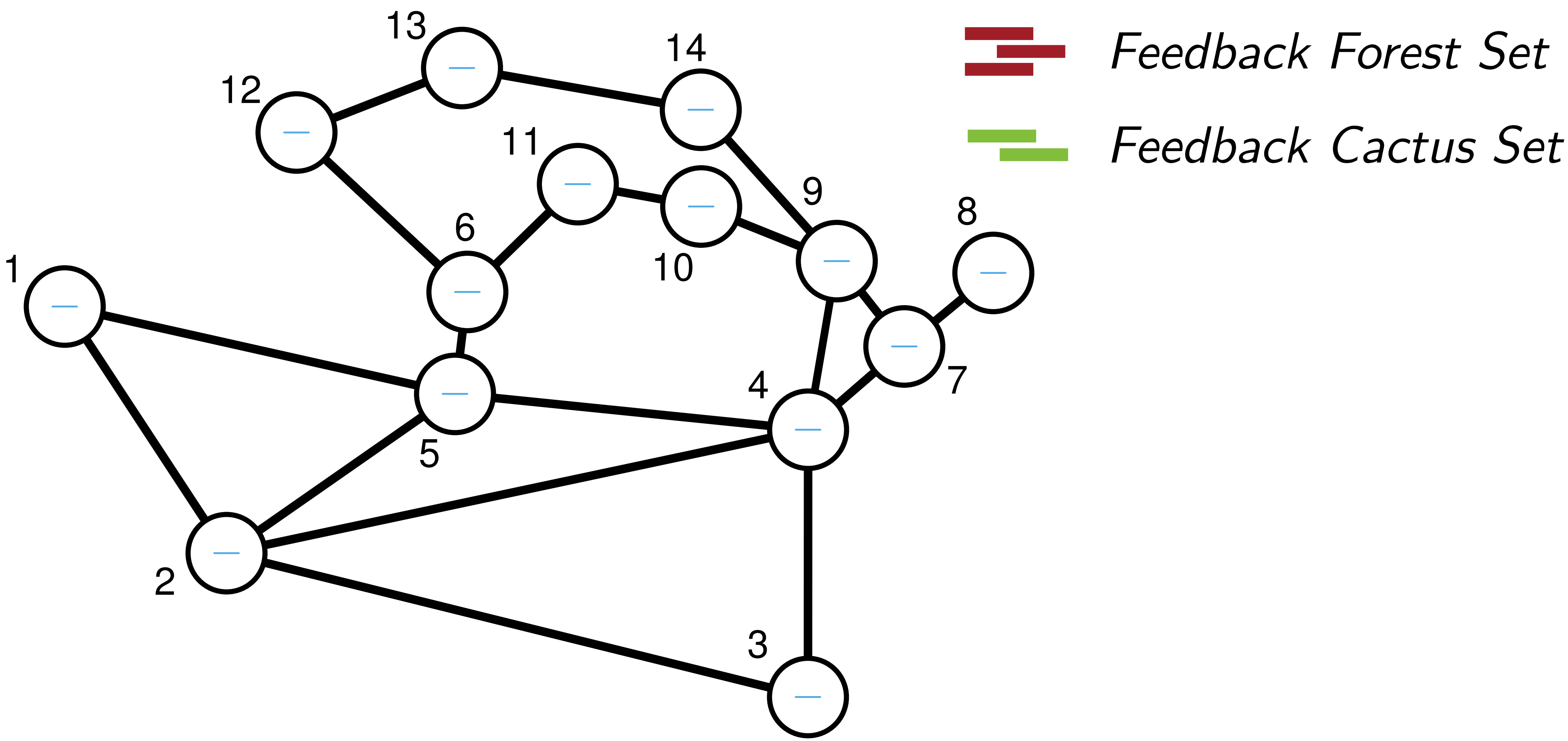
Feedback Cactus Set [Leibfried et al.& Mchedlidze et al., 2015]



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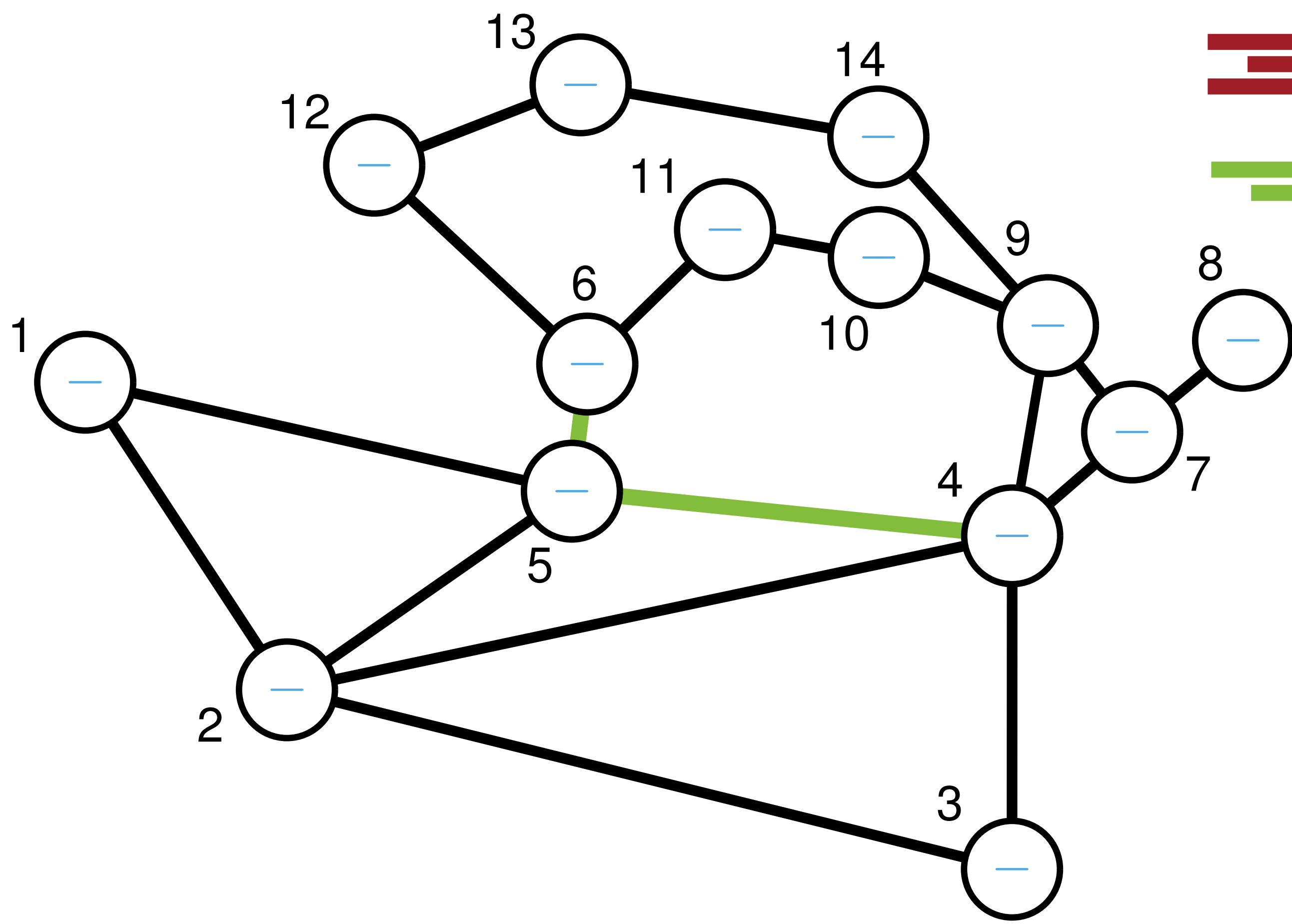


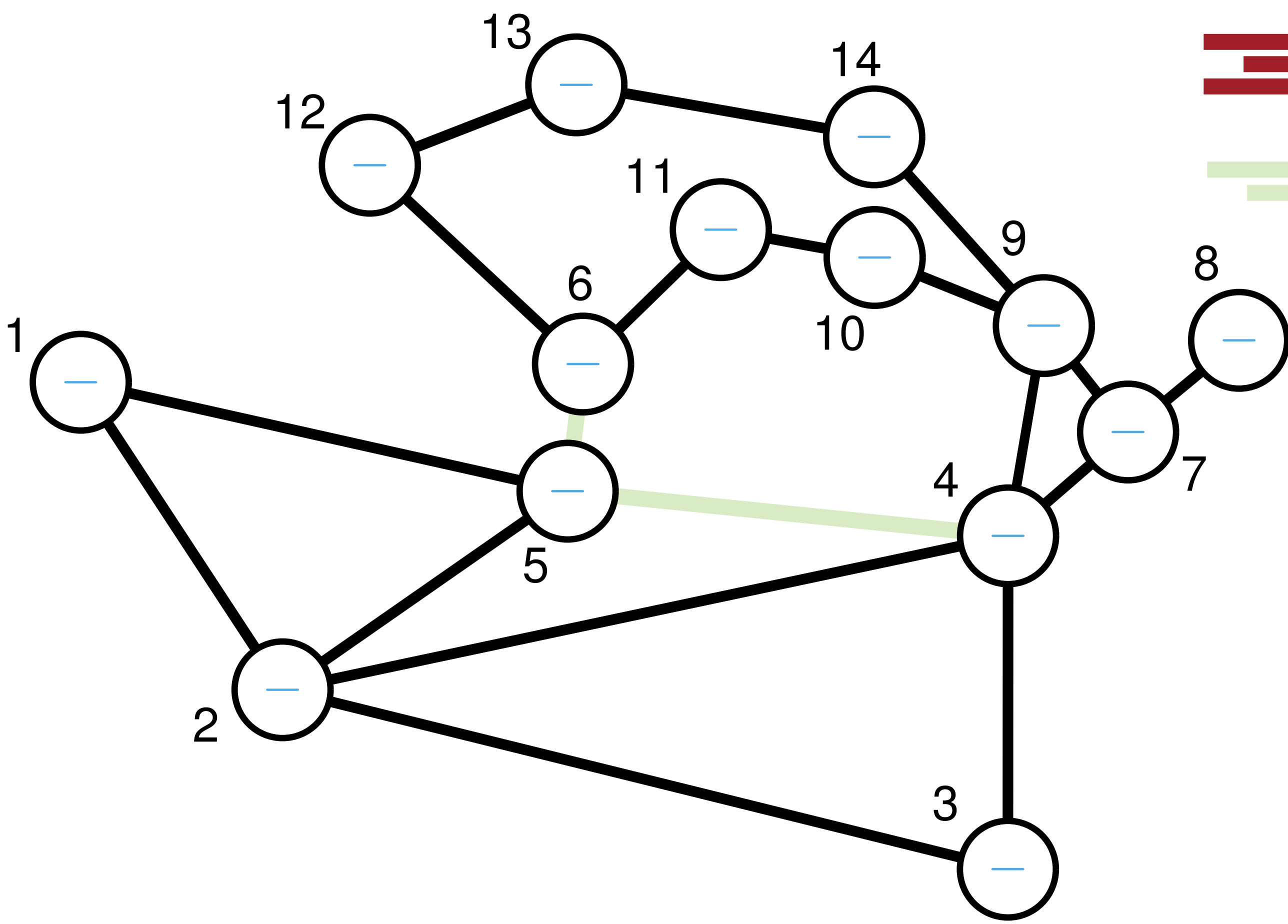
Feedback Forest Set

Feedback Cactus Set

$\Downarrow$

A set of *Cacti* remains!

Feedback **Cactus** Set [Leibfried et al.& Mchedlidze et al., 2015]



Feedback Forest Set

Feedback Cactus Set

⇓

A set of *Cacti* remains!

If the remaining graph is a cactus and the capacities on the cycles are suitably bounded then there is for every flow a cost-equivalent feasible power flow.

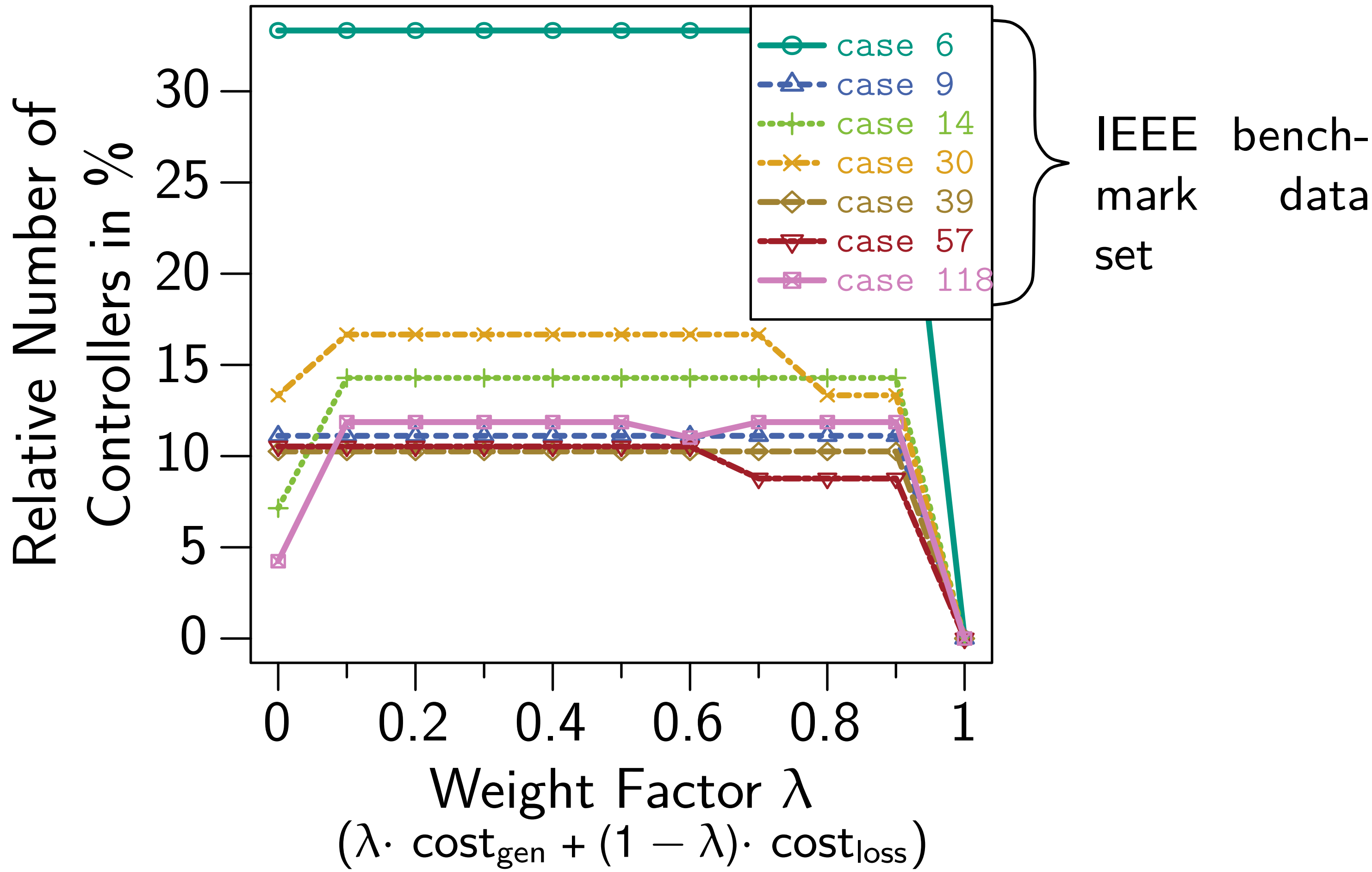
Research Questions

Control units are expensive – how many do we need?

Q1) How many controlled buses are necessary for globally optimal power flows? Which buses need to be controlled?

Q2) For a given number of available control buses, is there a positive effect on flow costs and operability when approaching grid capacity limits?

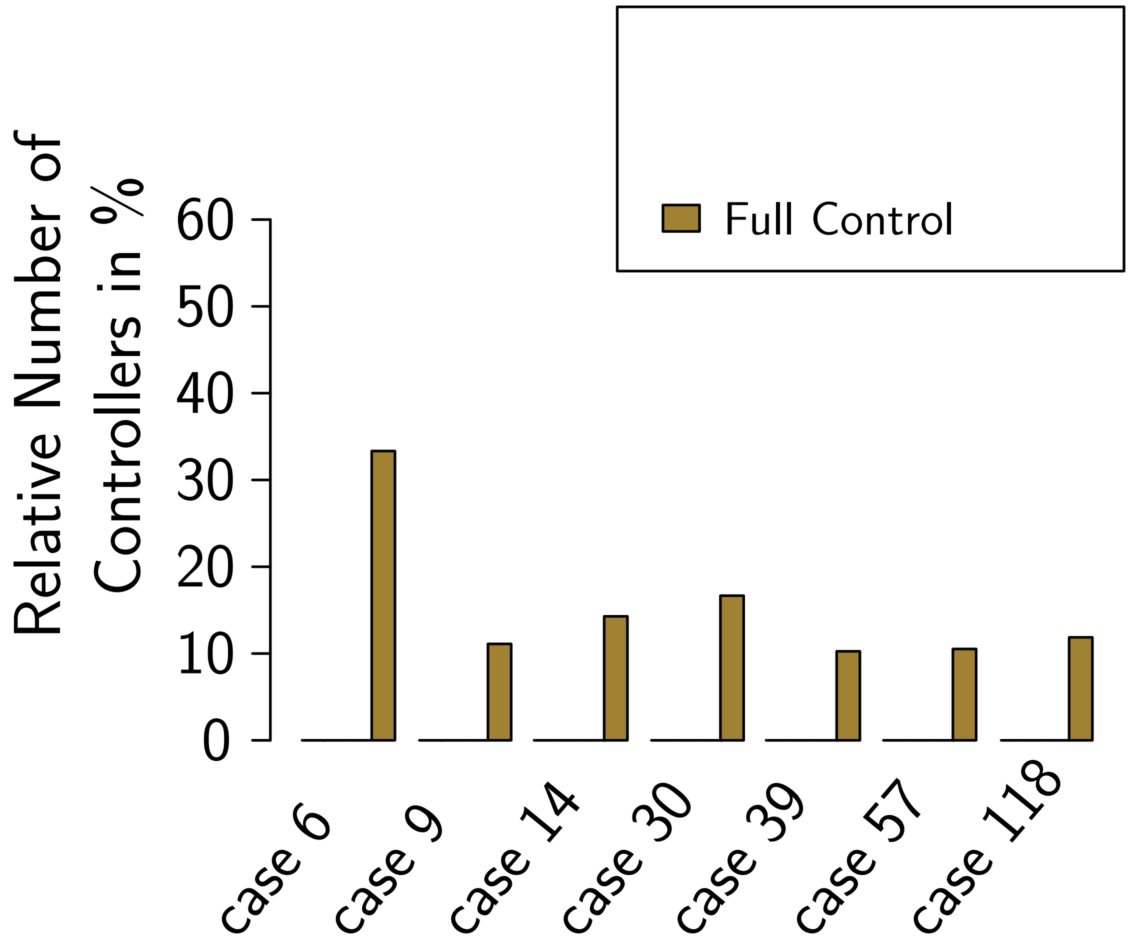
Number of Control Buses



Observation from experiments:

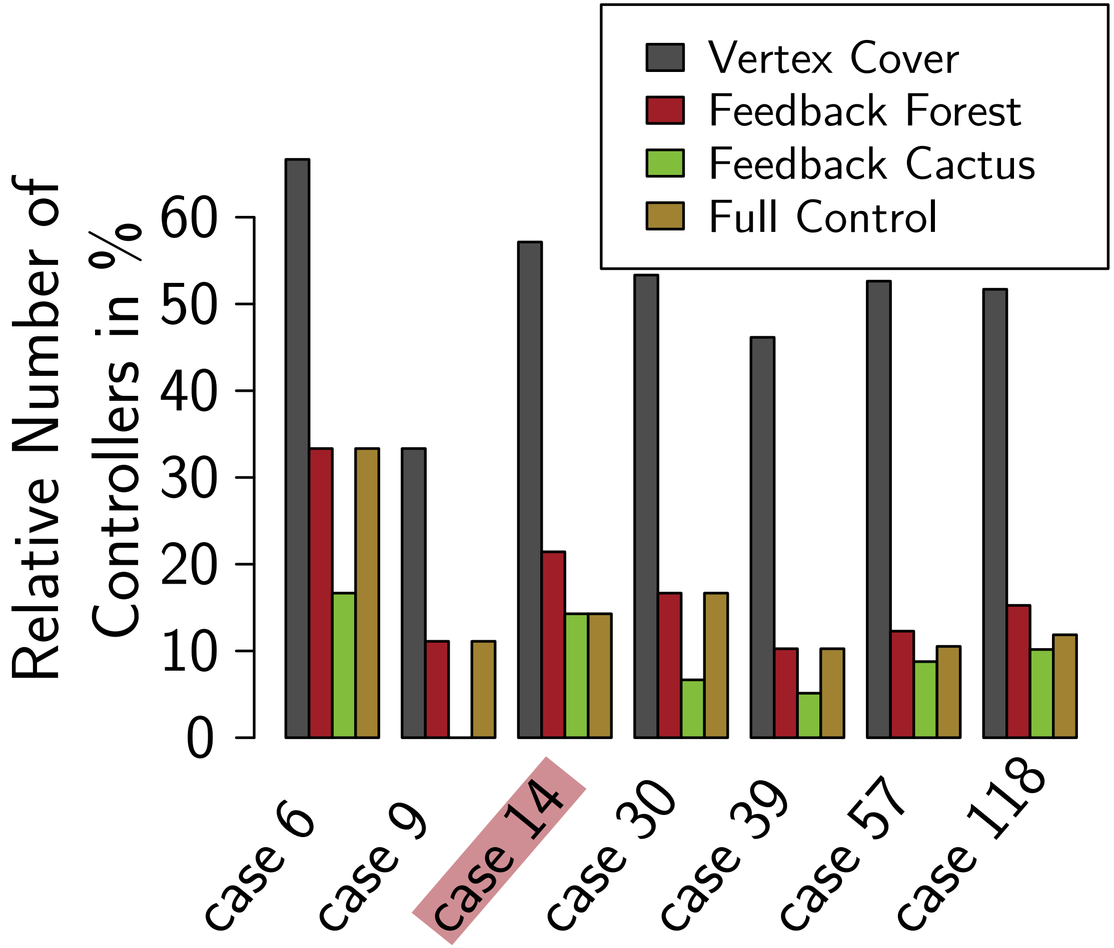
- Few control buses suffice for obtaining optimal solutions

Number of Control Buses

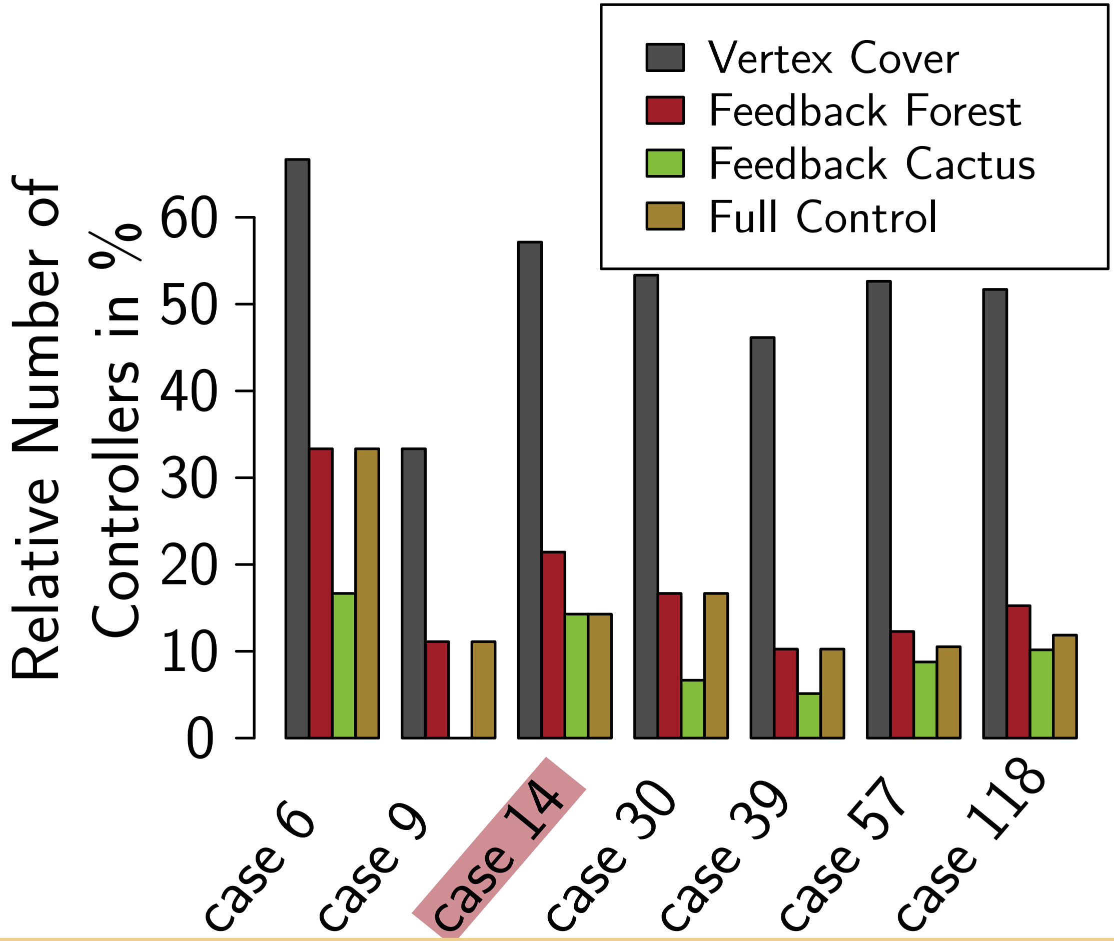


- For each benchmark case: $\max_\lambda \min \#Controller$

Number of Control Buses vs. Structural Results



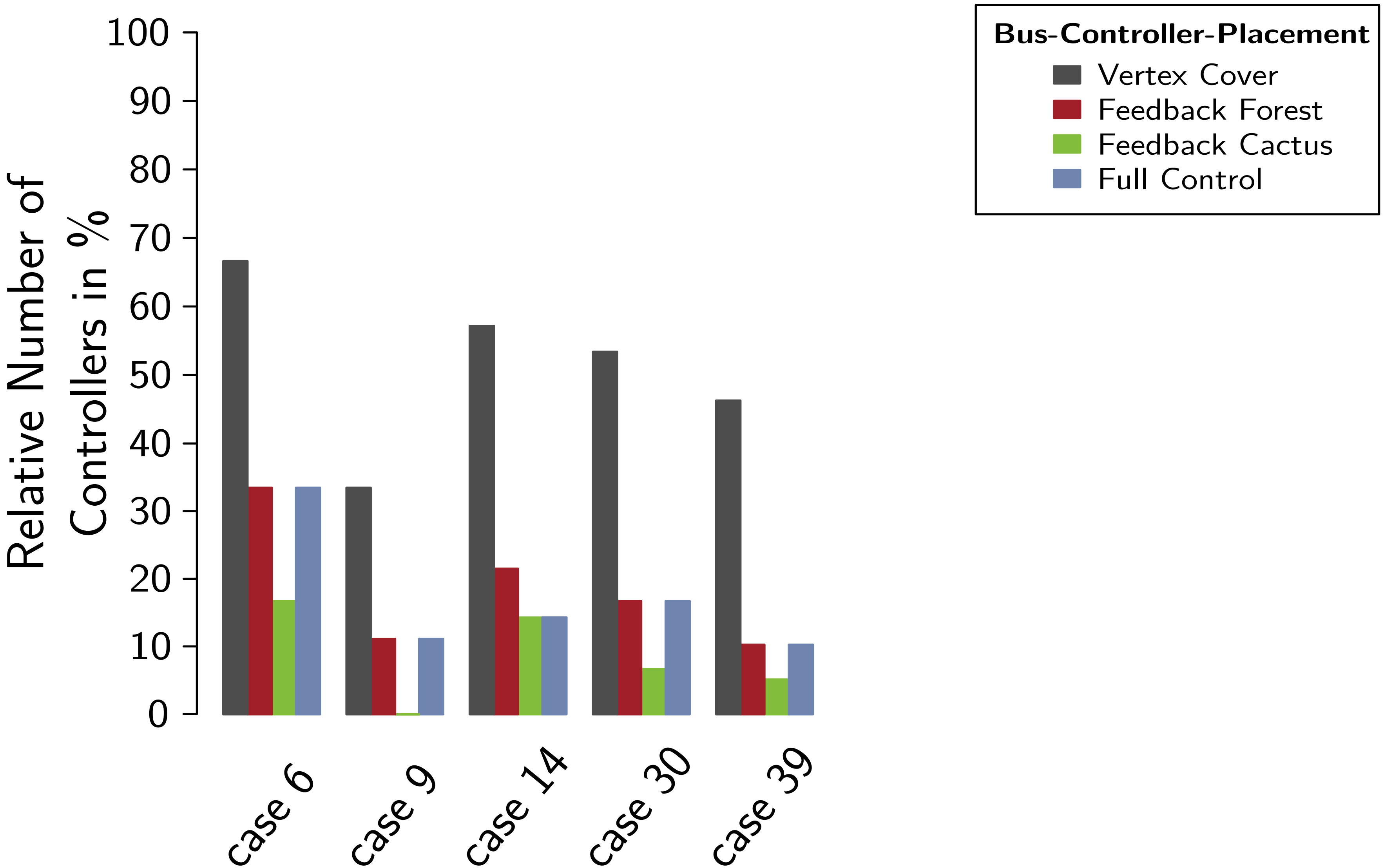
Number of Control Buses vs. Structural Results



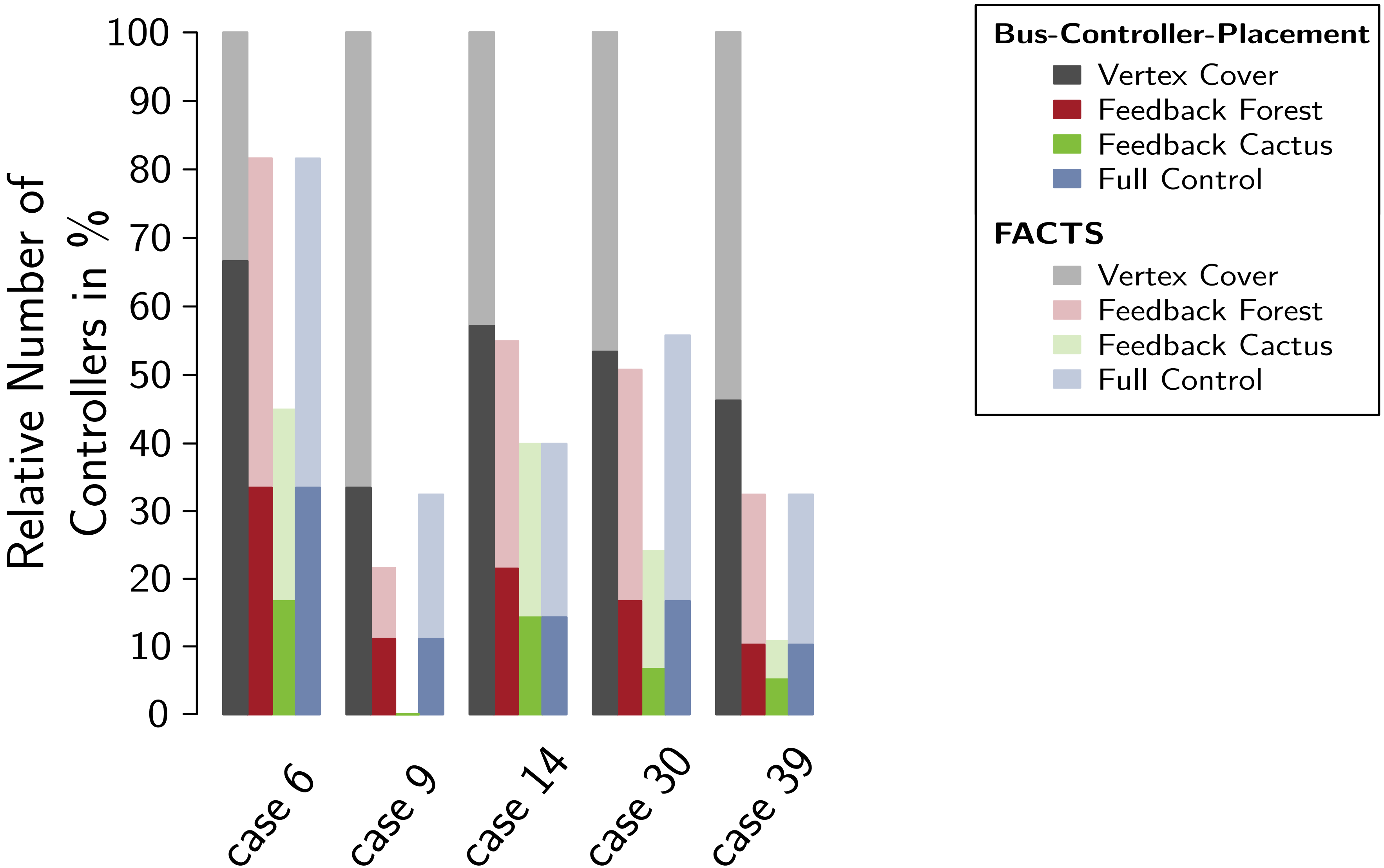
Findings

Often a small number of flow control buses suffices for matching cost of the flow model.

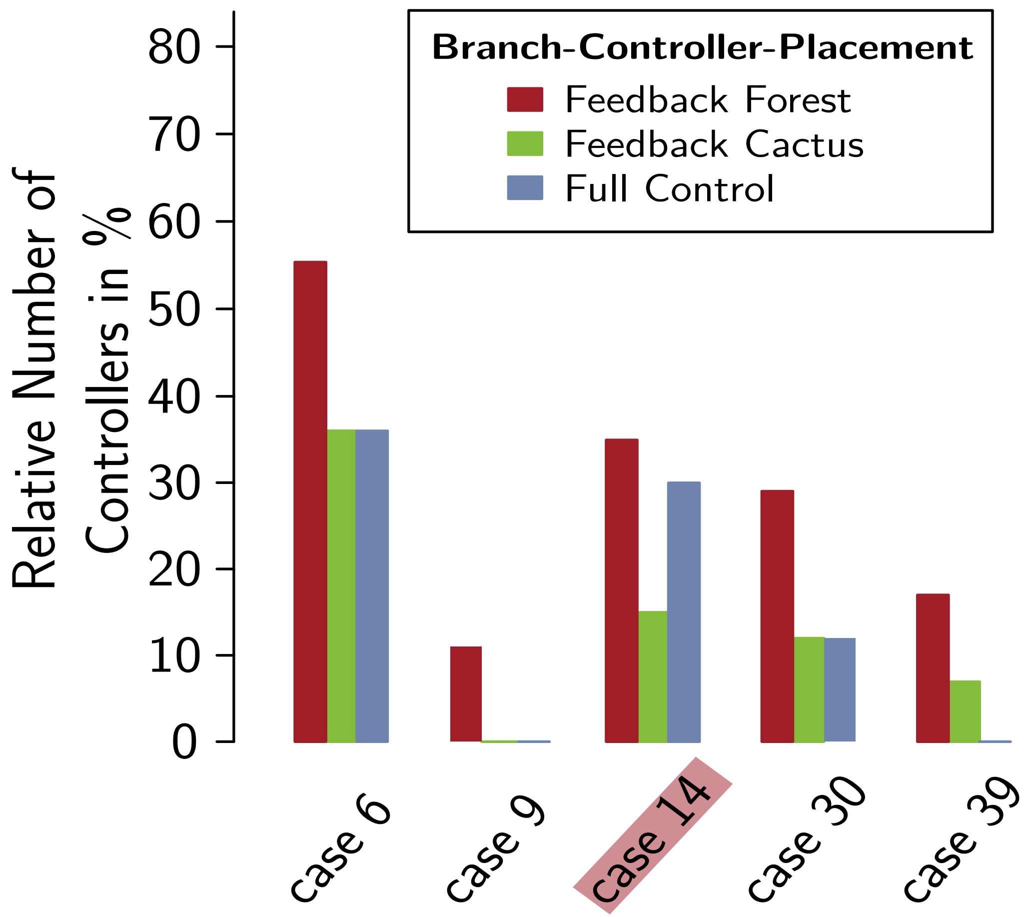
Controller Placement on Buses [Leibfried et al., 2015]



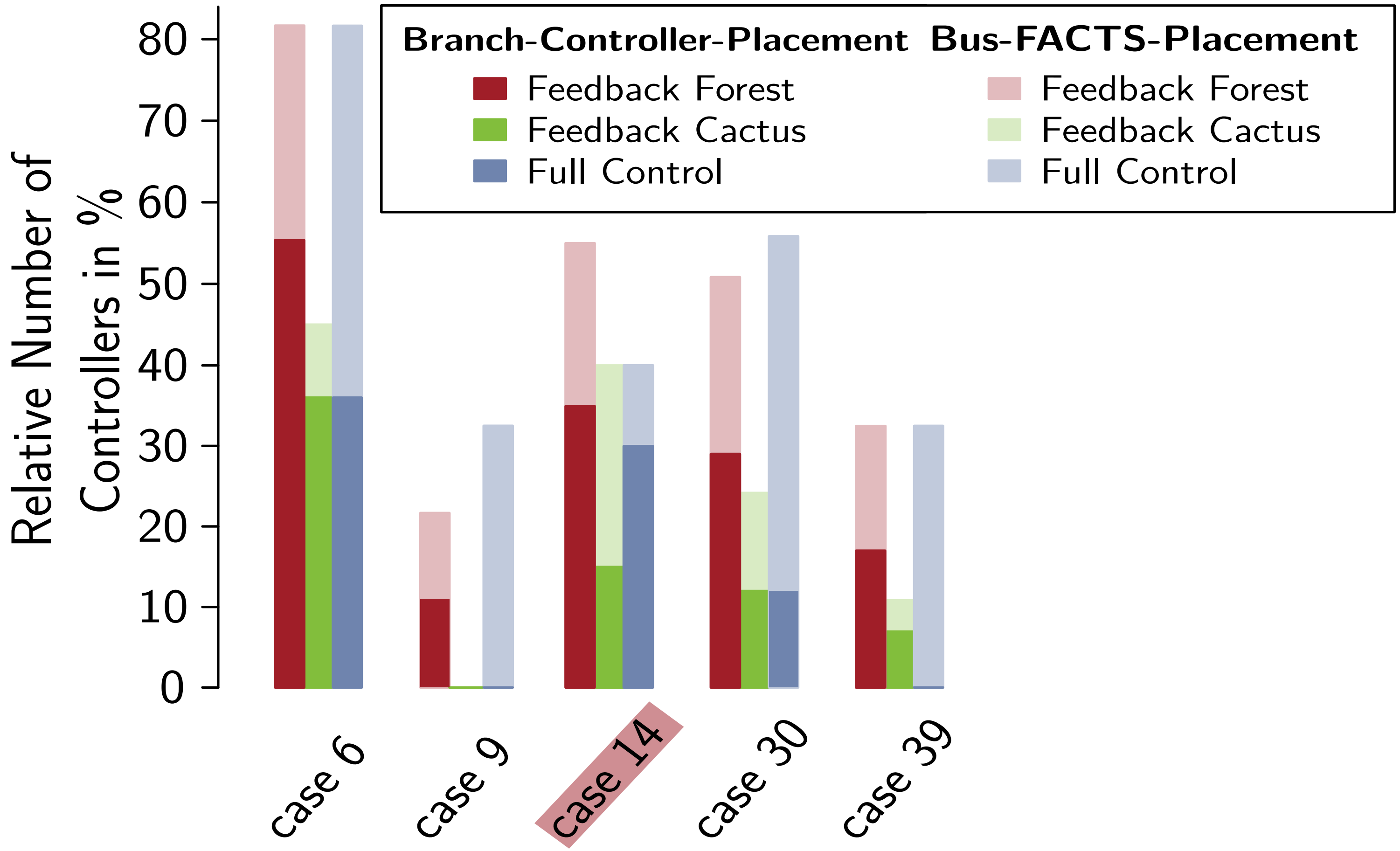
Controller Placement on Buses [Leibfried et al., 2015]



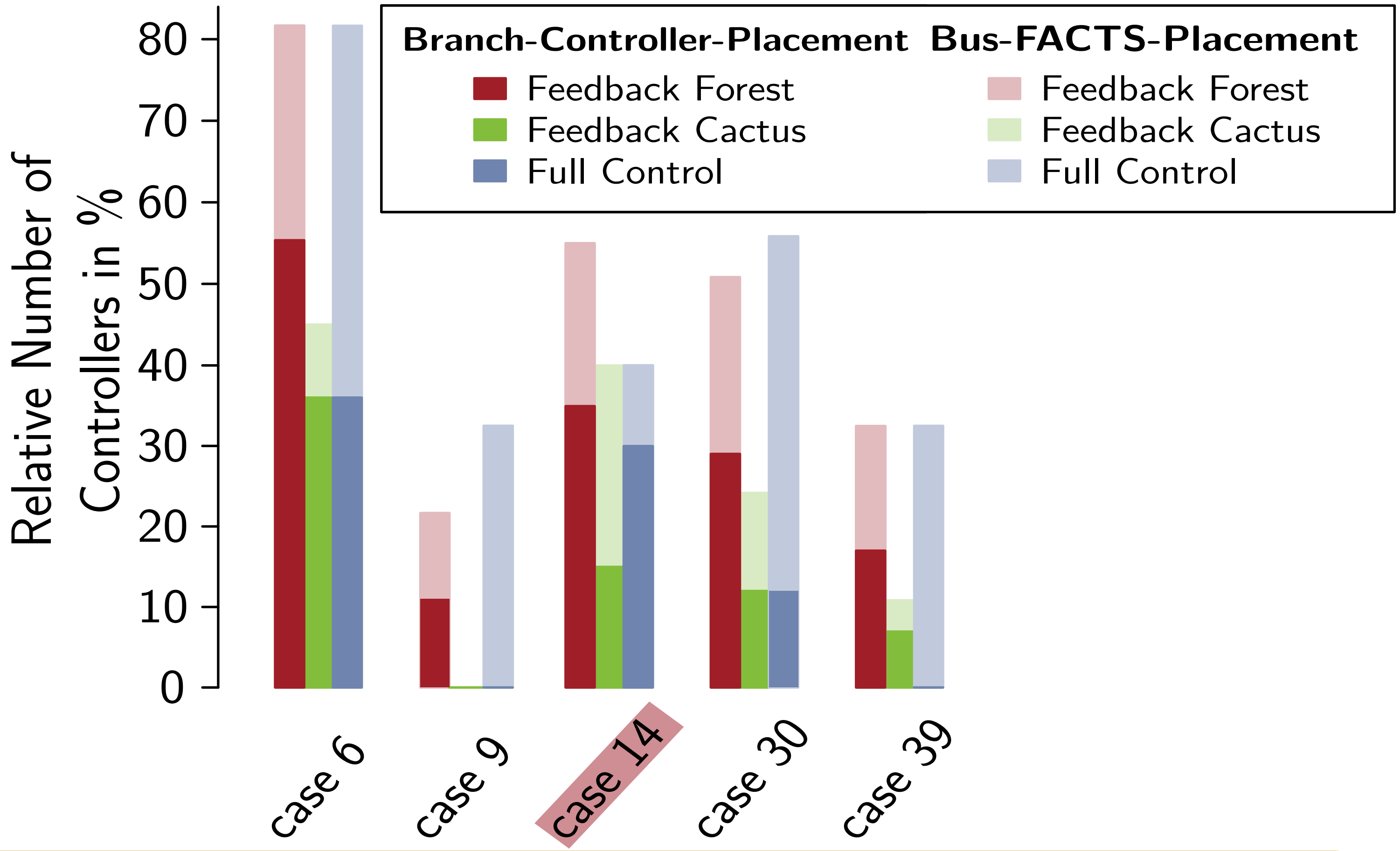
Control Branches vs. Control Buses



Control Branches vs. Control Buses



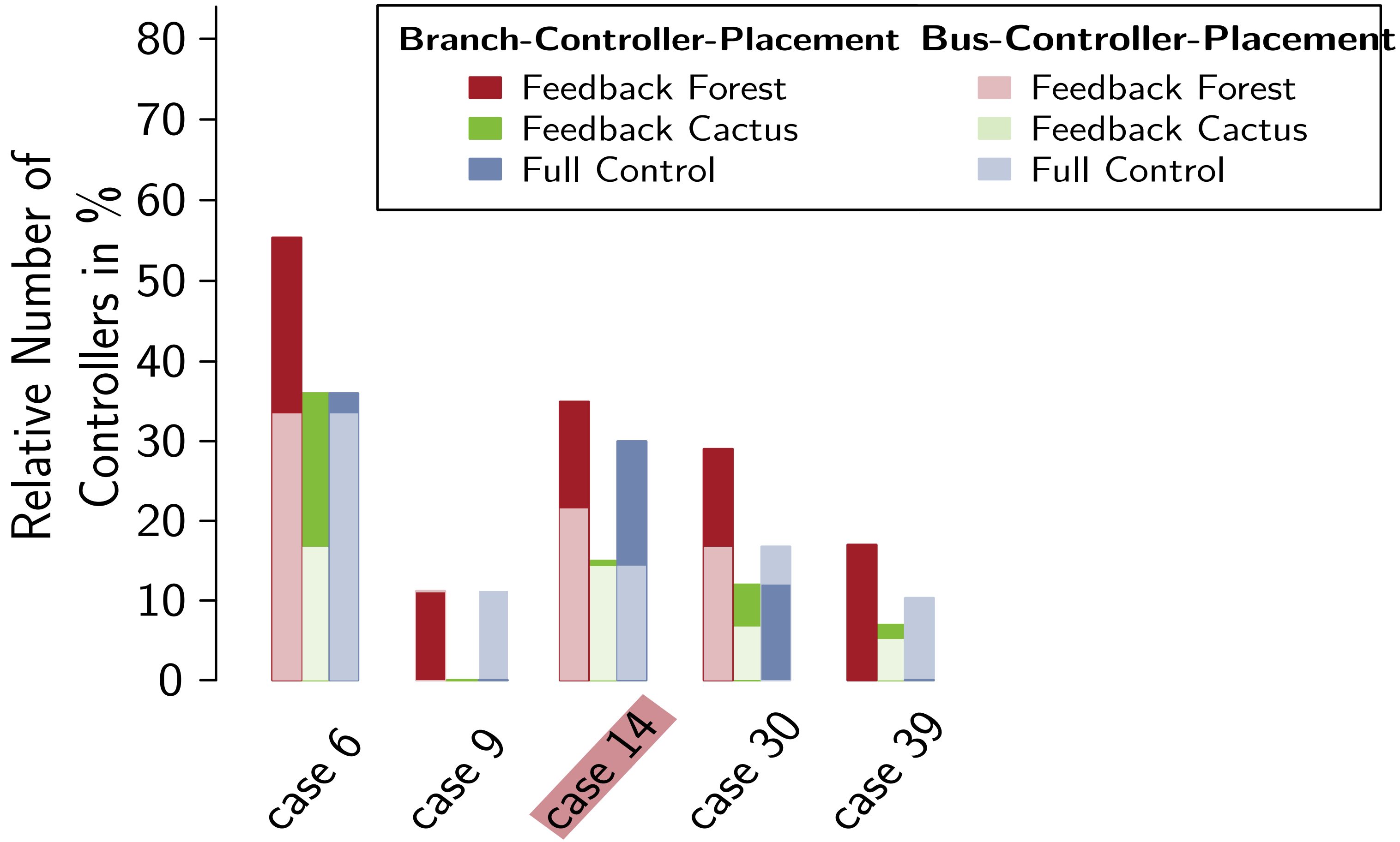
Control Branches vs. Control Buses



Findings

Smaller number of FACTS are sufficient for placing controller on branches rather than buses.

Control Branches vs. Control Buses



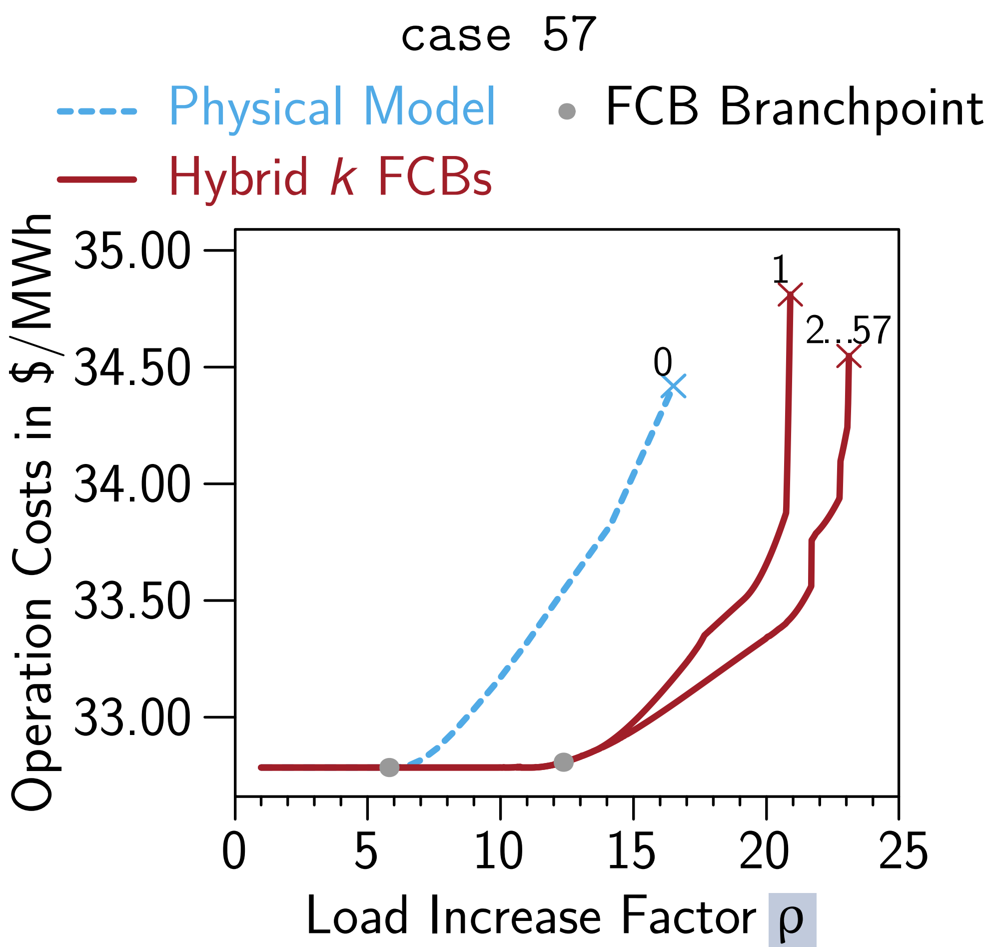
Effect of Few Flow Control Buses

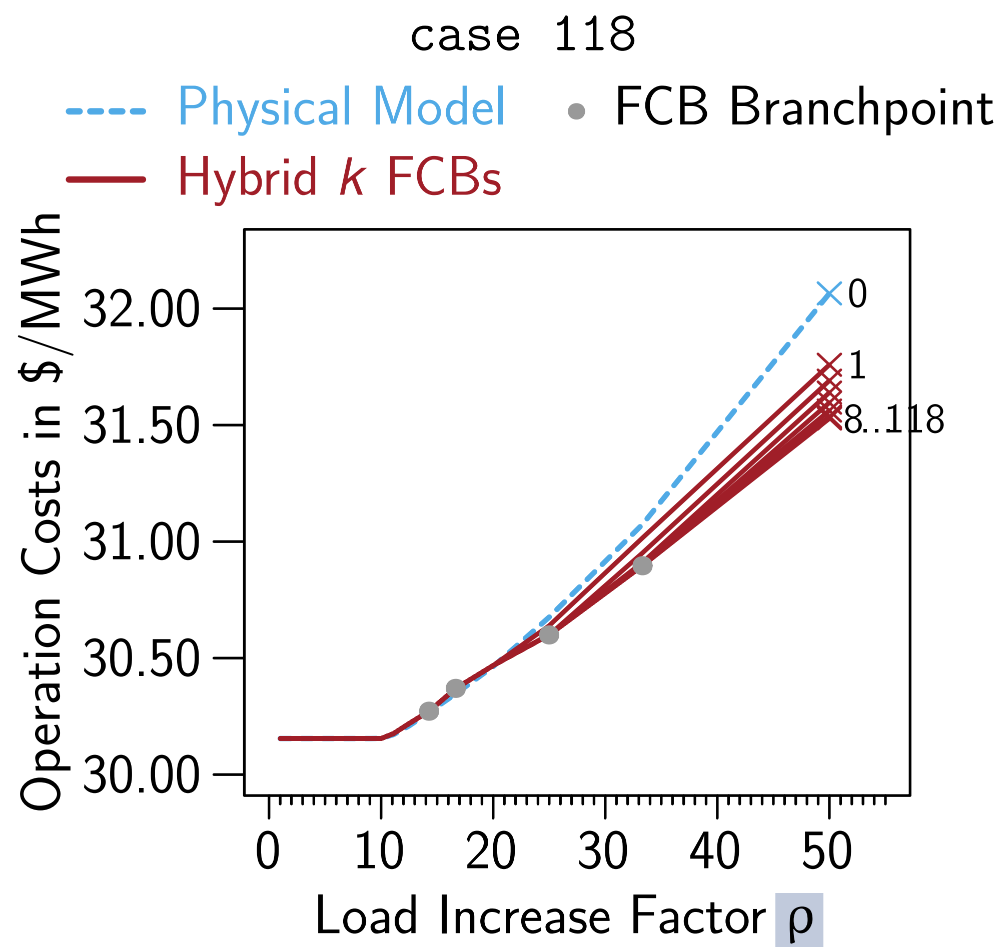
- Simulate load increase by a load increase factor ρ
- Simulations with different numbers of flow controllers

Test Data:

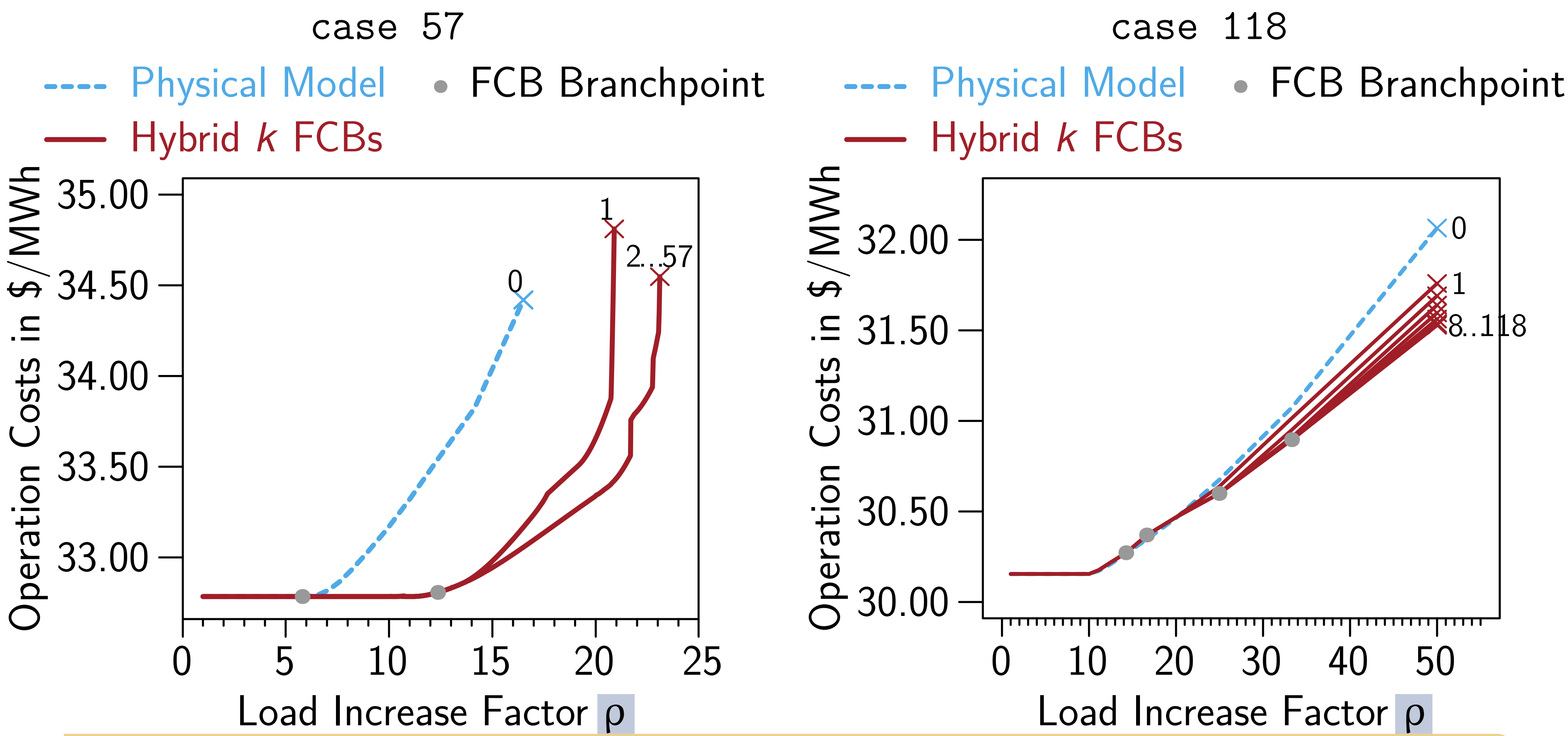
- IEEE instances have basically "unlimited" edge capacities
- Reduce capacities to total demand (no effect on cost and feasibility)
- Gradually increase all loads by factor ρ, or, alternatively, reduce all capacities by $1/\rho$
- Compute generation cost and required number of controllers for optimality

Hybrid Model Operation under Increasing Loads





Hybrid Model Operation under Increasing Loads

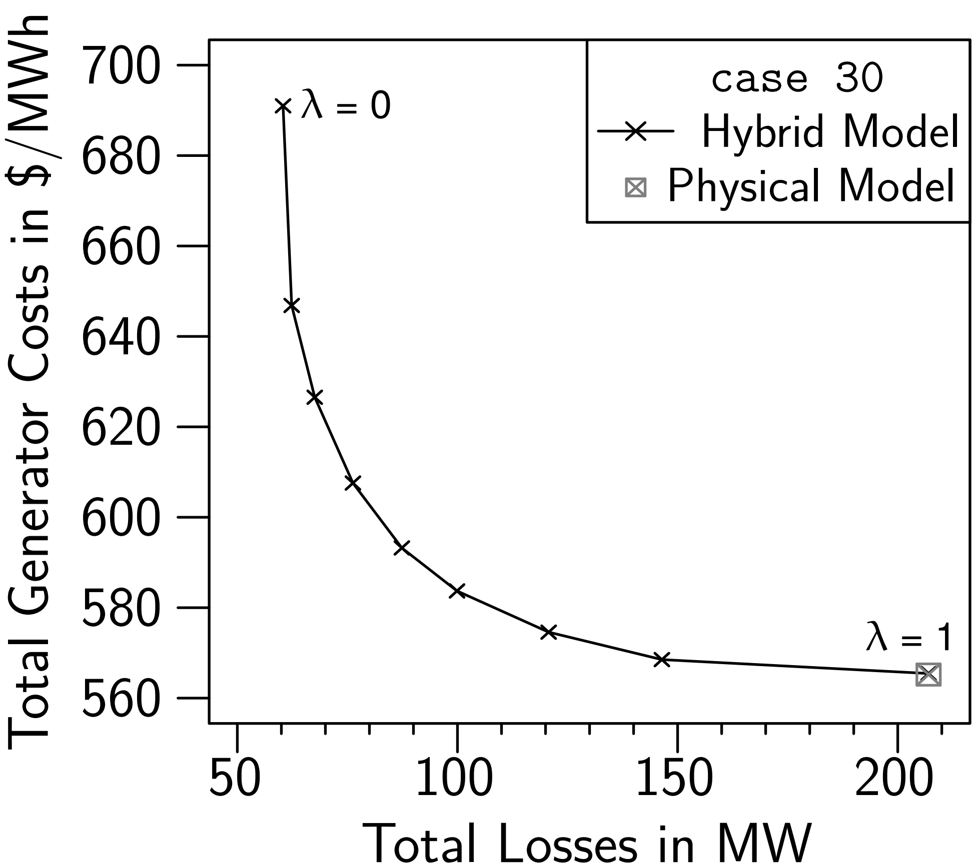


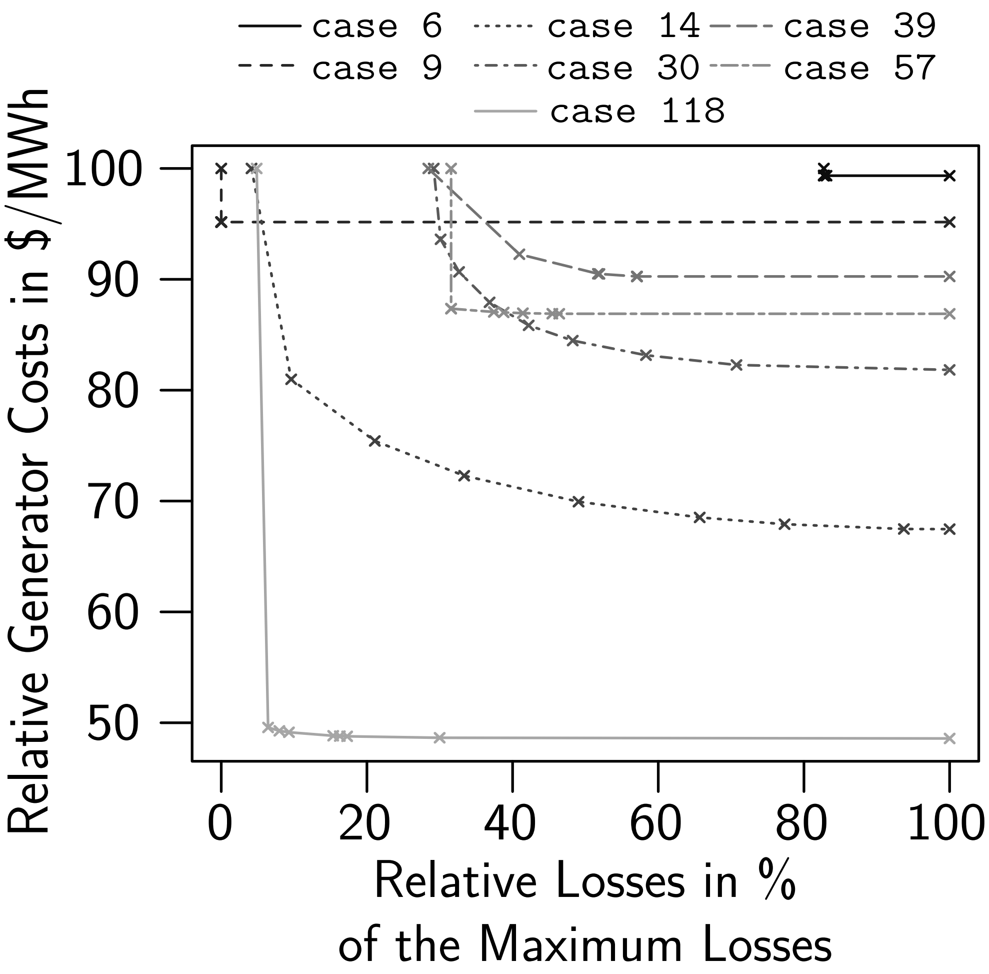
Findings

Very few flow control buses extend the operation point, while having lower operation cost.

Backup 1

Weighted cost function $\lambda \cdot \text{cost}_{\text{gen}} + (1 - \lambda) \cdot \text{cost}_{\text{loss}}$





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