Towards Realistic Flow Control in Power Grid Operation

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Tamara Mchedlidze, Martin Nöllenburg, Ignaz Rutter, Dorothea Wagner and Franziska Wegner

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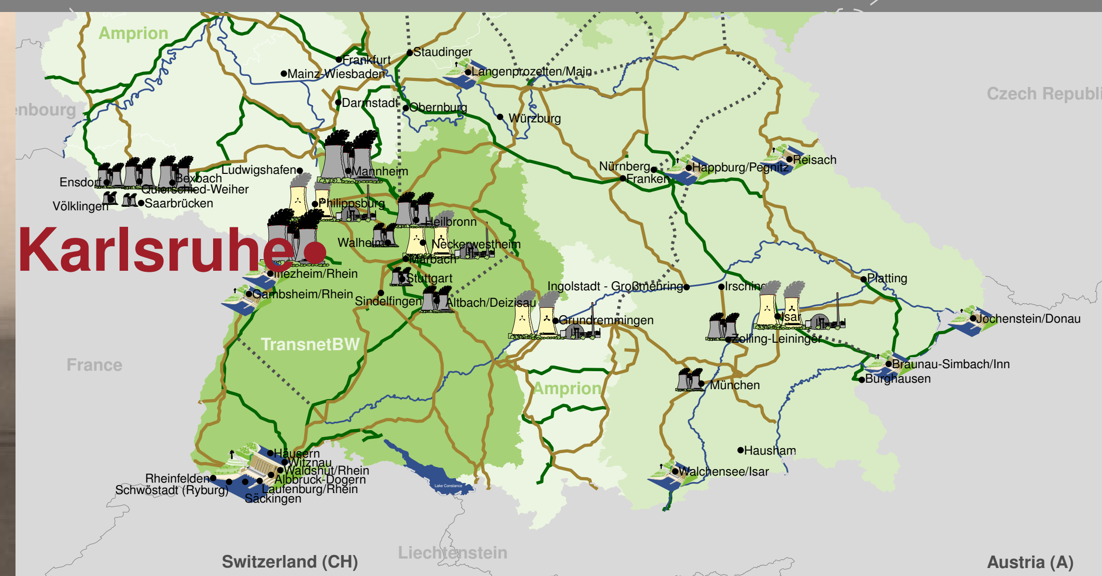
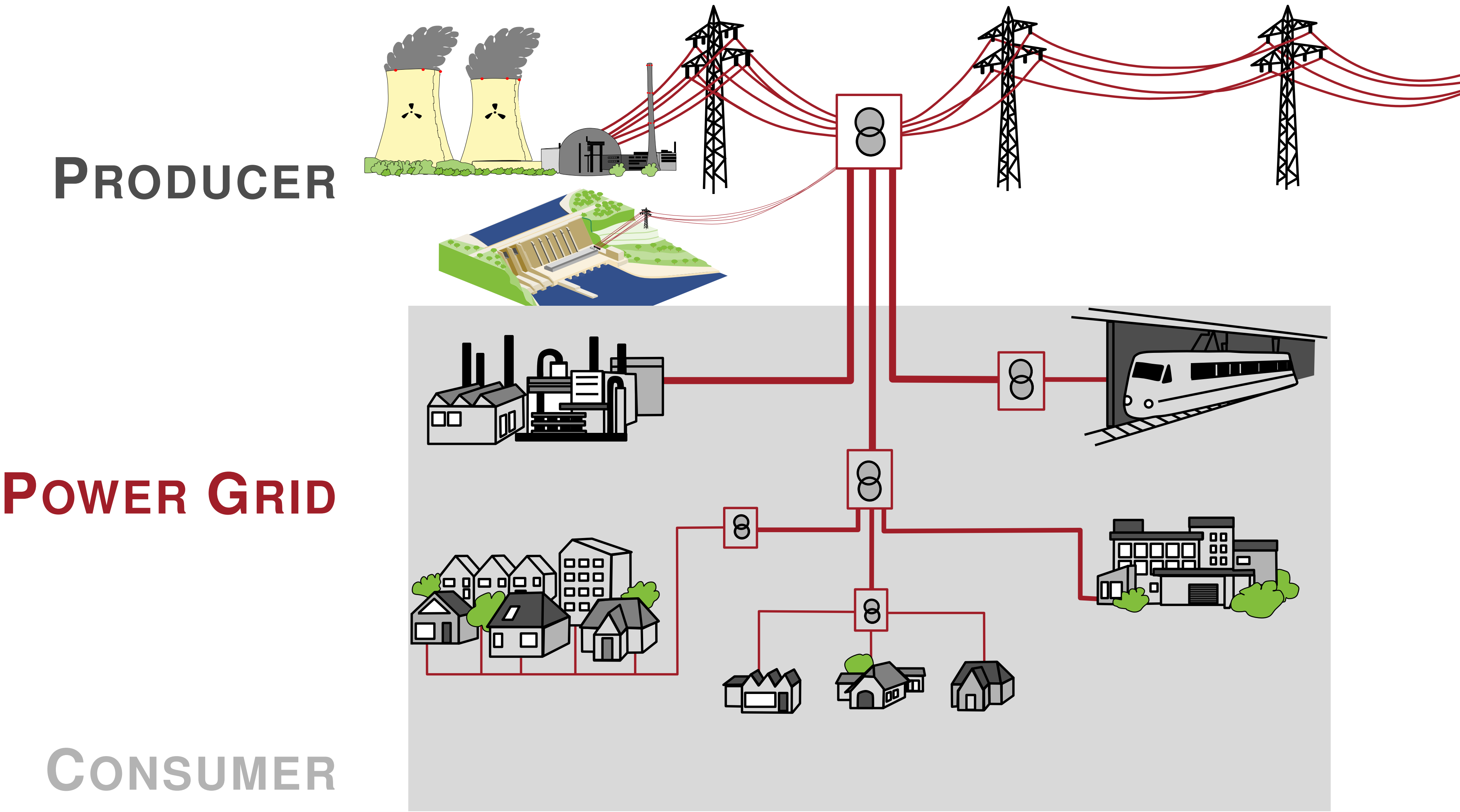
[1] http://img.welt.de/img/deutschland/crop124593297/5546936773-ci3x2l-w900/Strommasten.jpg



Recent Development in Power Grids



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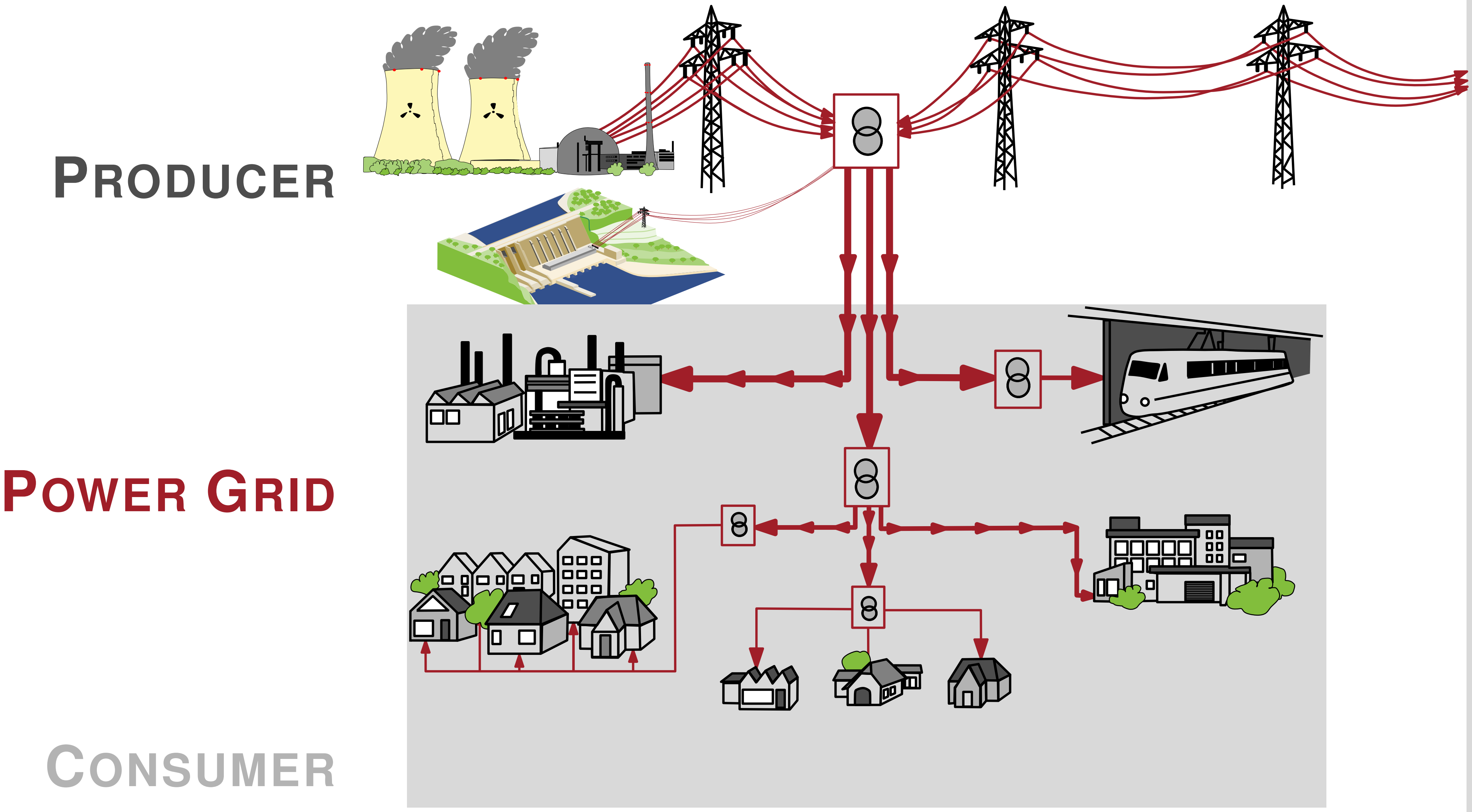
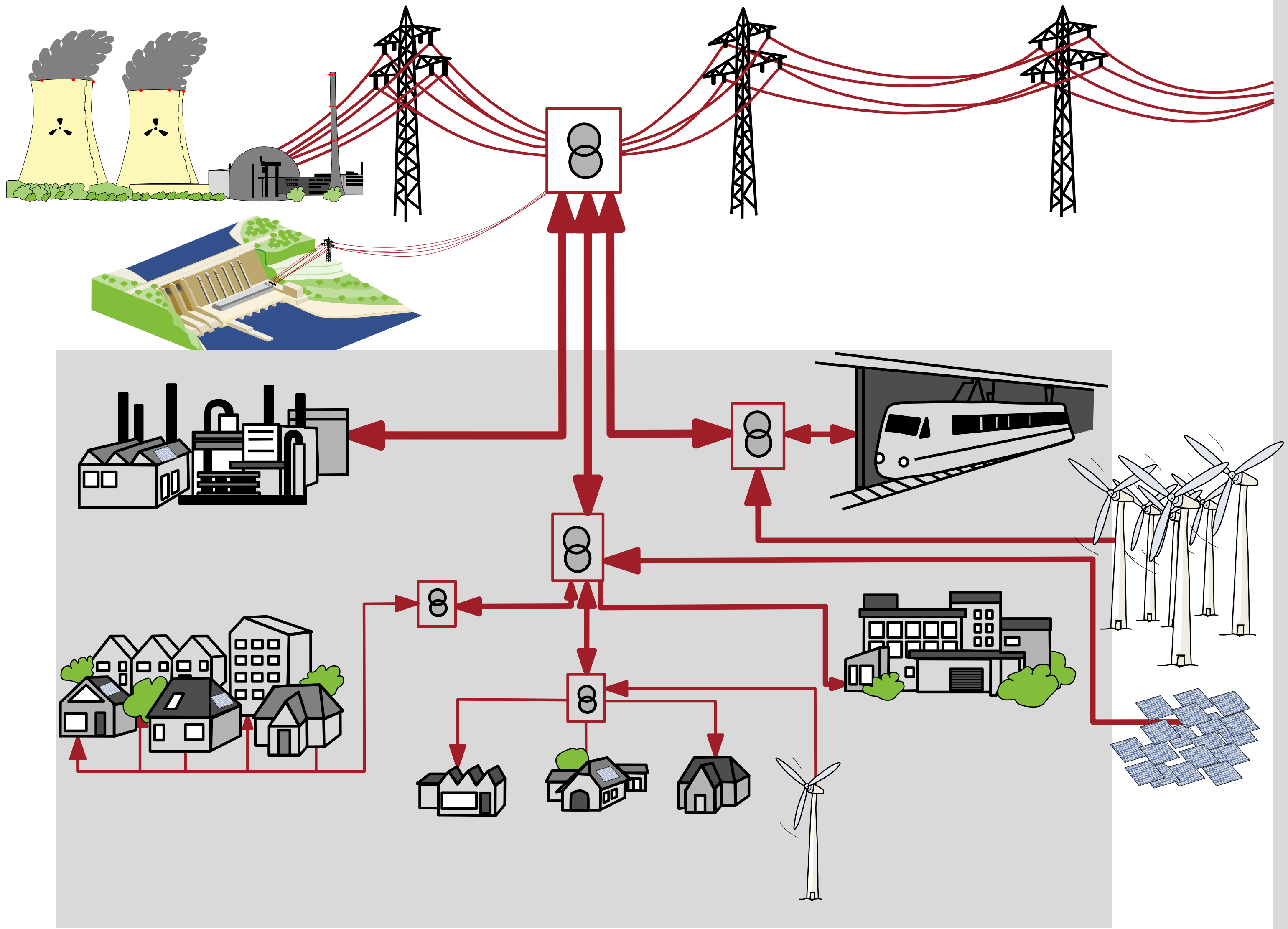


Recent Development in Power Grids

PRODUCER

POWER GRID

PROSUMER



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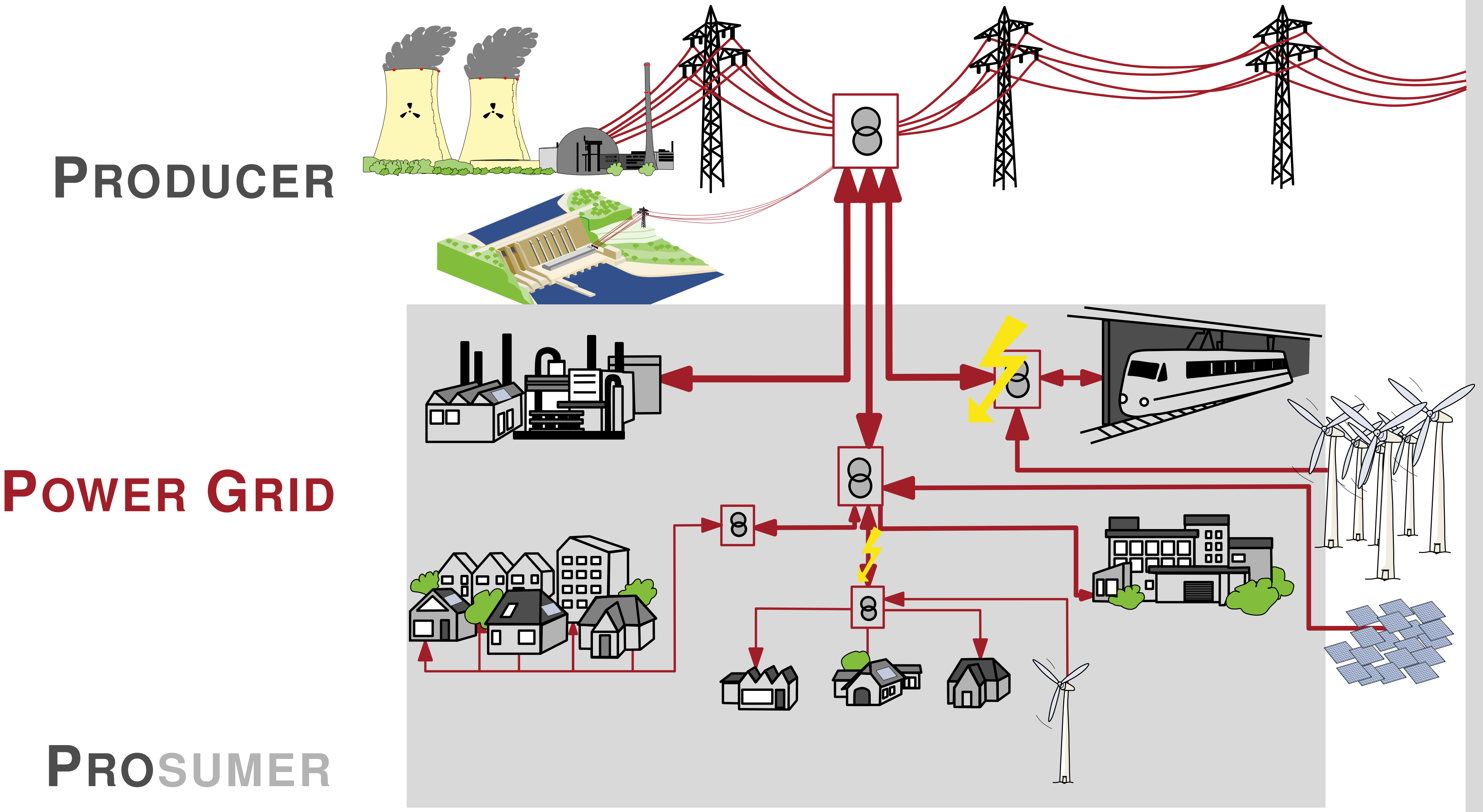
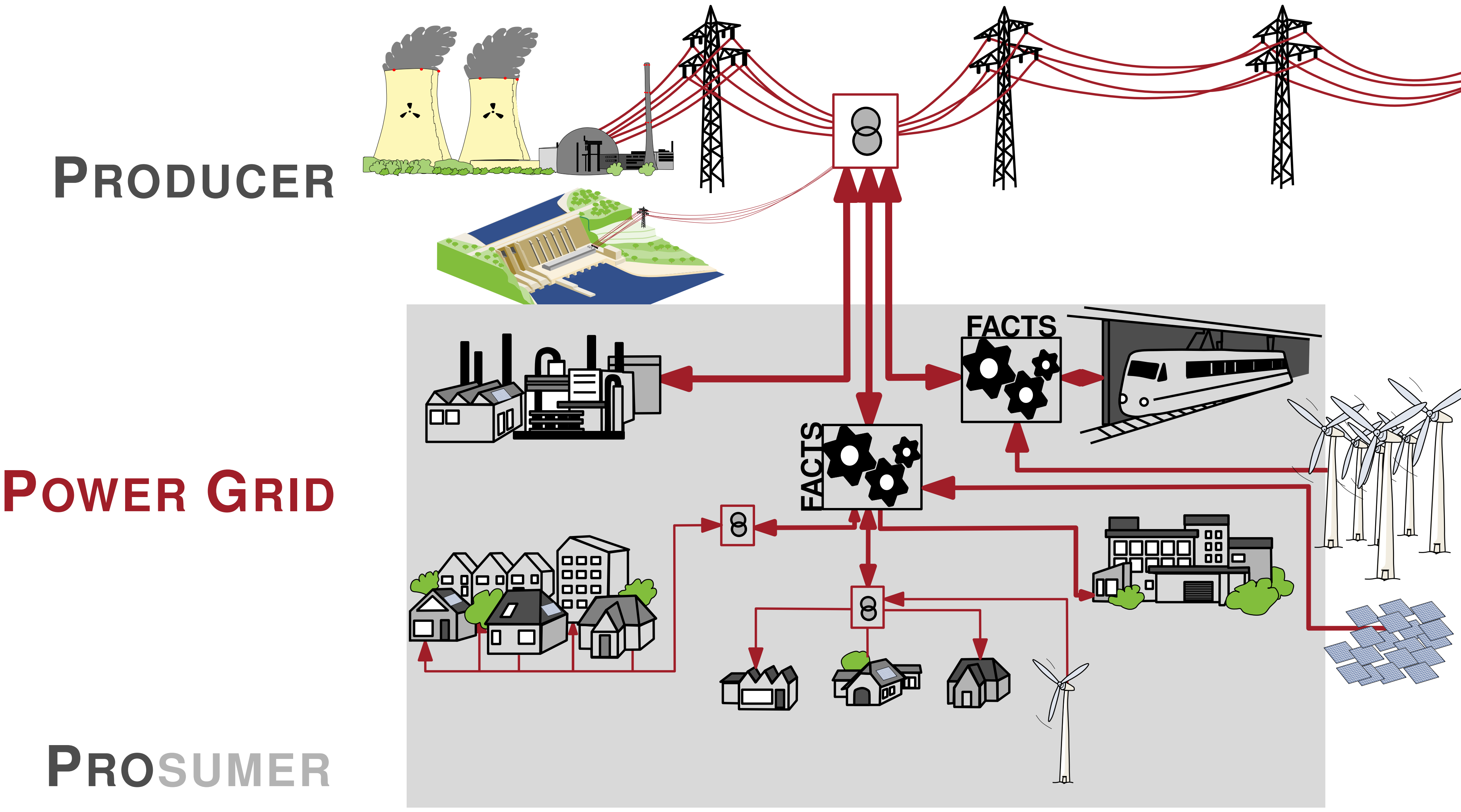
Recent Development in Power Grids



Recent Development in Power Grids



Motivation

Challenges

- Increasingly distributed energy production
- Independent power producers
- Volatile power flows and flow directions

⇒ Operating the power grid gets more demanding

Strategies to cope with the challenges

- Network expansion
- Investment in advanced control units (e.g. FACTS) for better utilization of existing grid

Problem of Power Grid Operator

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Given:

- Power grid with parameters

Find:

- Valid operation point (respecting thermal branch limits) for power grid with control units at selected branches
- Energy production of each power generator

Goals:

- Minimize production cost (similar to OPF)
- Minimize branch losses

} operation cost

How may we simplify the power grid operator's work?

Problem of Power Grid Operator

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} operation cost

How may we simplify the power grid operator's work?

$\Rightarrow$ Place FACTS to enhance controllability.

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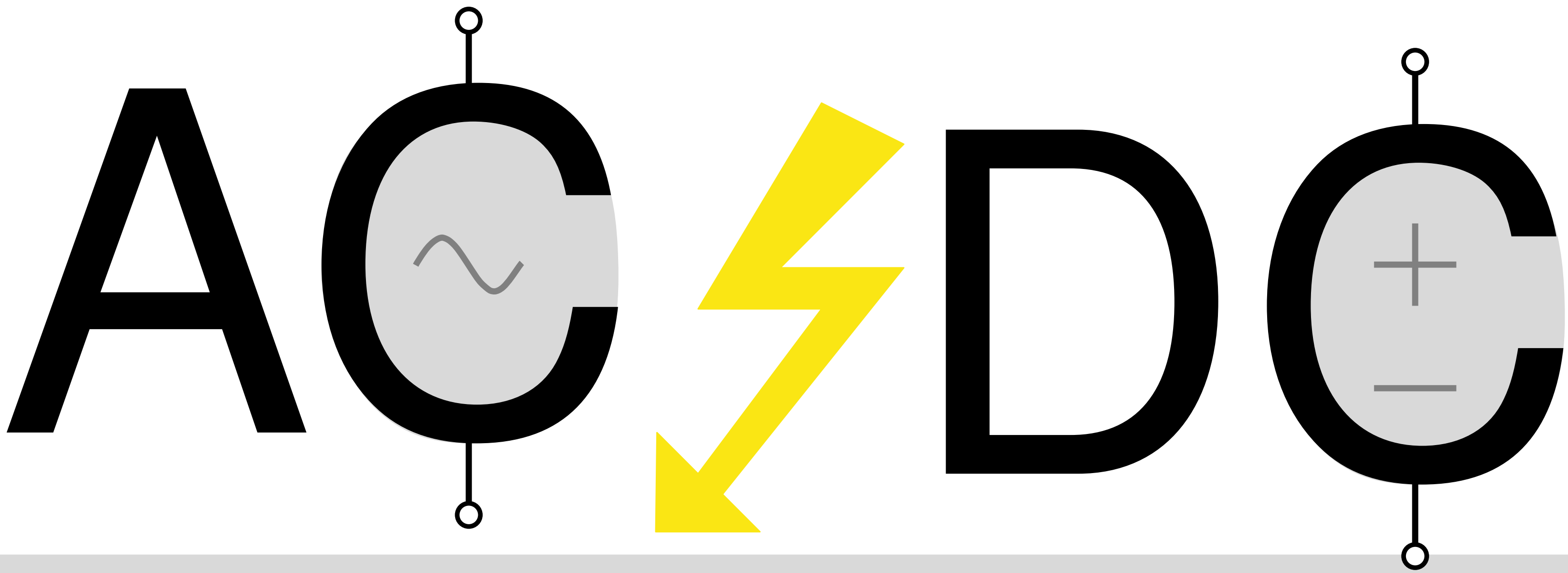
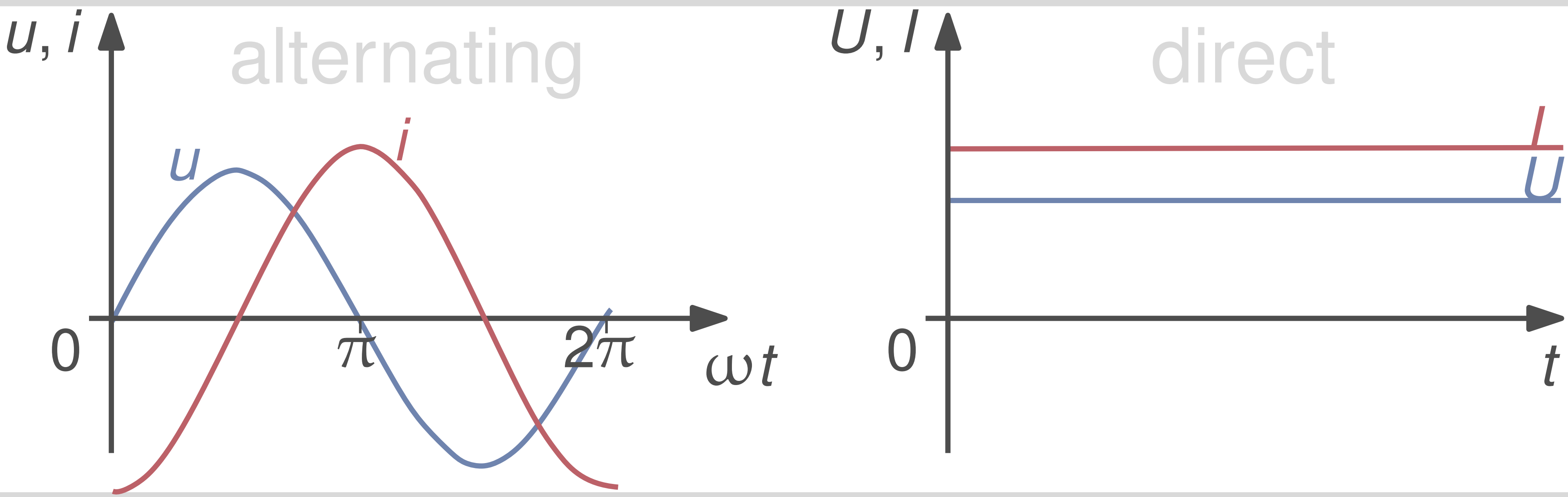


DC-based Flow Models



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Graph Model

Straight-forward transformation:

- Power grid $\rightarrow$ graph $G = (V, E)$

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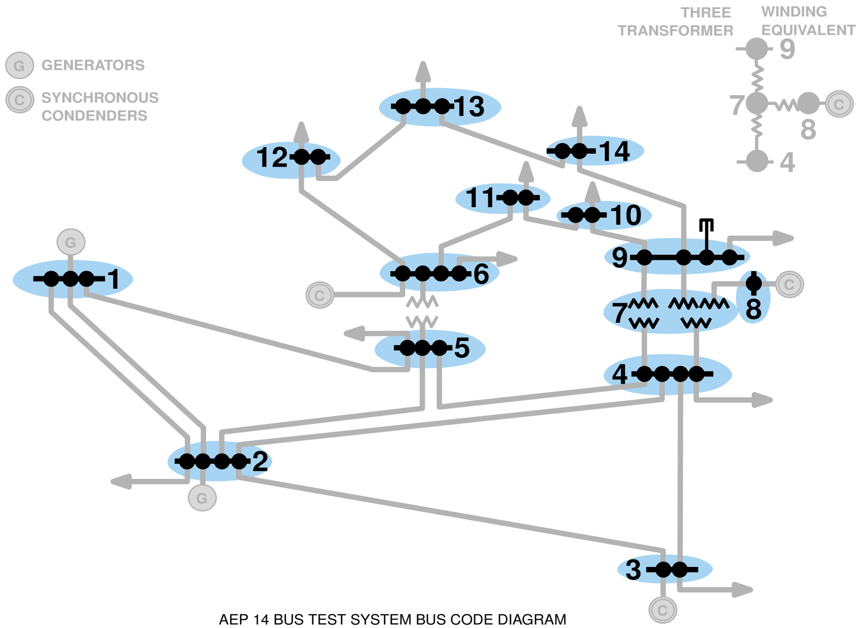
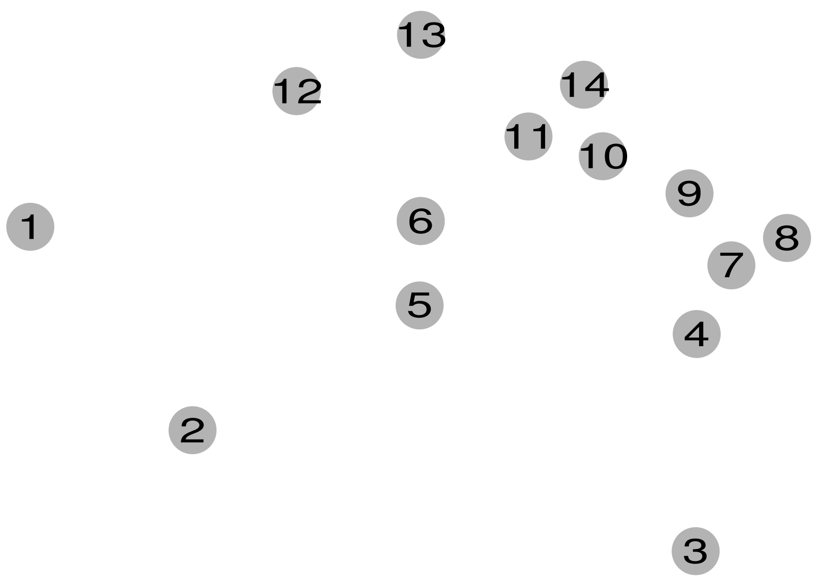
Graph Model

Straight-forward transformation:

- Power grid $\rightarrow$ graph $G = (V, E)$
- Buses $\rightarrow$ vertex set V



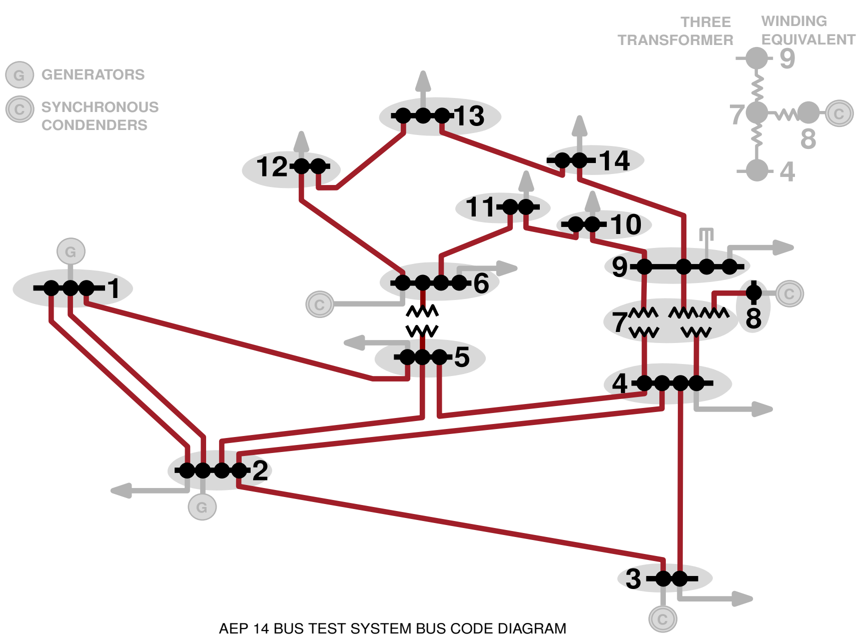
AEP 14 BUS TEST SYSTEM BUS CODE DIAGRAM



Graph Model

Straight-forward transformation:

- Power grid $\rightarrow$ graph $G = (V, E)$
- Buses $\rightarrow$ vertex set V
- Branches $\rightarrow$ edge set E with capacity function $c(e)$



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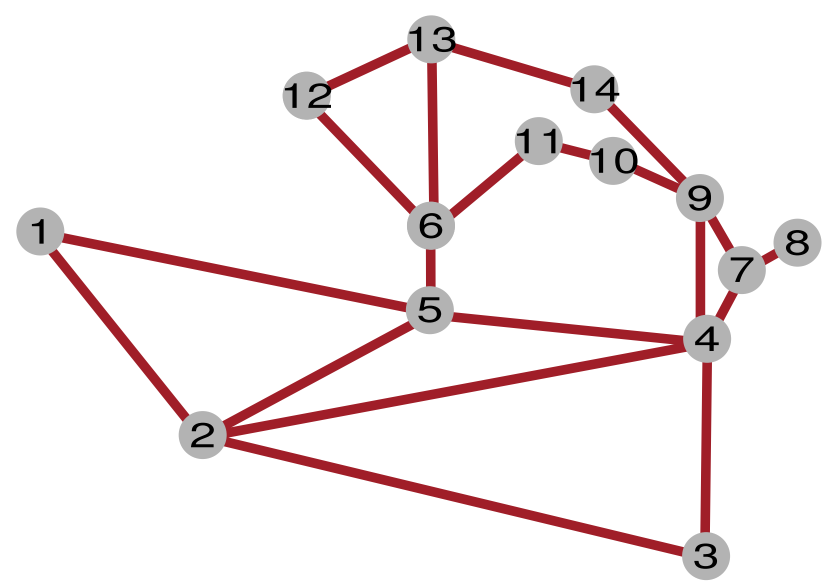

Graph Model

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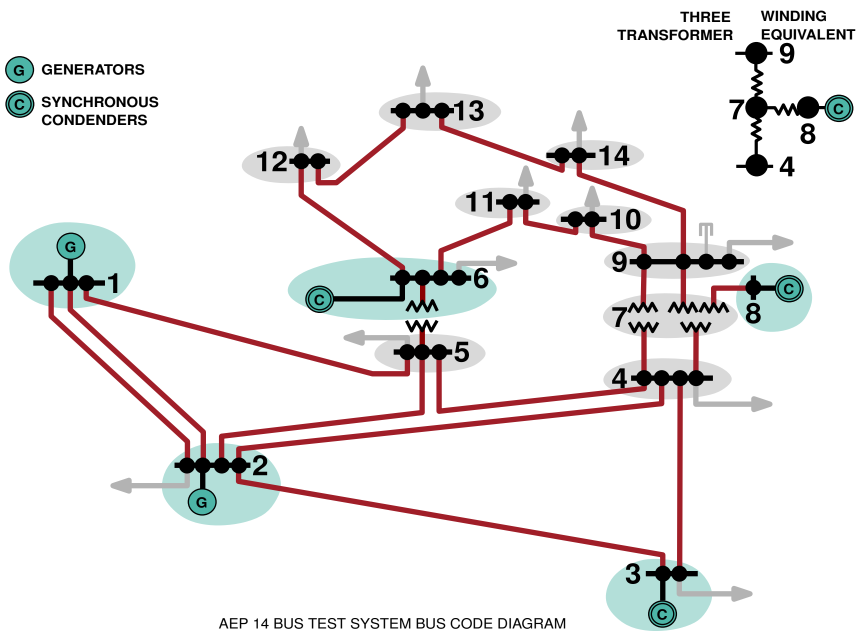

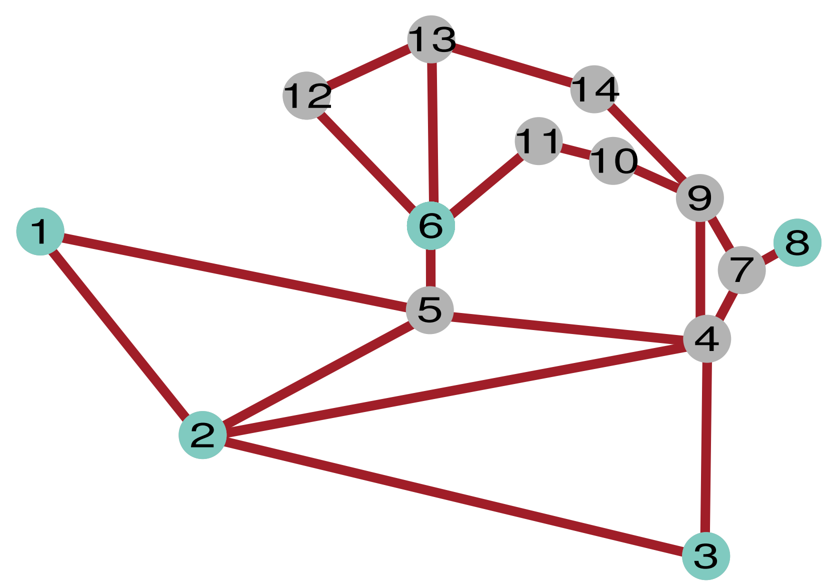

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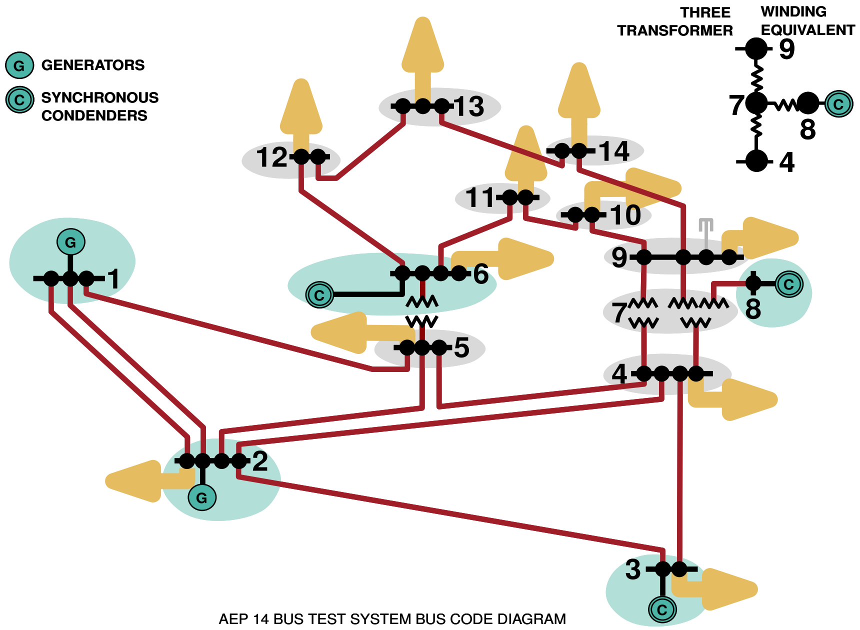
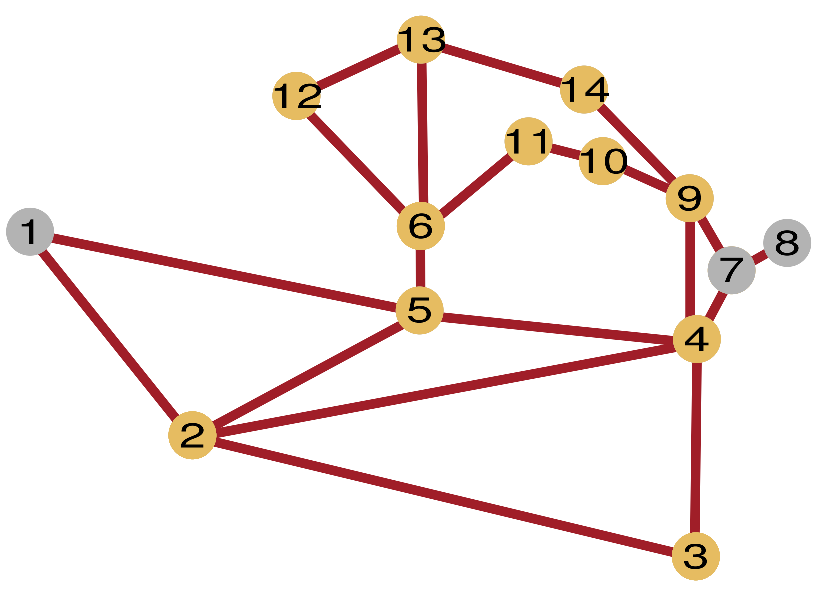
- Load $\rightarrow$ set $V_L \subseteq V$ of load buses





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Hybrid Flow Model

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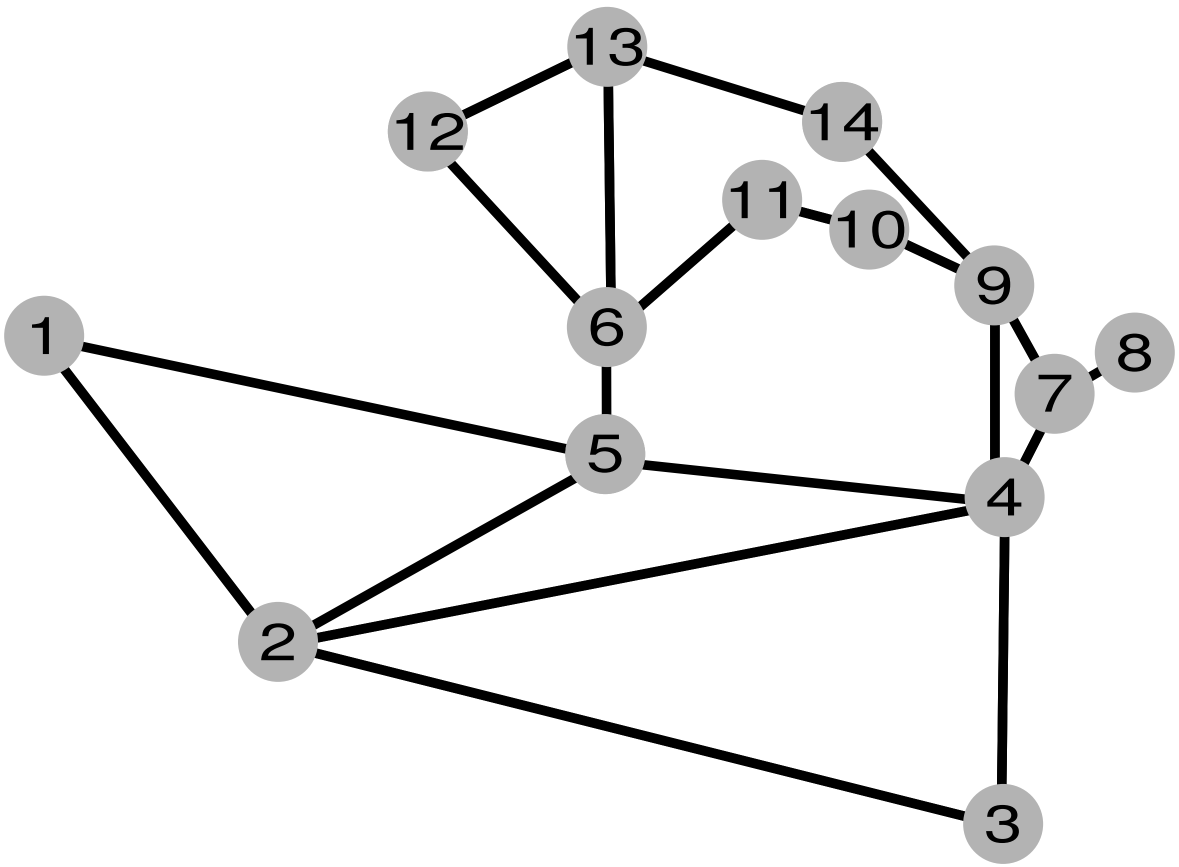

Kirchhoff's circuit laws:

Kirchhoff's current law ✓

Kirchhoff's voltage law ✓

Physical Model
(as a DC approximation)

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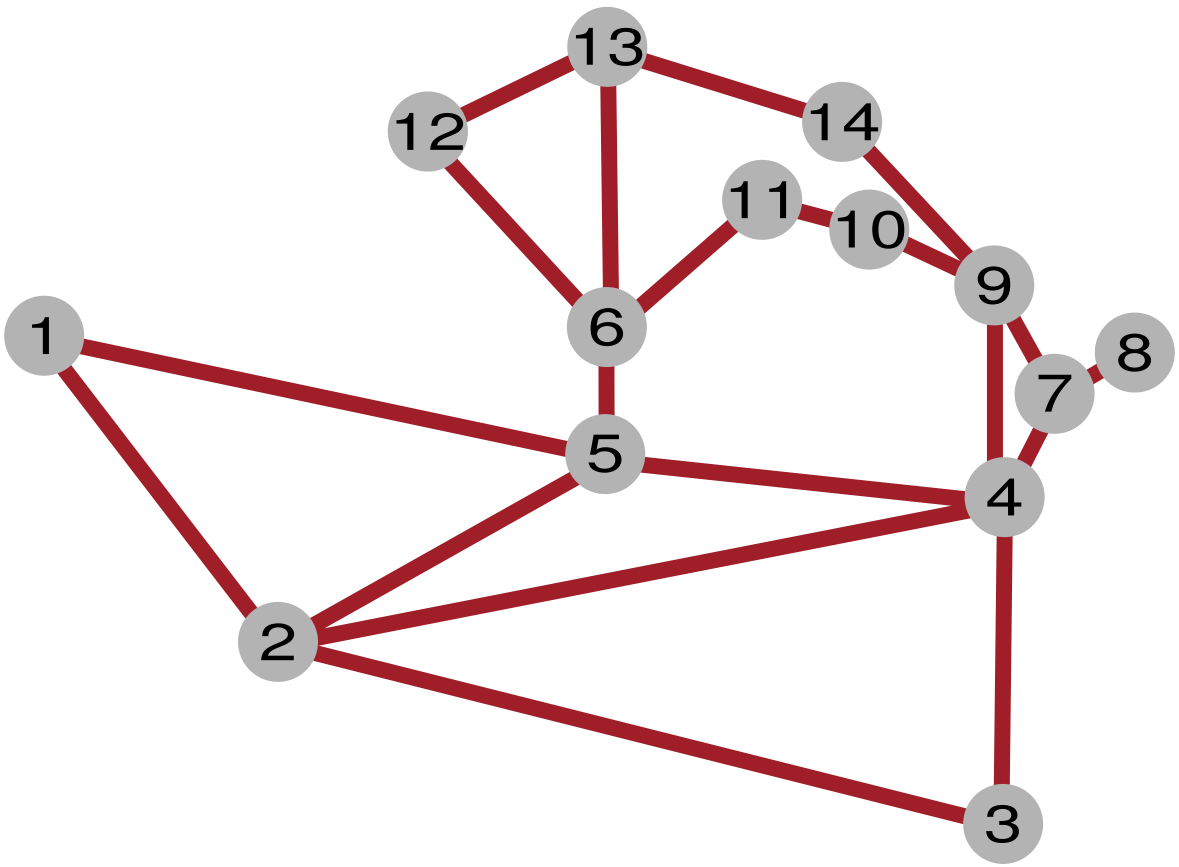
Hybrid Flow Model



control unit

Kirchhoff's circuit laws:

Kirchhoff's current law

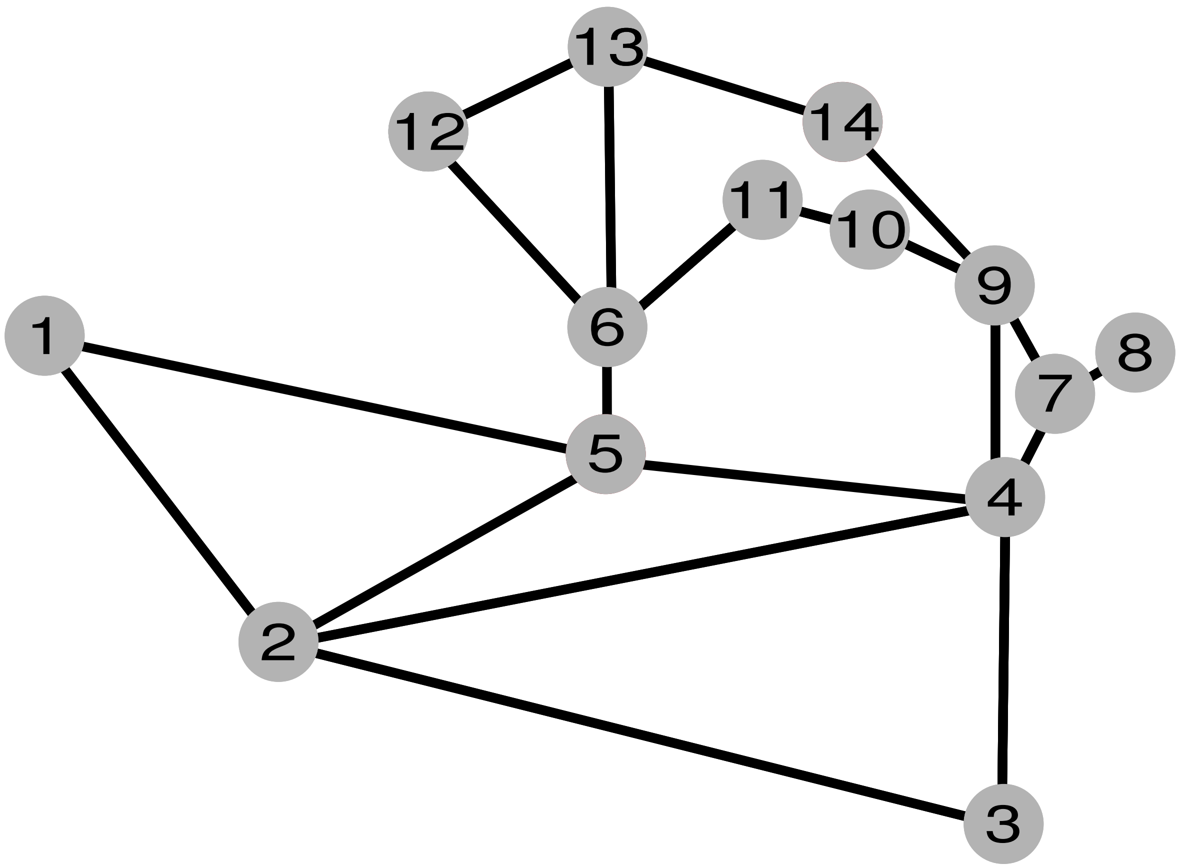
Kirchhoff's voltage law

Kirchhoff's current law ✓

Kirchhoff's voltage law ✗

Flow Model

Hybrid Flow Model



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Kirchhoff's current law

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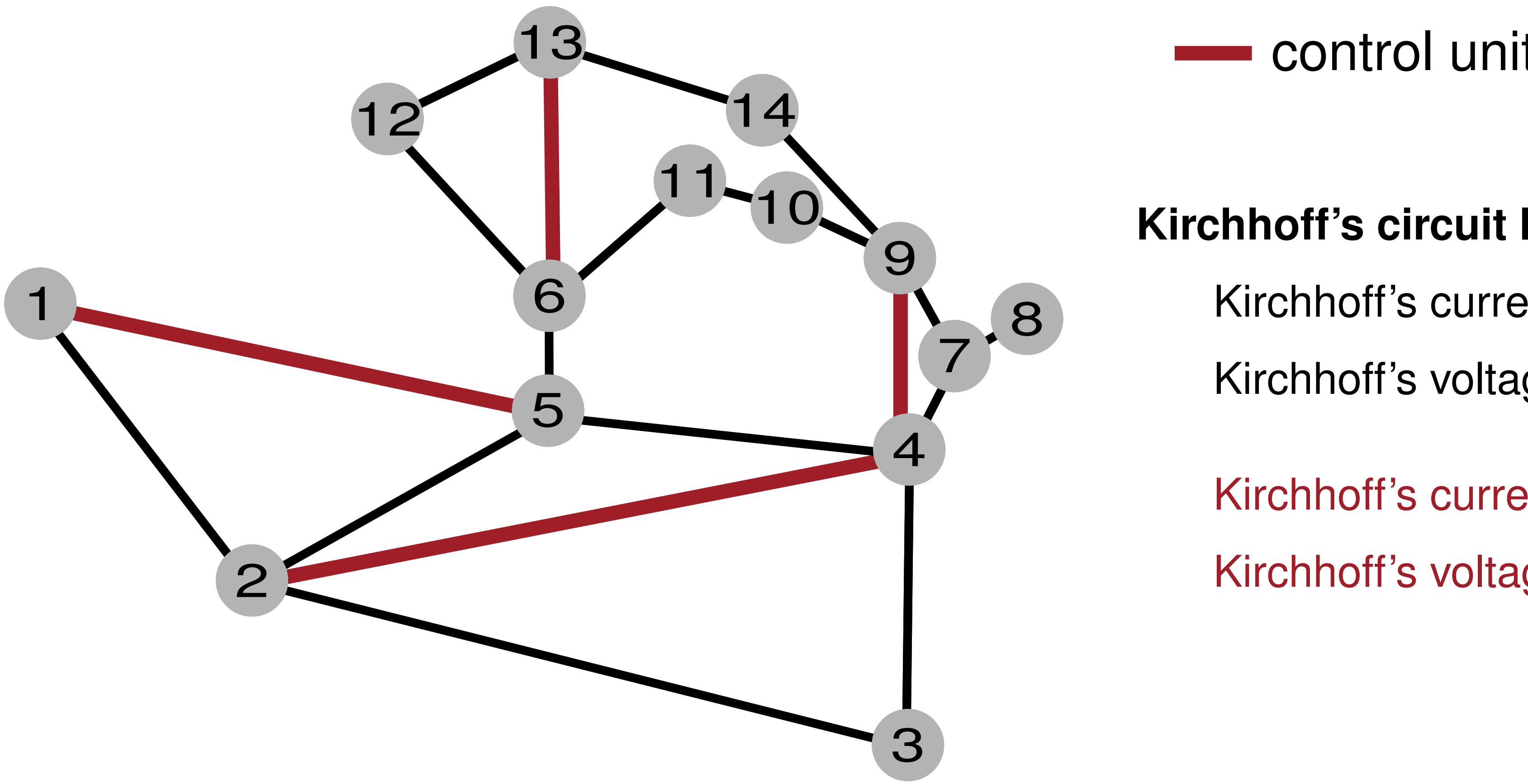
Hybrid Model = Flow Model + Physical Model

Hybrid Flow Model



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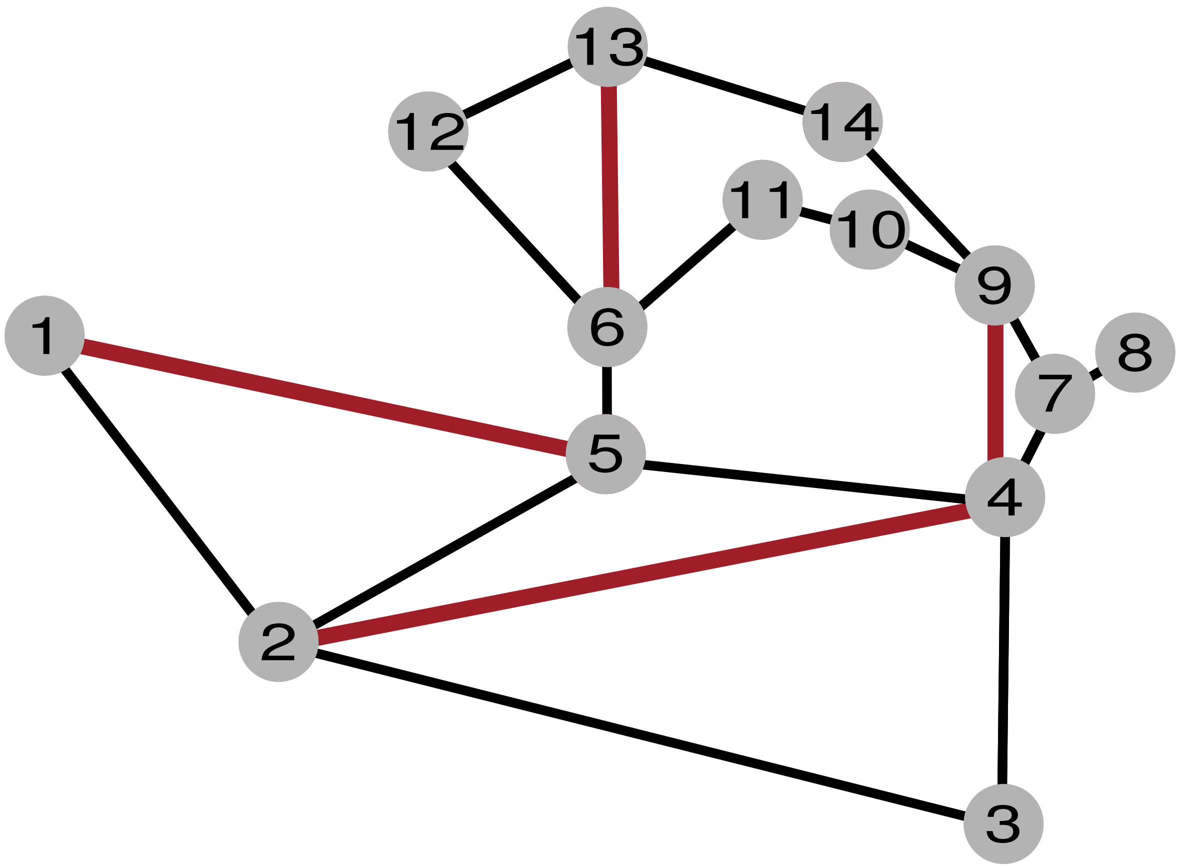
Hybrid Model = Flow Model + Physical Model

Hybrid Flow Model



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Hybrid Model = Flow Model + Physical Model

$\Downarrow$

Lower Bound

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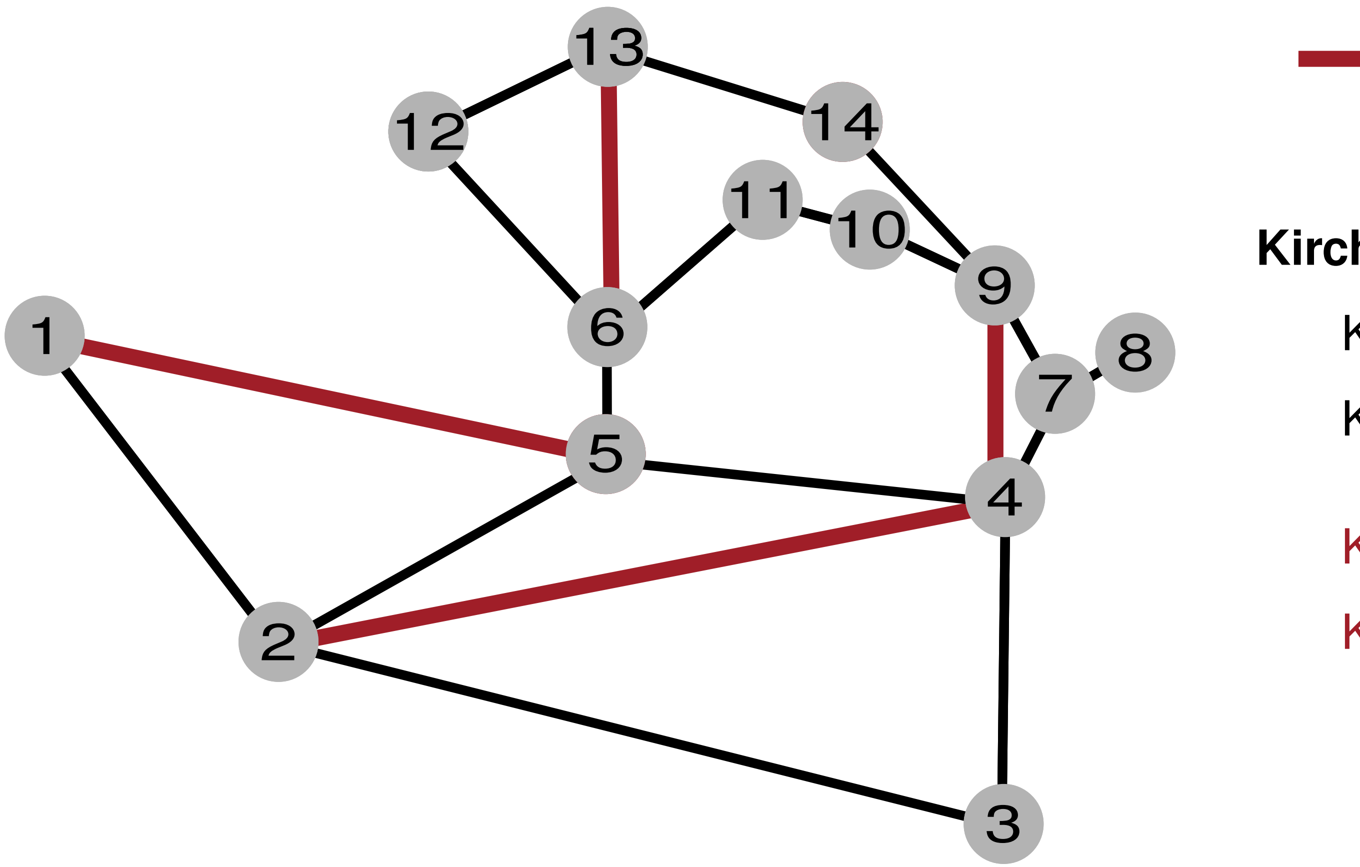
Hybrid Flow Model



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Kirchhoff's current law ✓

Kirchhoff's voltage law ✗

Hybrid Model = Flow Model + Physical Model

⇓ Lower Bound ⇓ Upper Bound

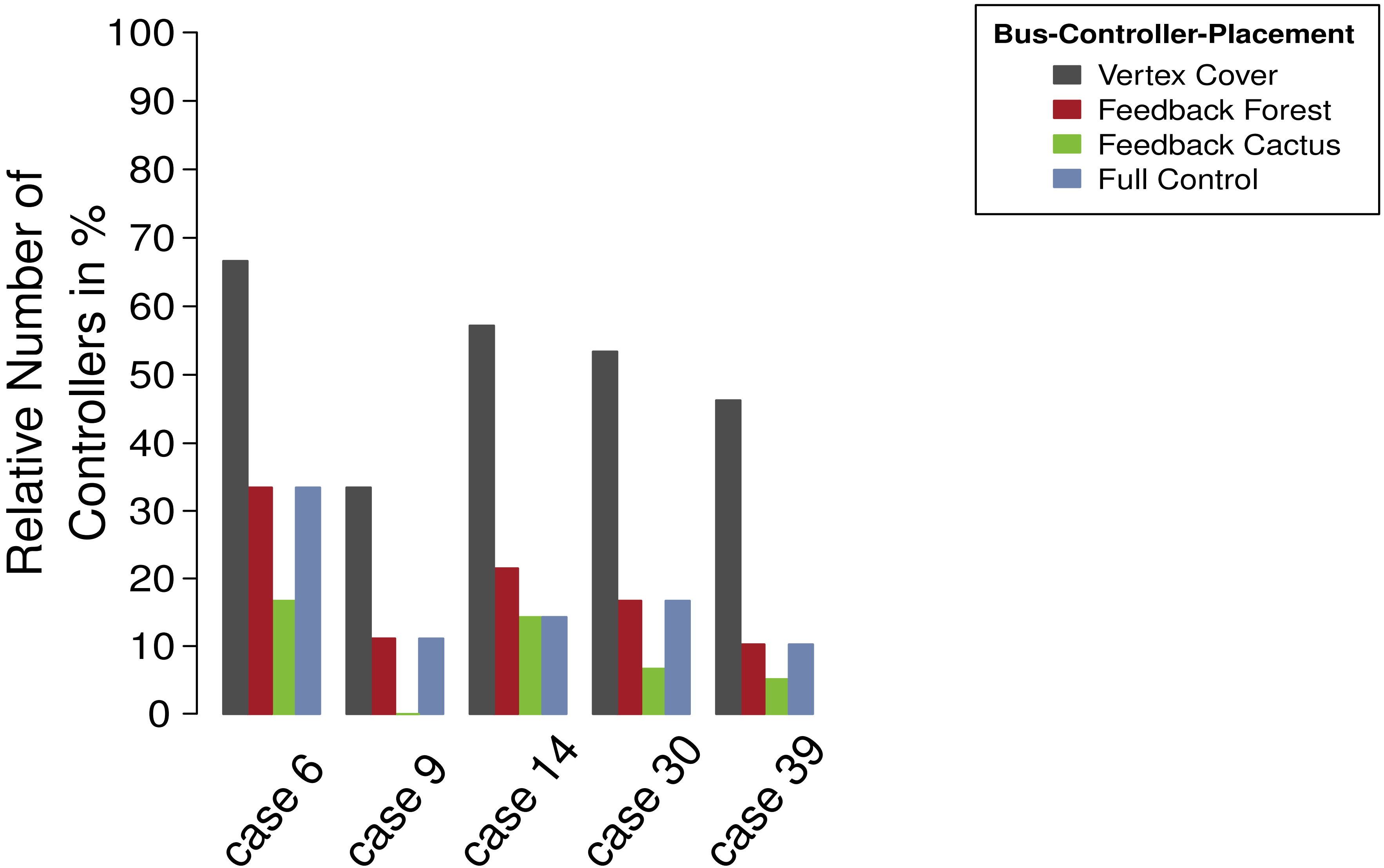
Research Questions

Control units are expensive – how many do we need?

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

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

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



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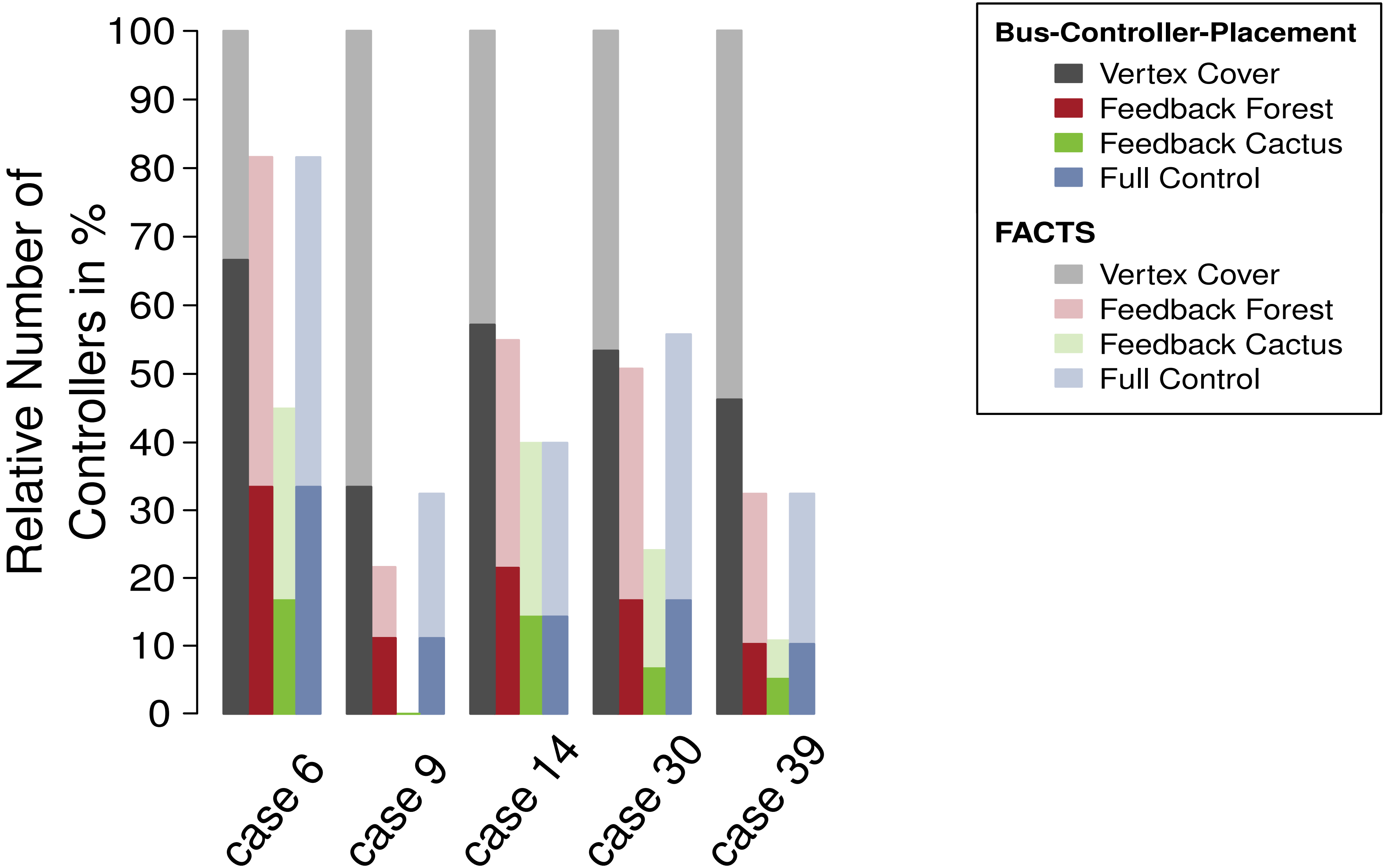
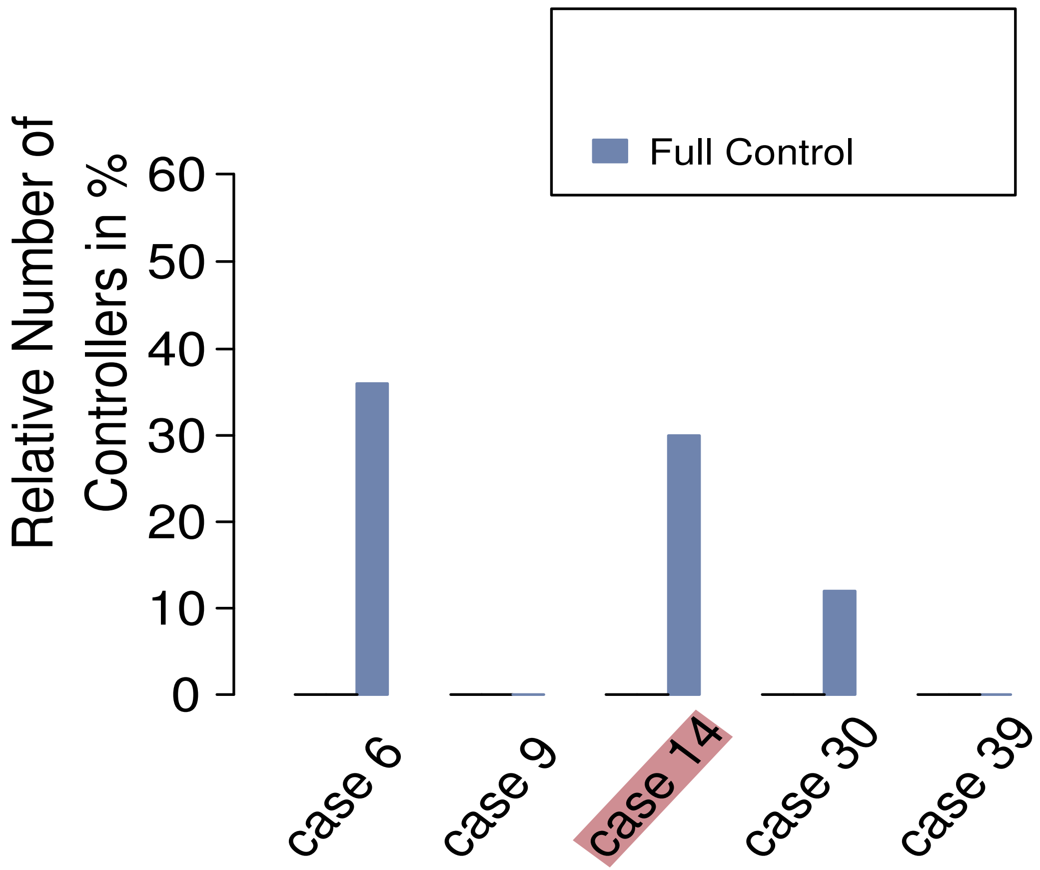


Number of Control Branches



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

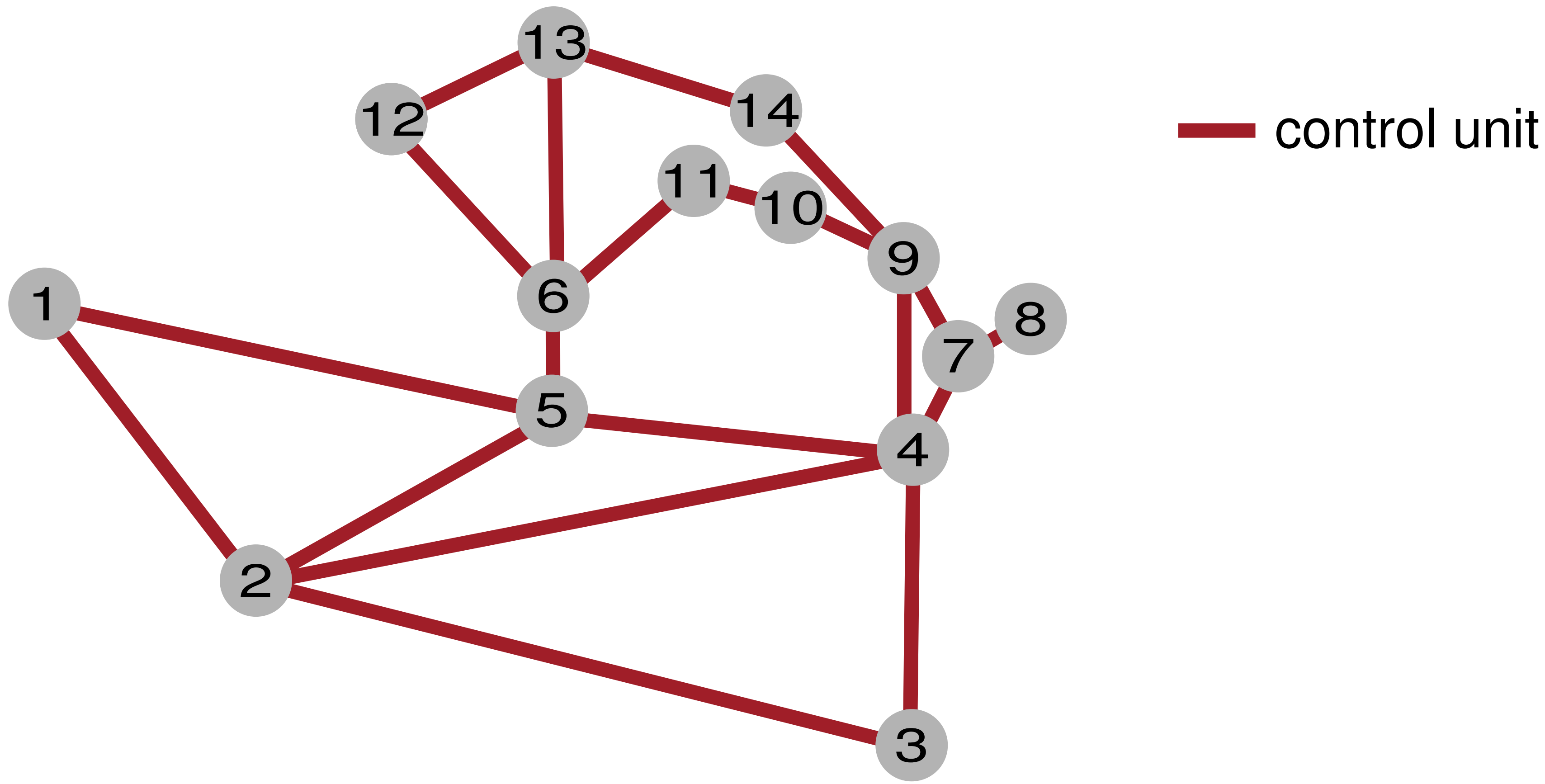


Matching the Flow Model (Q1)

- How many flow control branches are necessary to obtain globally optimal power flows and which branches need to be controlled?

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

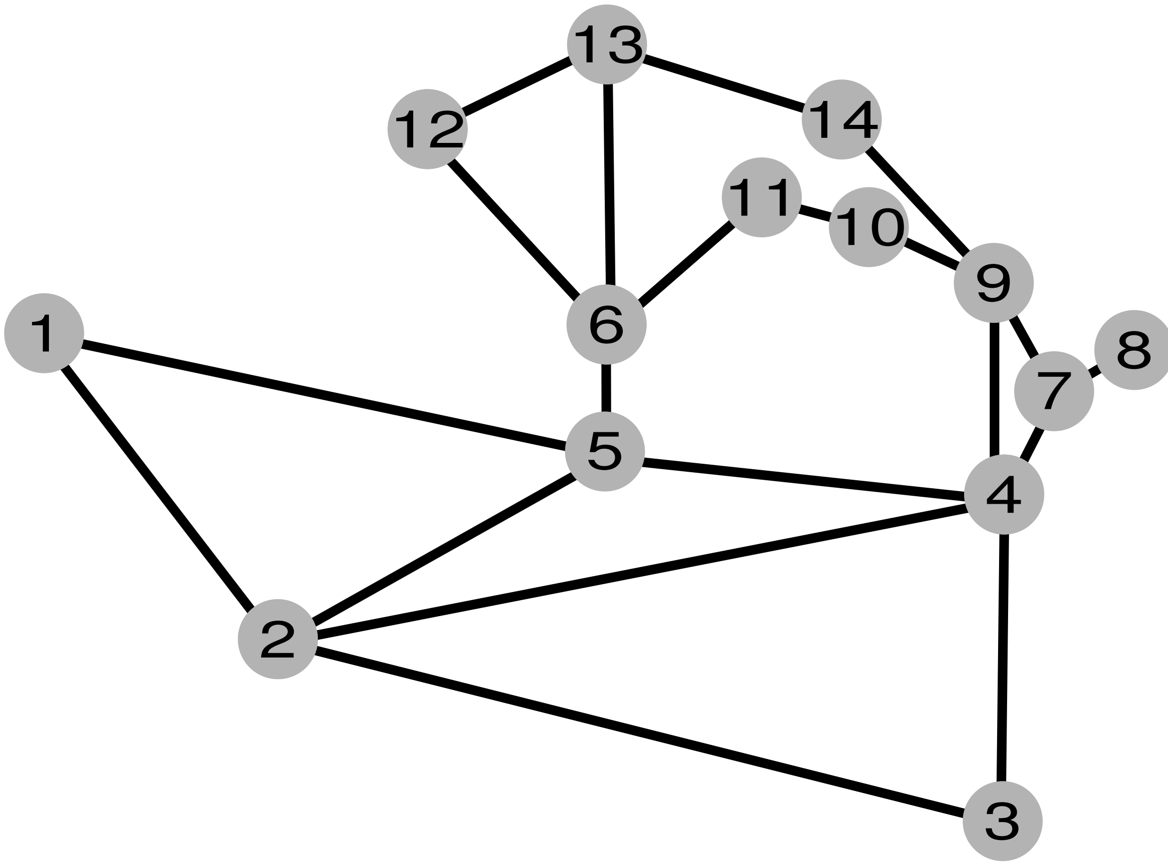
Globally Optimal Power Flows



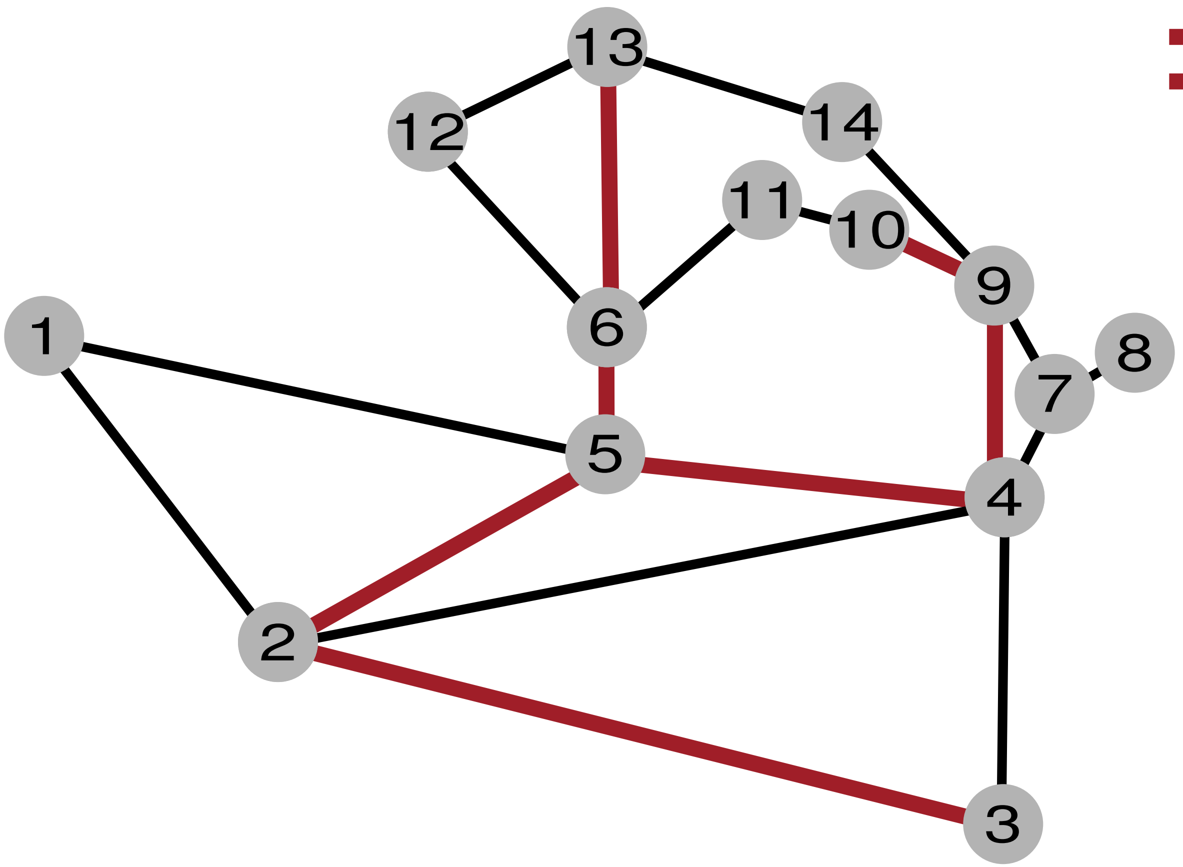
Can we become as good as the Flow Model
with fewer control branches?

Feedback Forest Set

feedback forest set



Feedback Forest Set

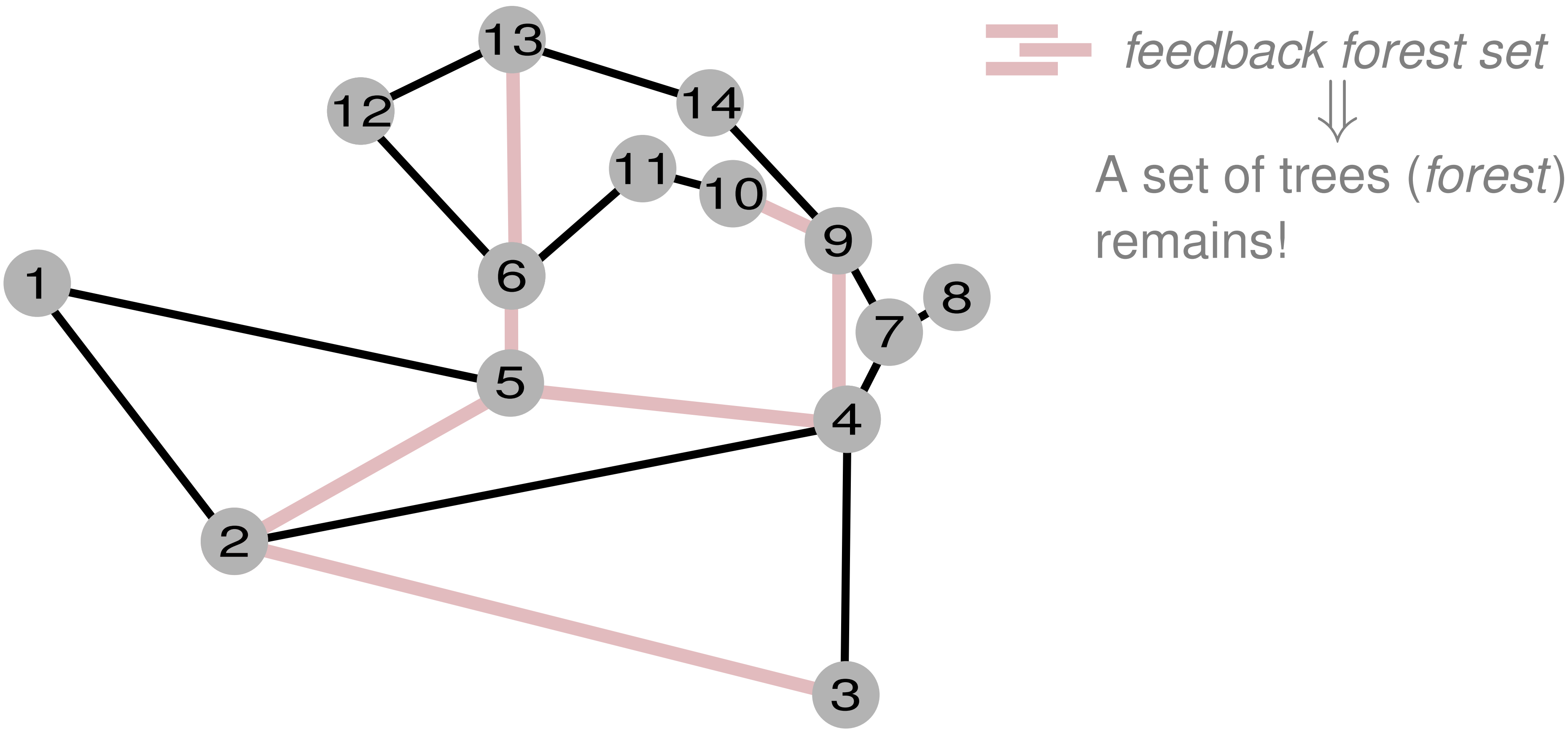


feedback forest set

⇓

A set of trees (*forest*) remains!

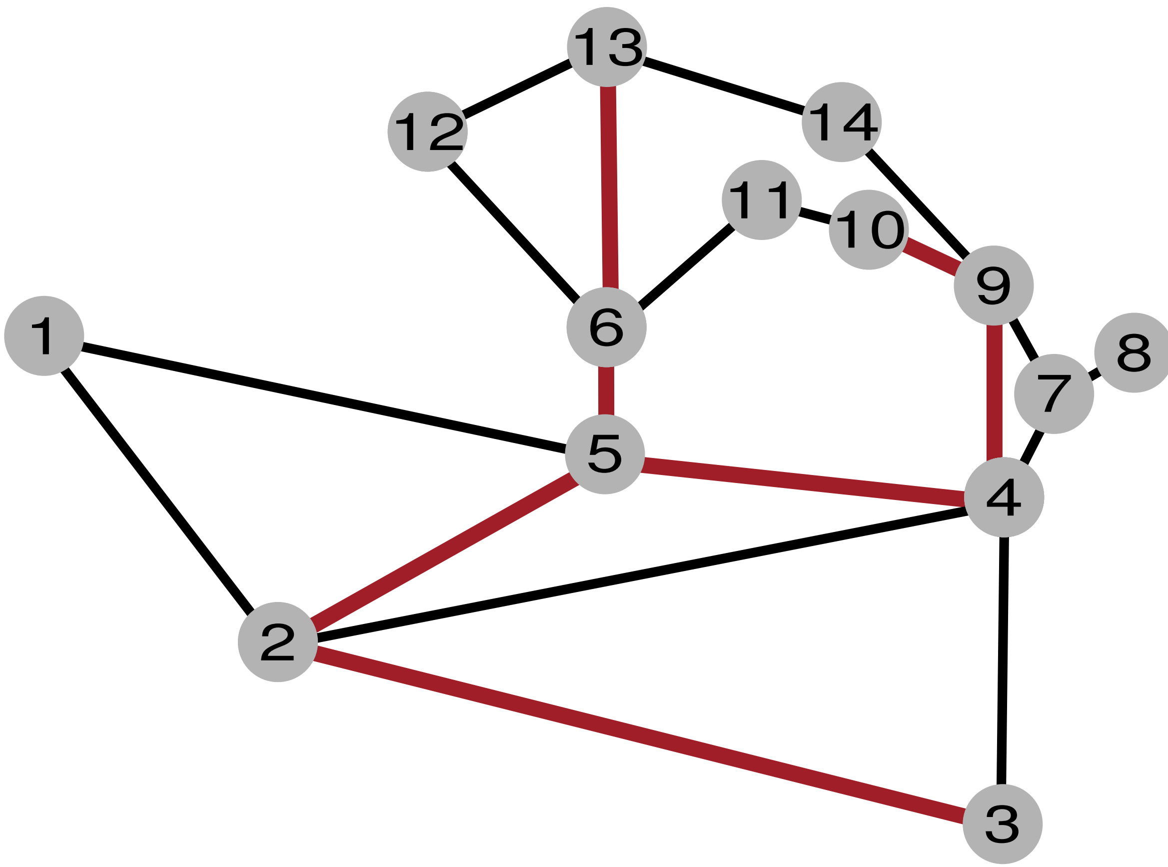
Feedback Forest Set



Theorem 1

Physical subgrid forest $\Rightarrow$ All flows obey voltage laws

Feedback Cactus Set



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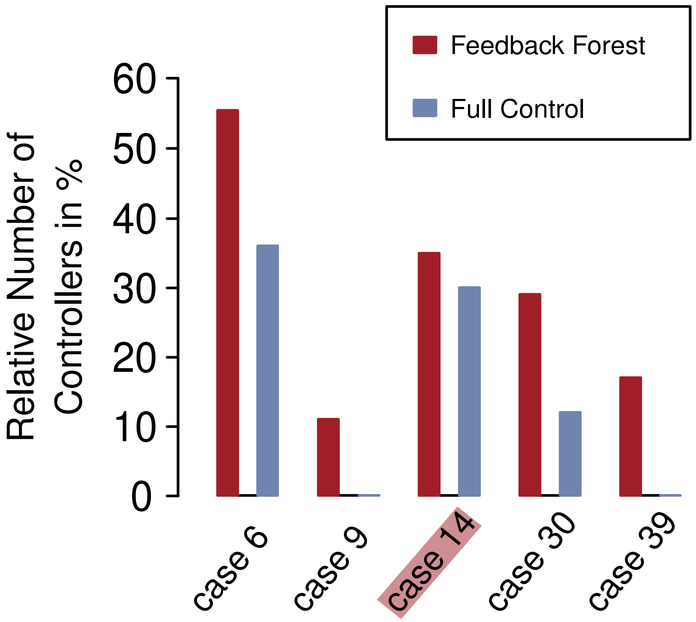
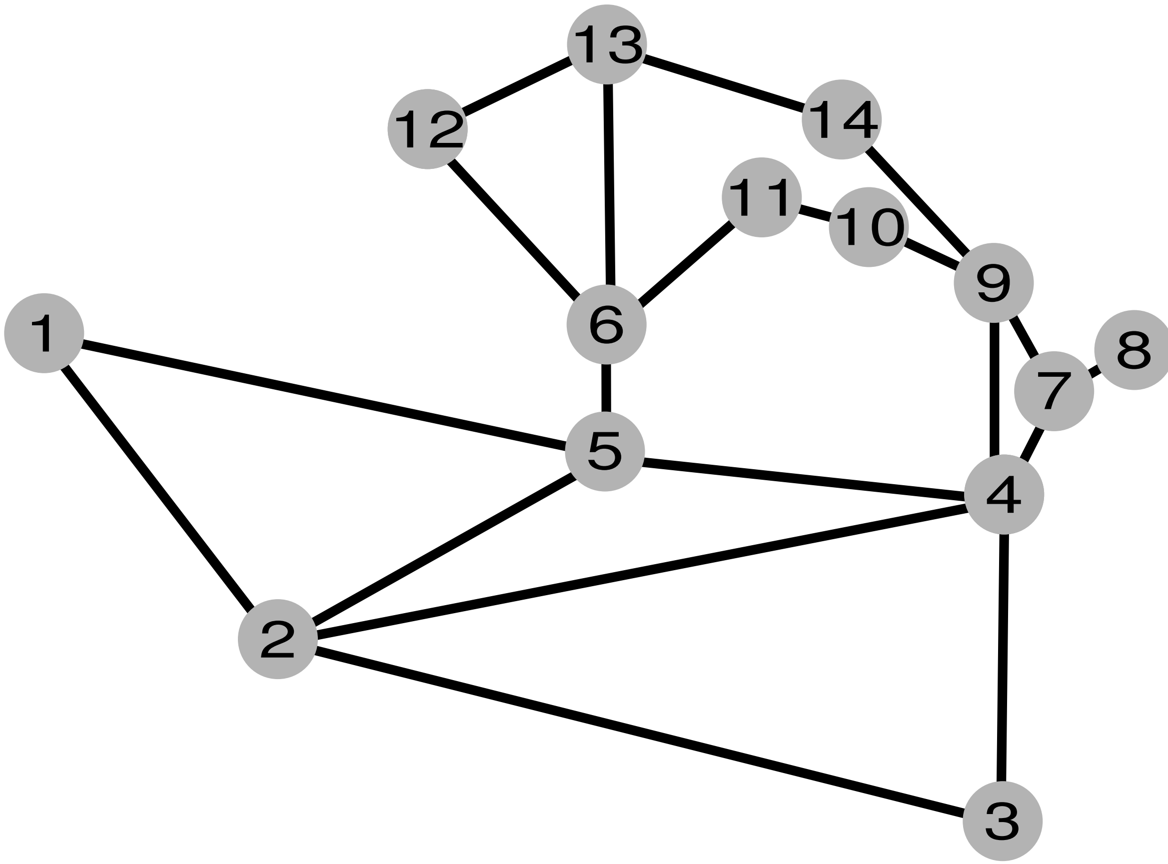


Fewer than 7 flow control buses sufficient?

Feedback Cactus Set



feedback cactus set

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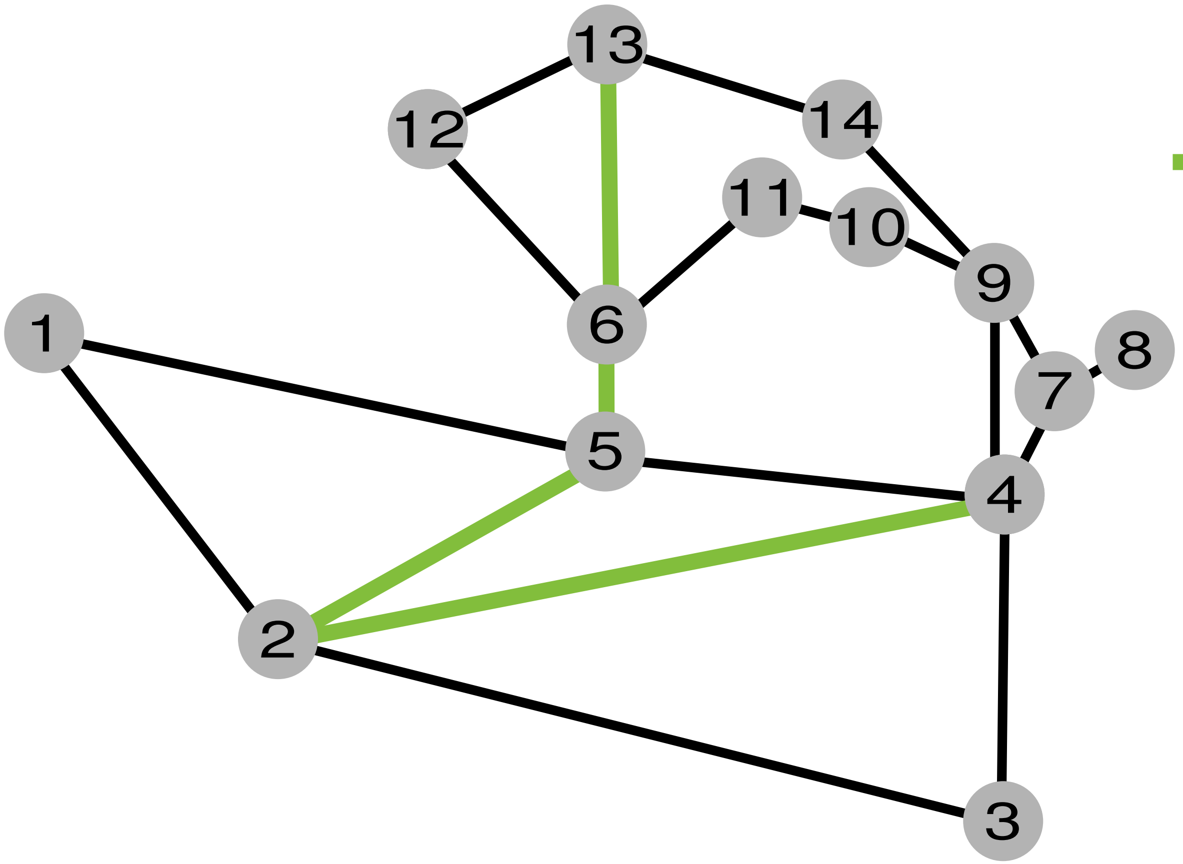
Feedback Cactus Set

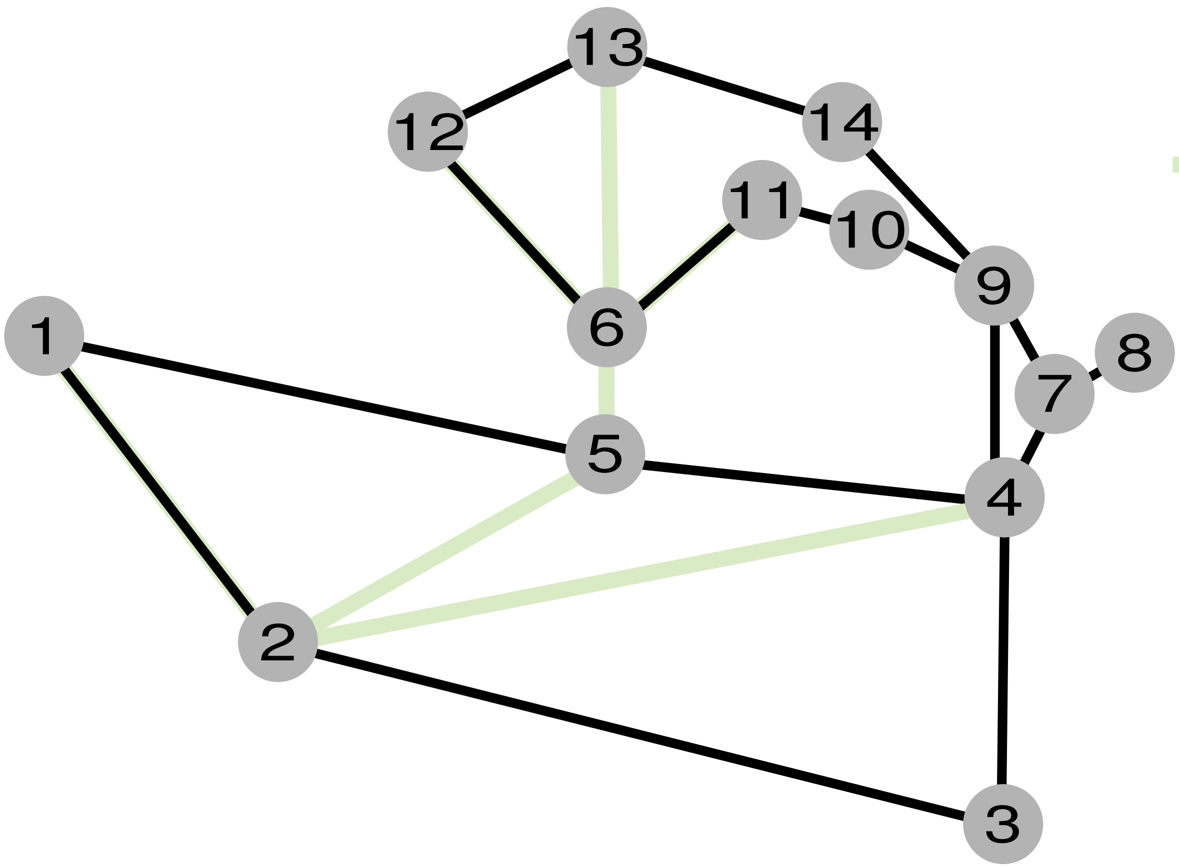


feedback cactus set

⇓

A set of *cacti* remains!

Feedback Cactus Set



feedback cactus set

⇓

A set of *cacti* remains!

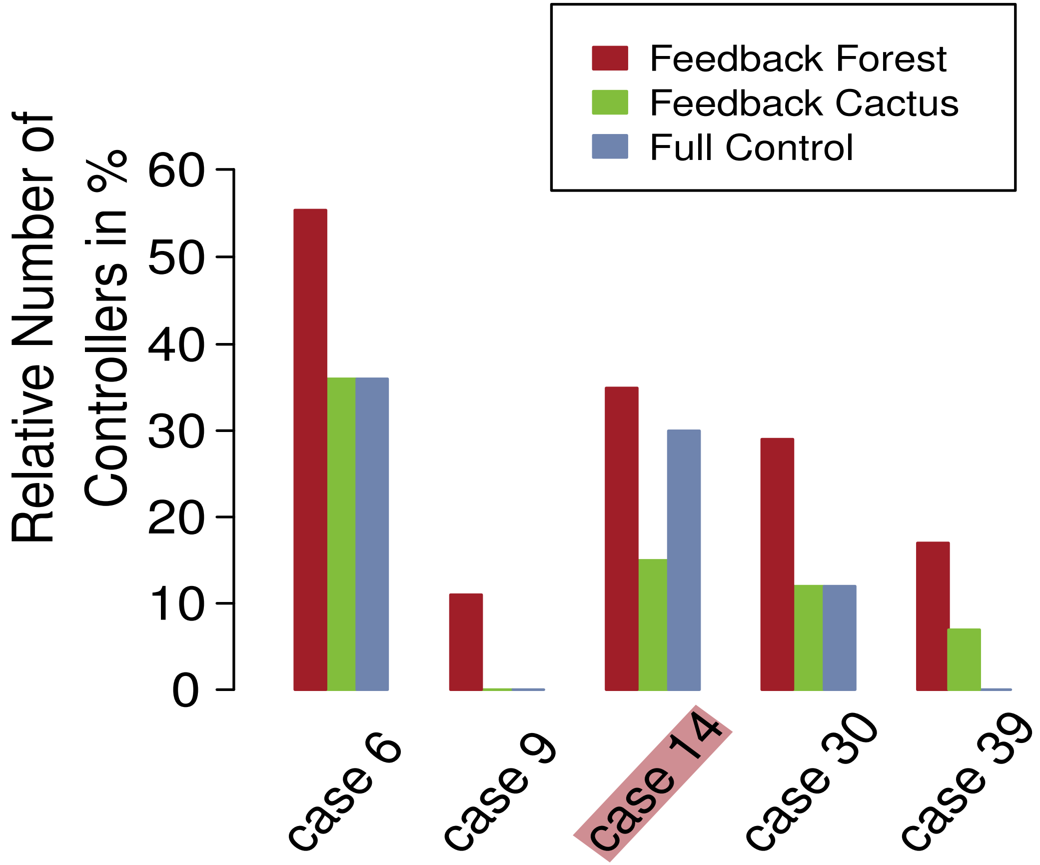
Theorem 2

Physical subgrid cactus, line limits on cactus suitably bounded.

$$\Rightarrow$$

For every flow there is a cost-equivalent flow obeying voltage laws.

Number of Control Branches vs. Structural Results



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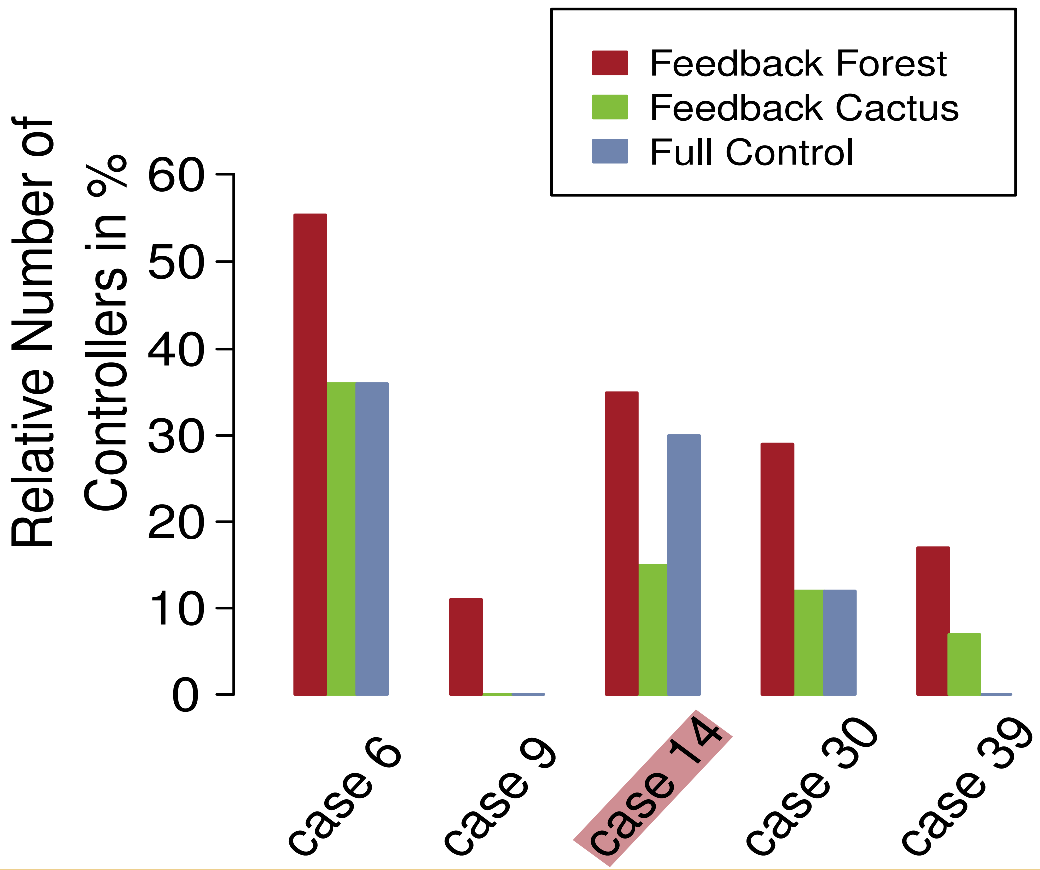
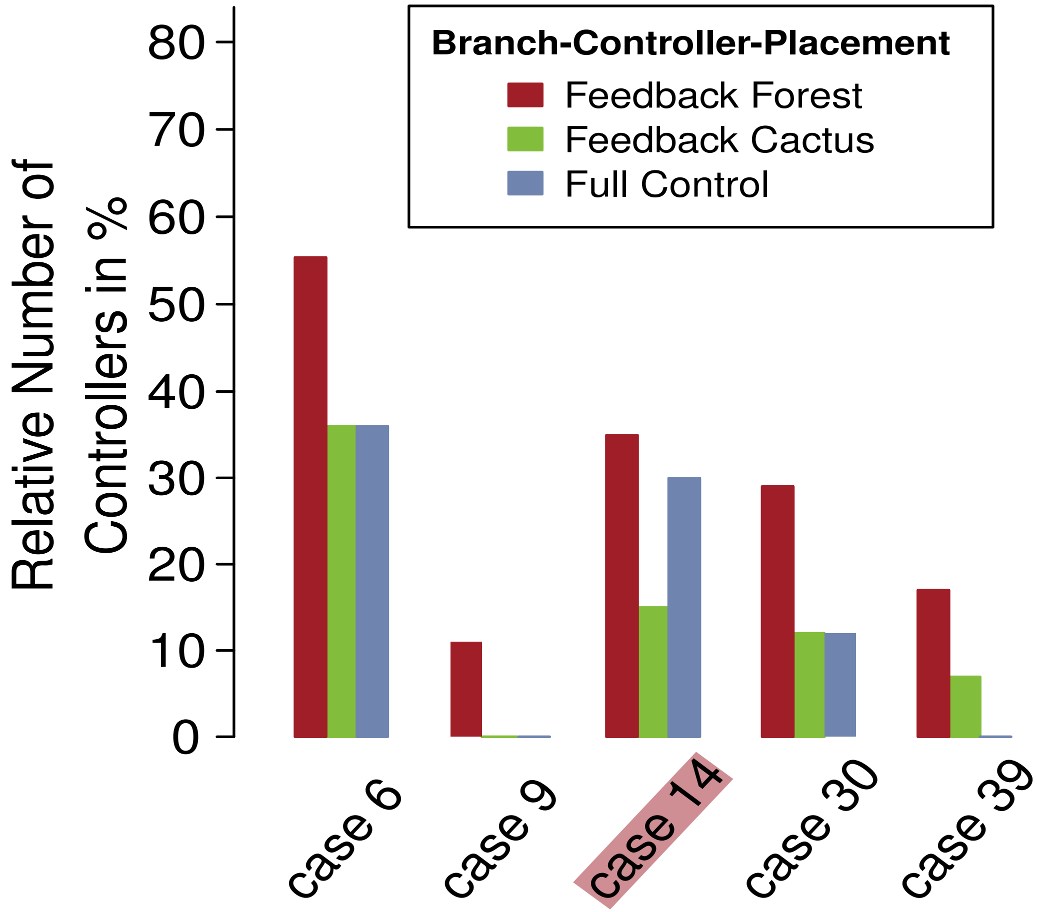


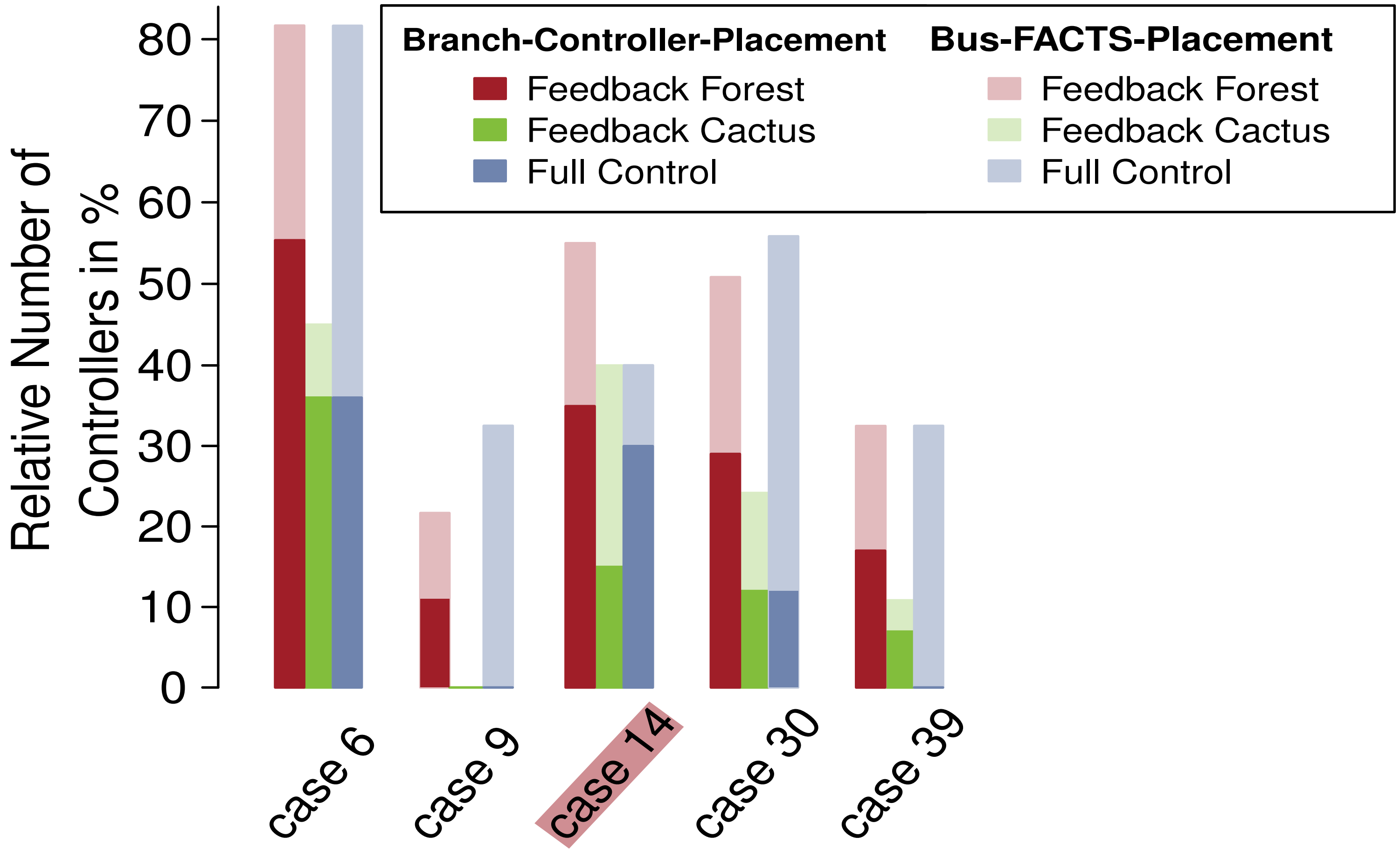
Findings

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

Control Branches vs. Control Buses



Control Branches vs. Control Buses



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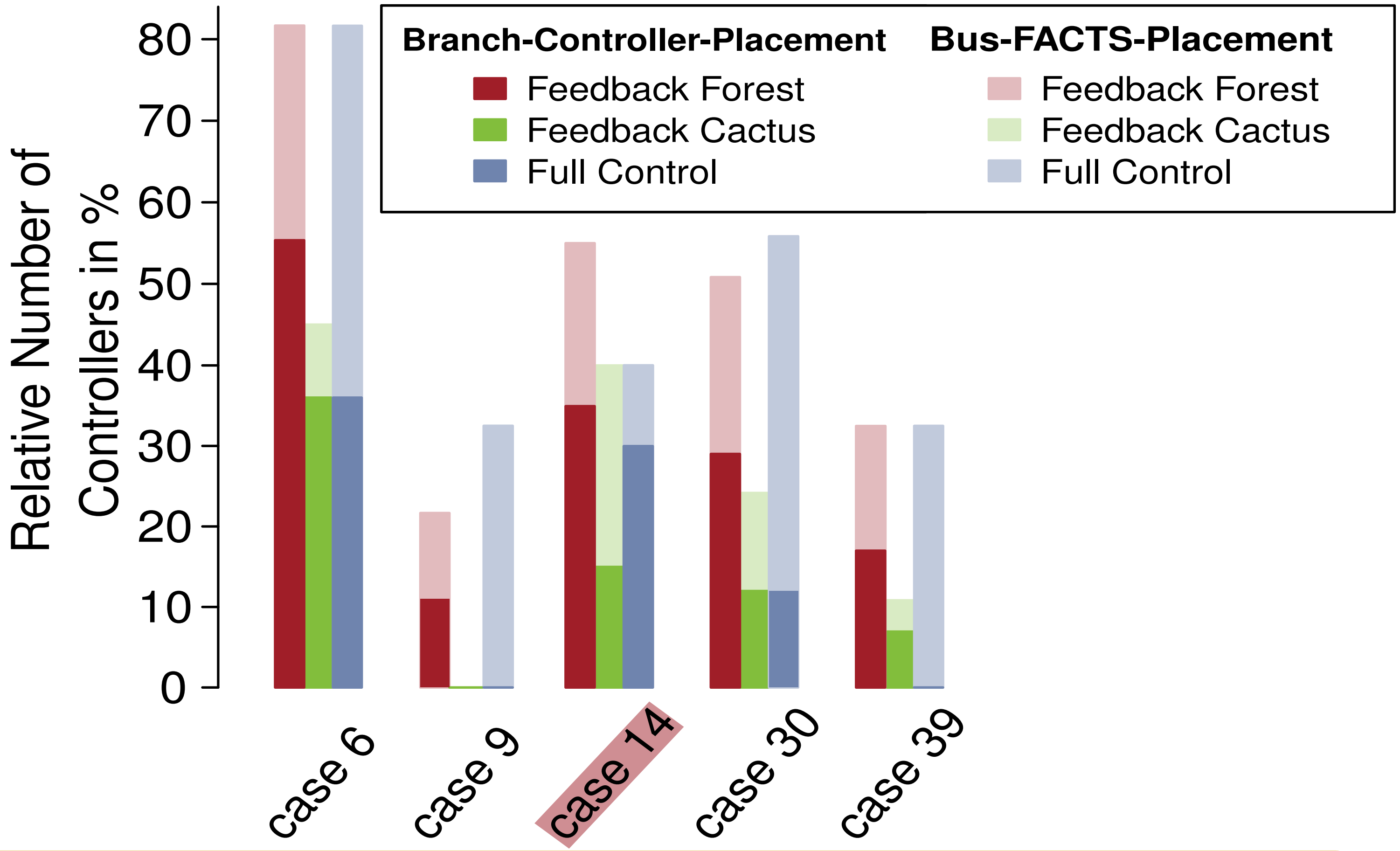
Control Branches vs. Control Buses



Findings

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

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Control Branches vs. Control Buses

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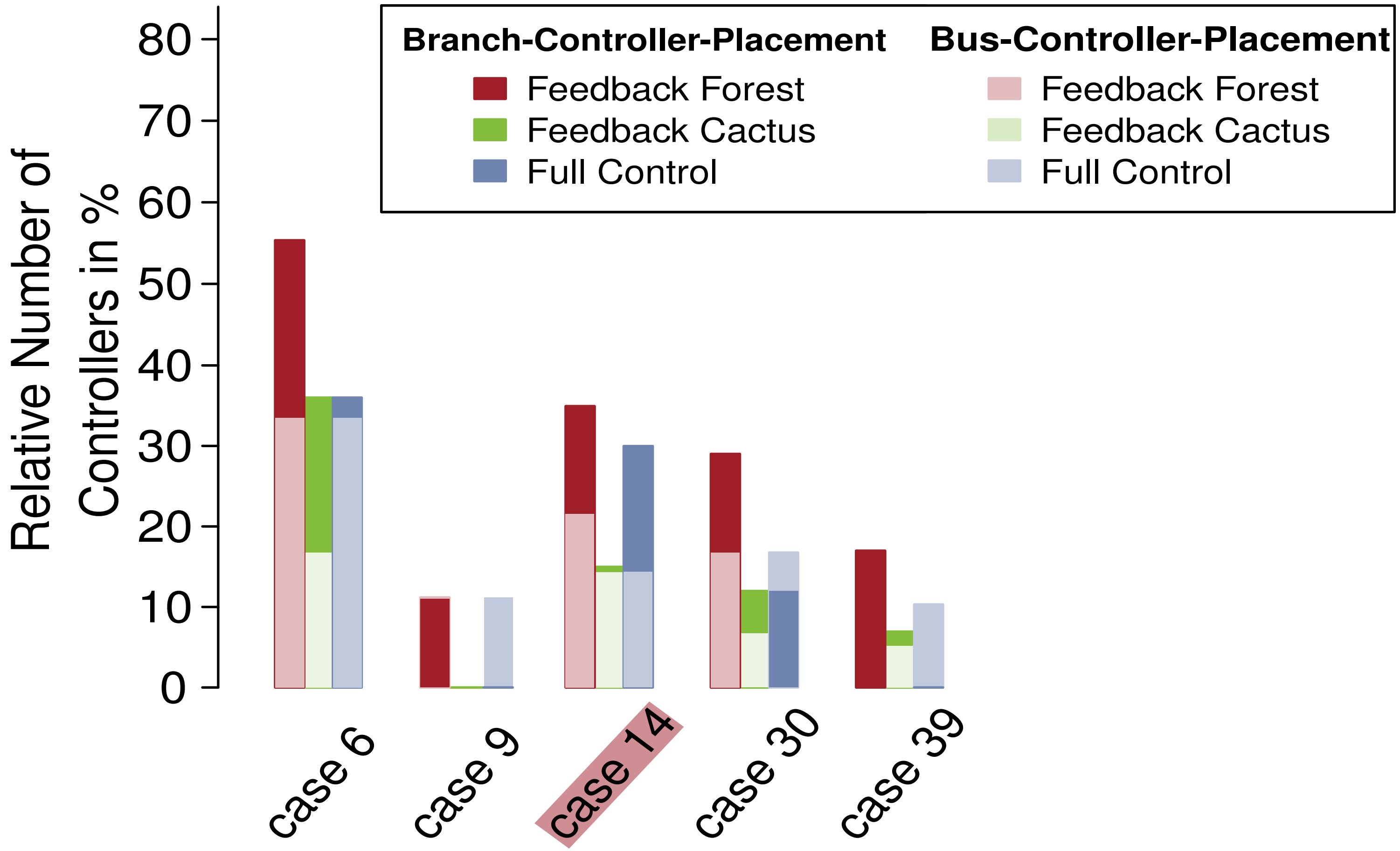

Effect of Few Flow Control Branches (Q2)

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

Figures FLTR:
[3] http://www.abb.com/cawp/seitp202/c36f4e62da52ab46c1257670003690d3.aspx
[4] http://electrical-engineering-portal.com/facts-flexible-ac-transmission-systems

Effect of Few Flow Control Branches

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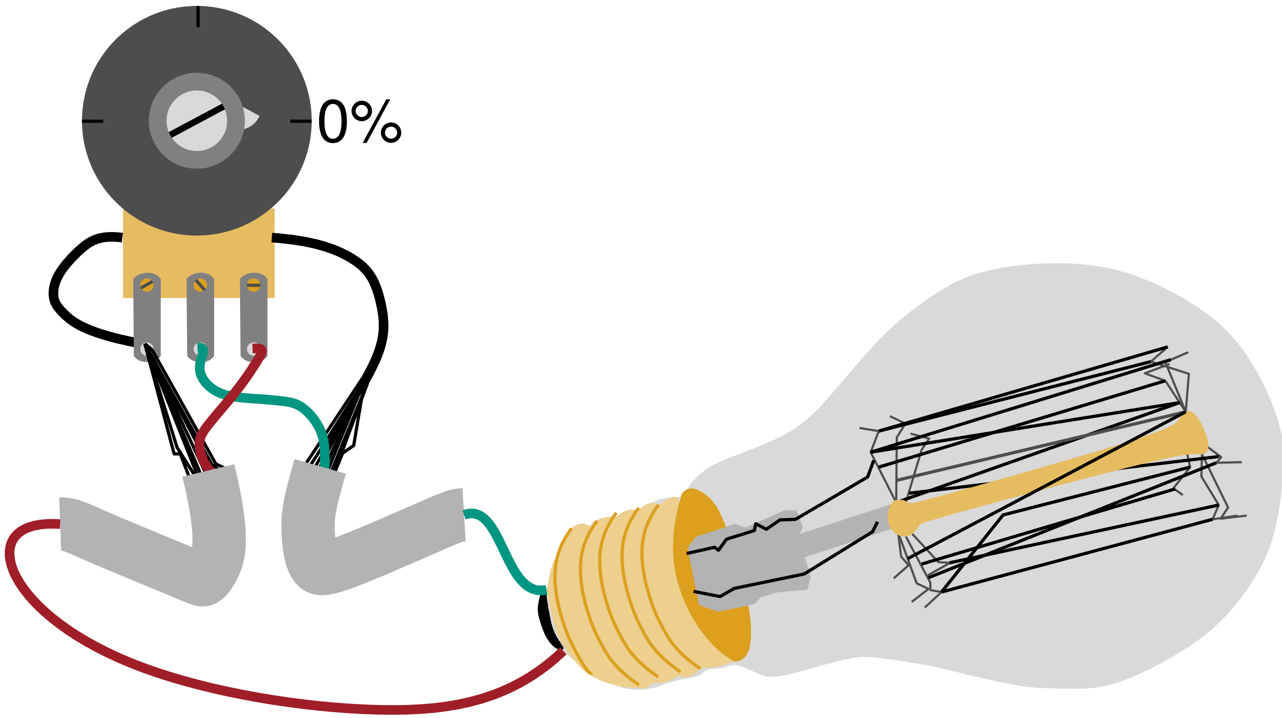
Simulate load increase by a load increase factor ρ,



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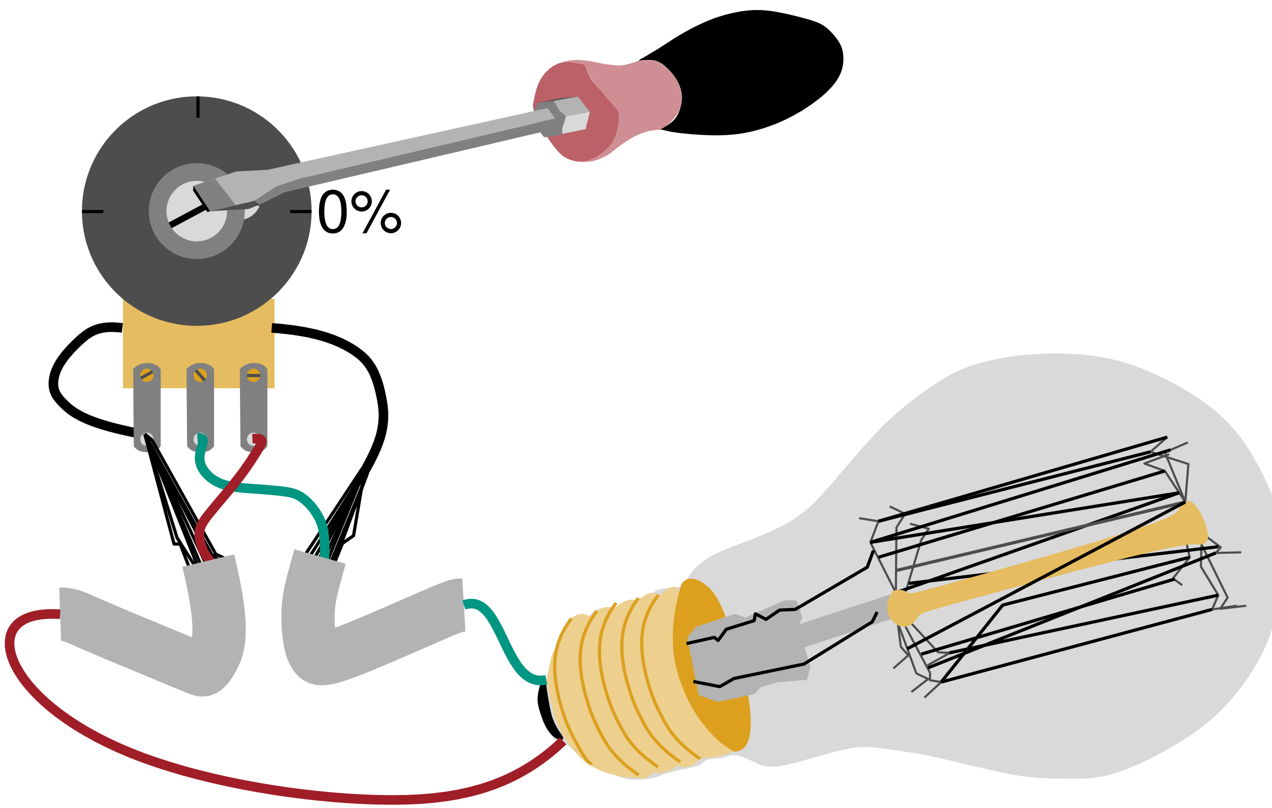

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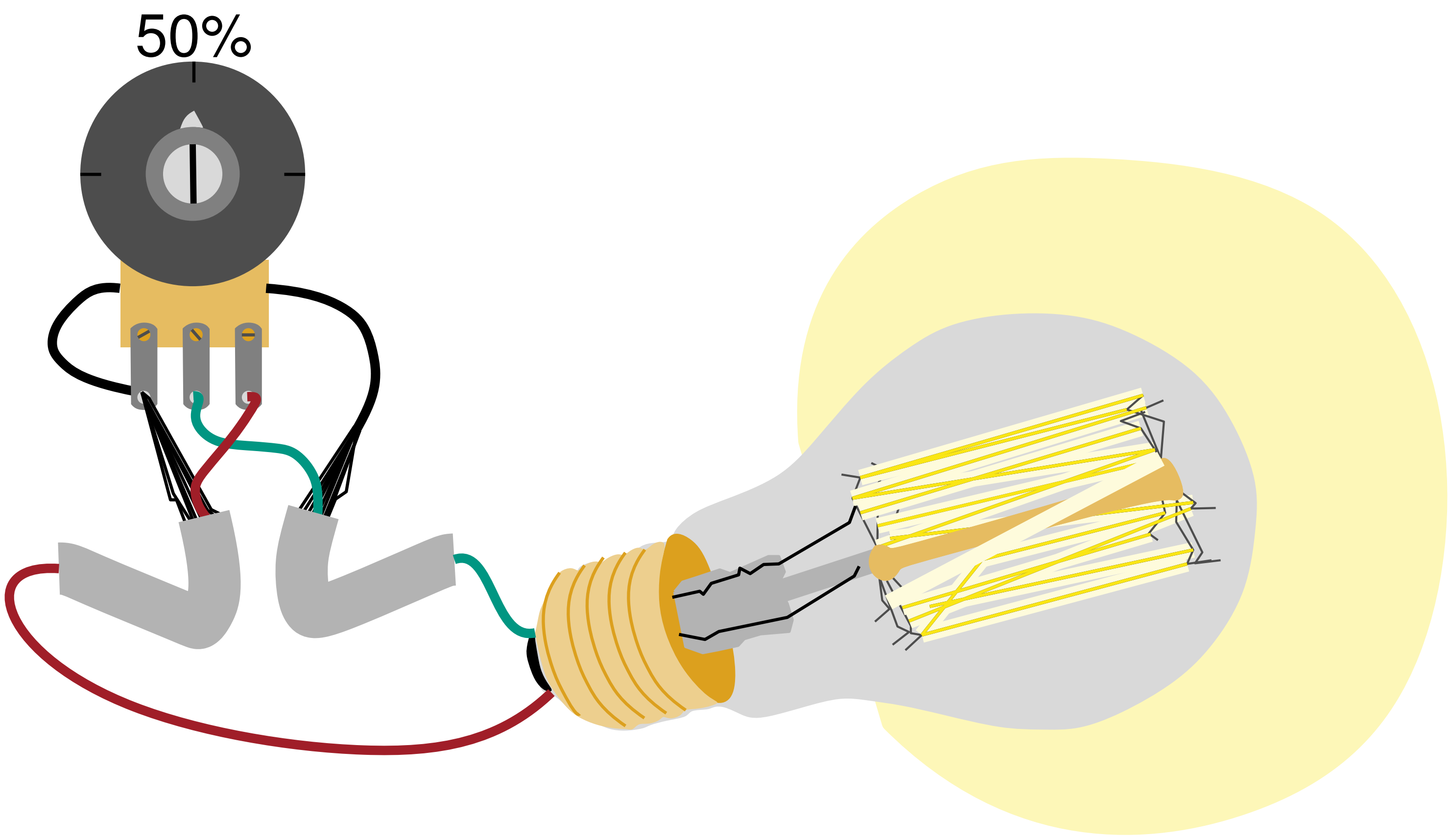

Effect of Few Flow Control Branches

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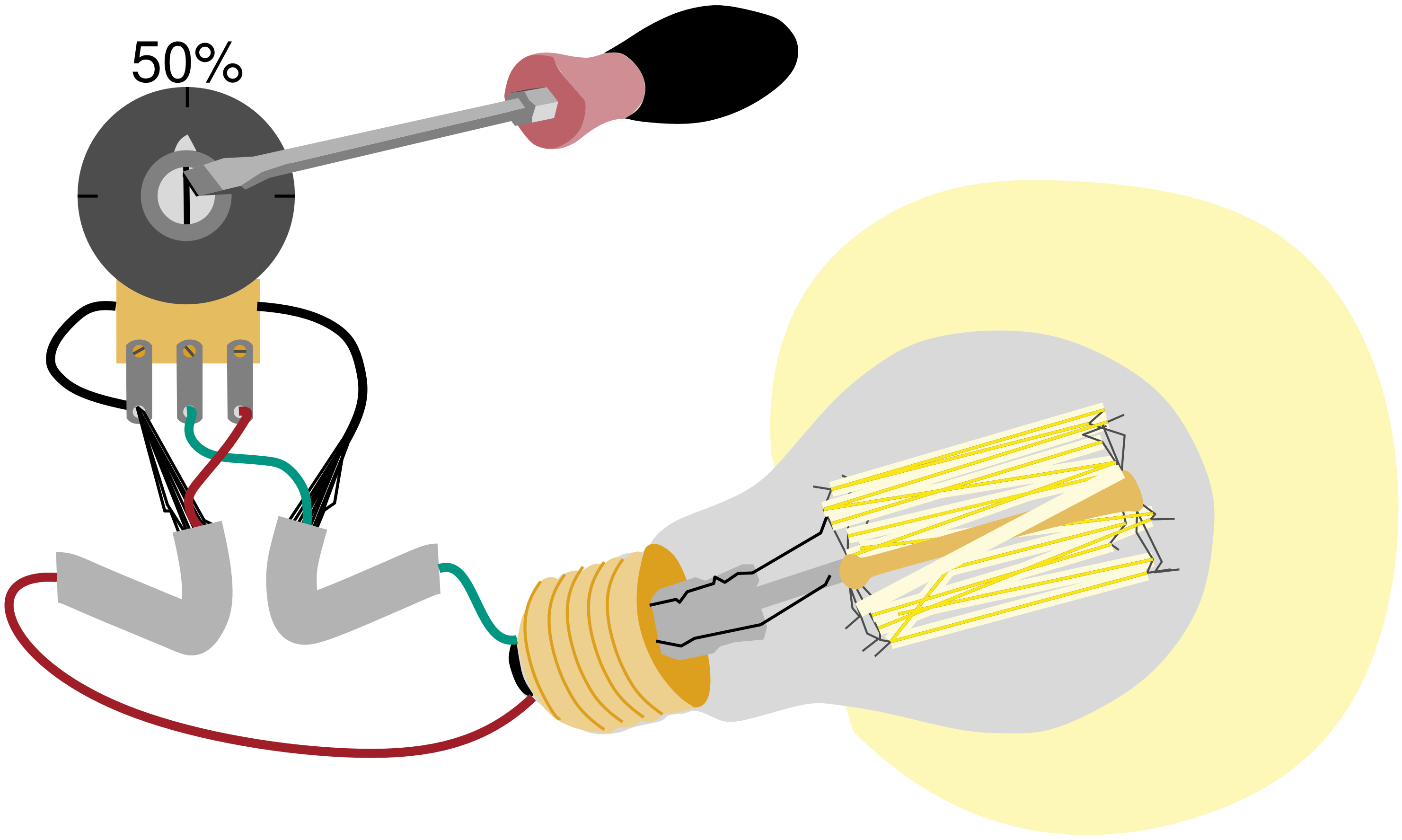

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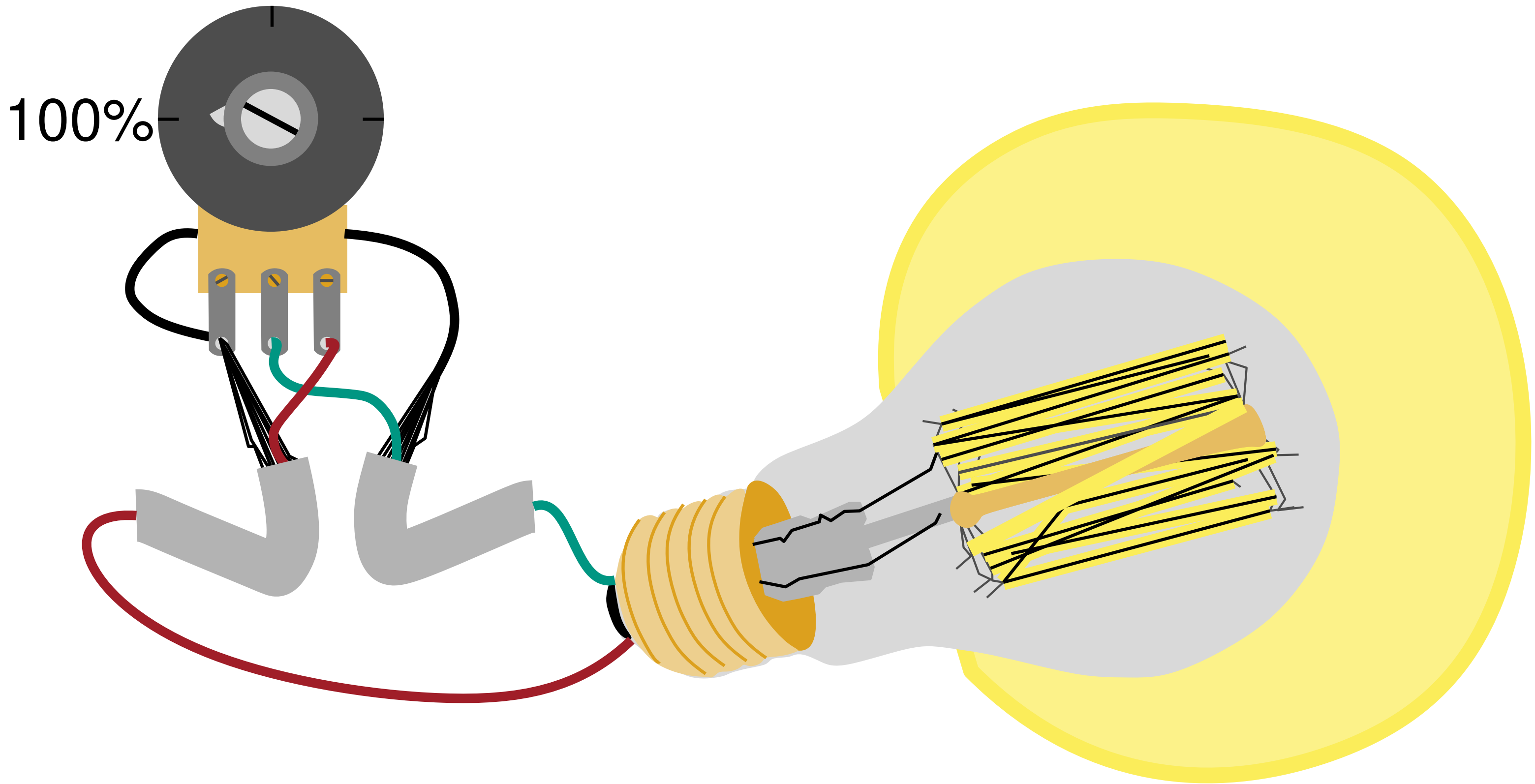
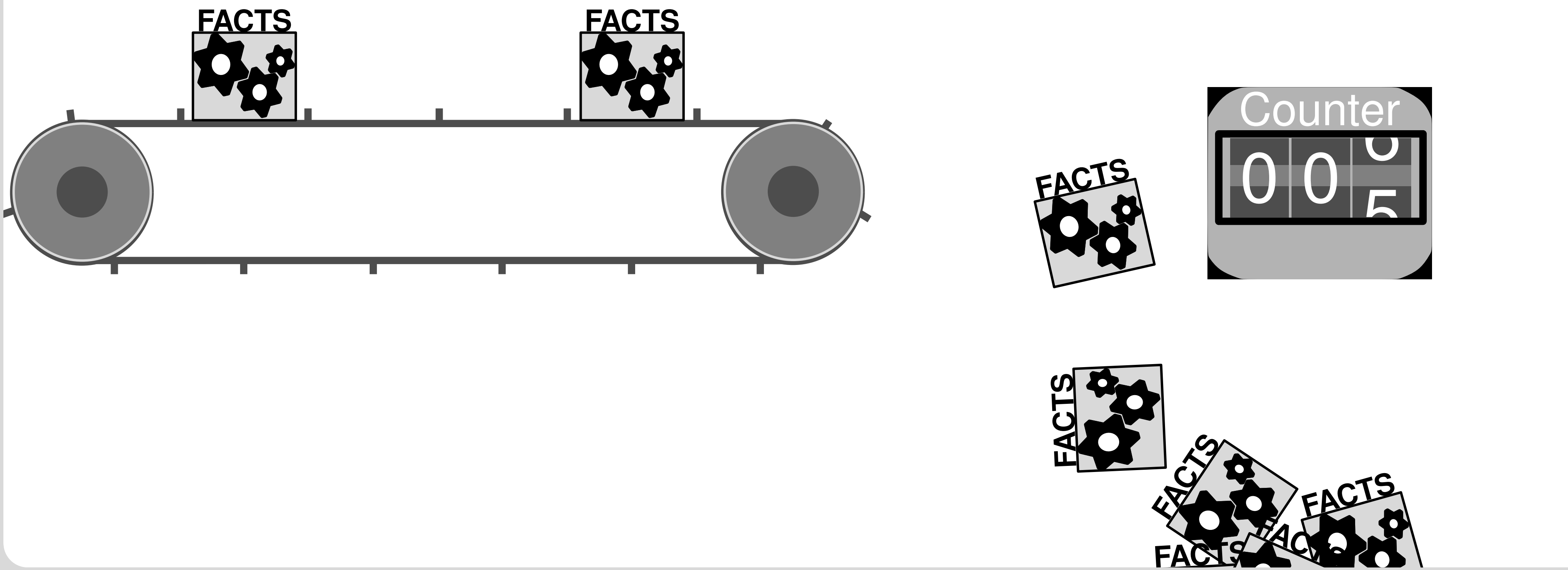


Effect of Few Flow Control Branches

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



Effect of Few Flow Control Branches

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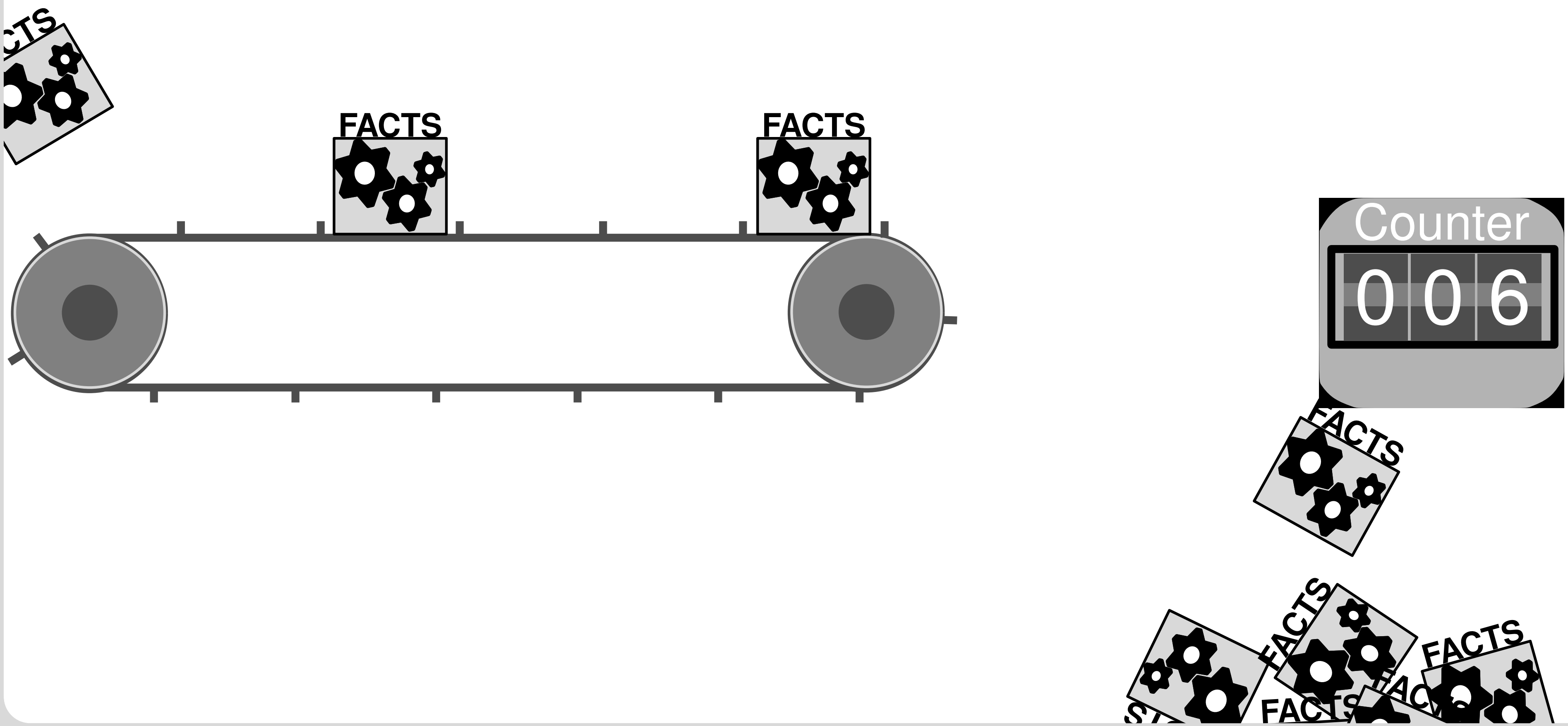

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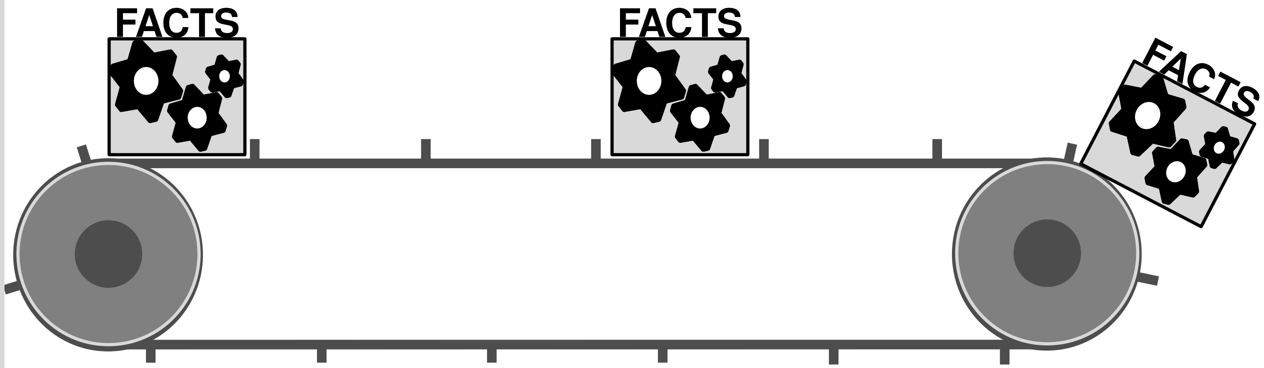

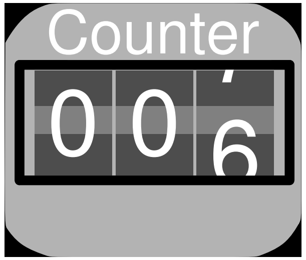

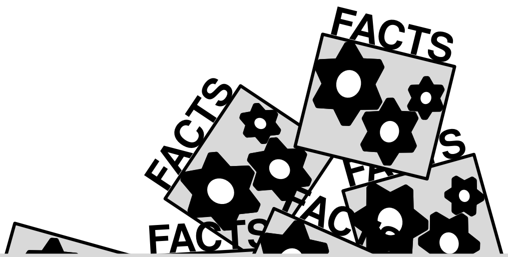

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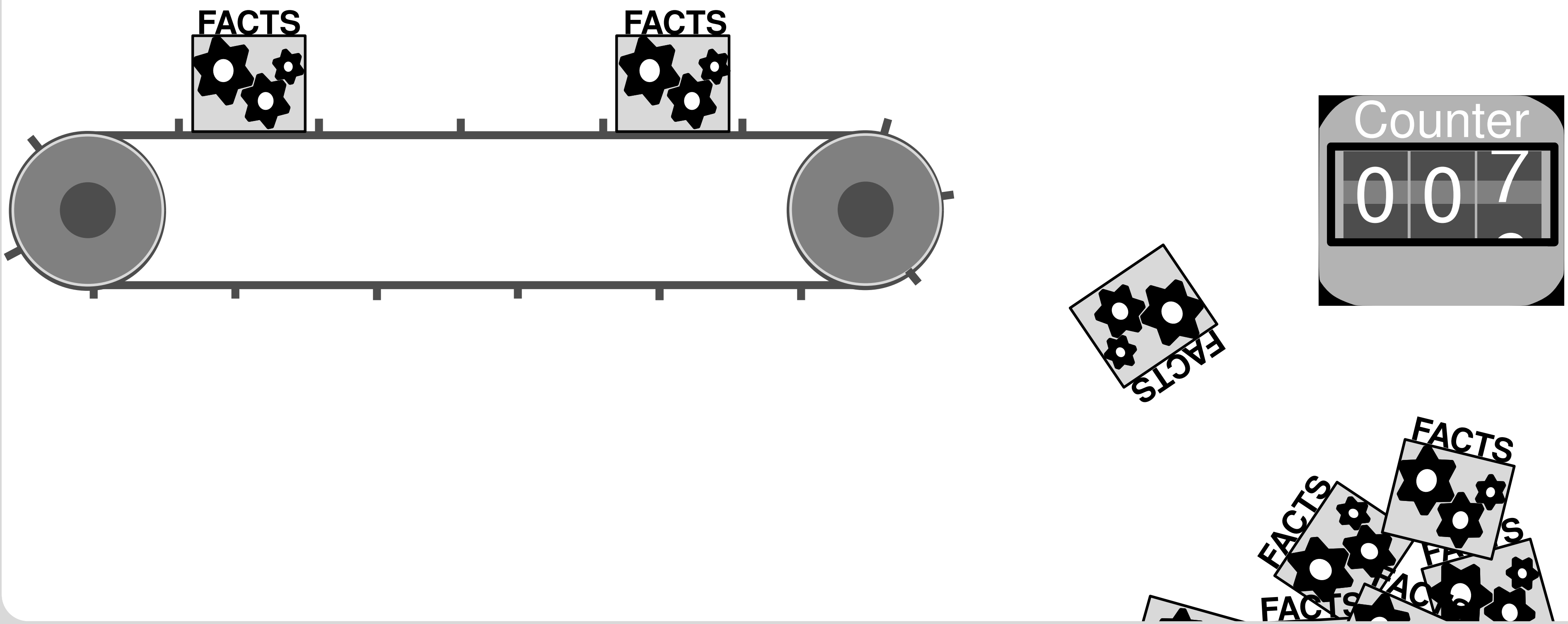


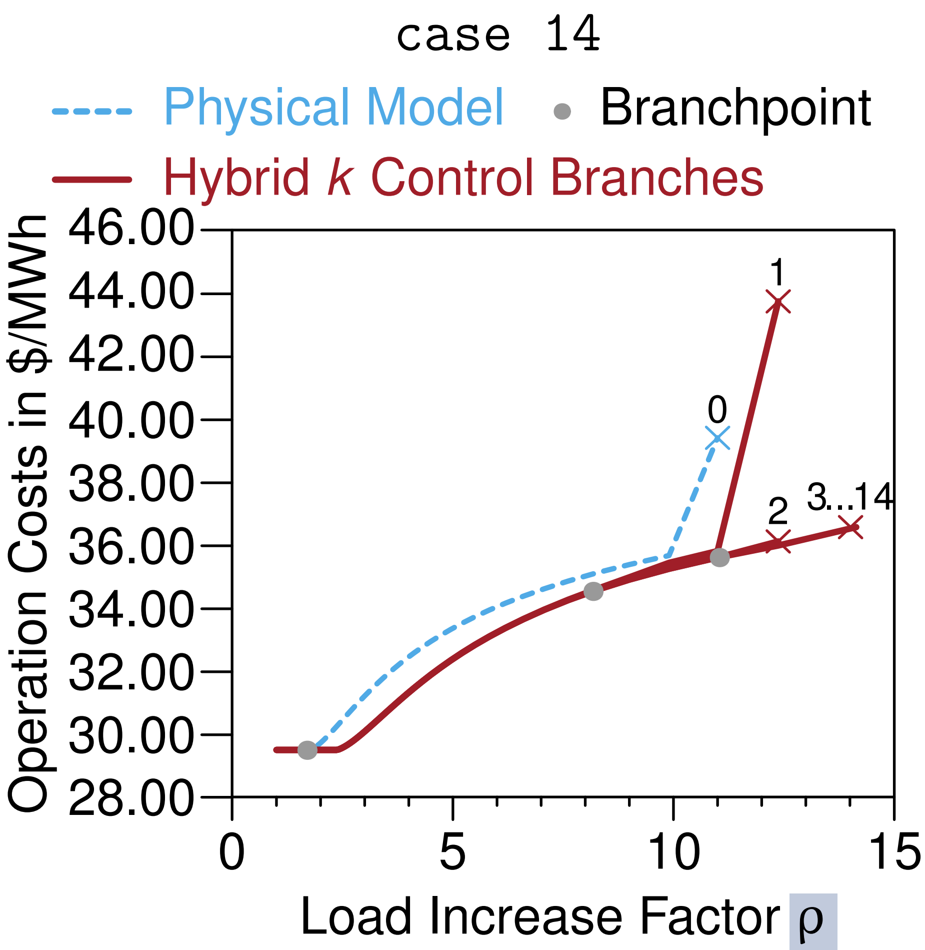
Effect of Few Flow Control Branches

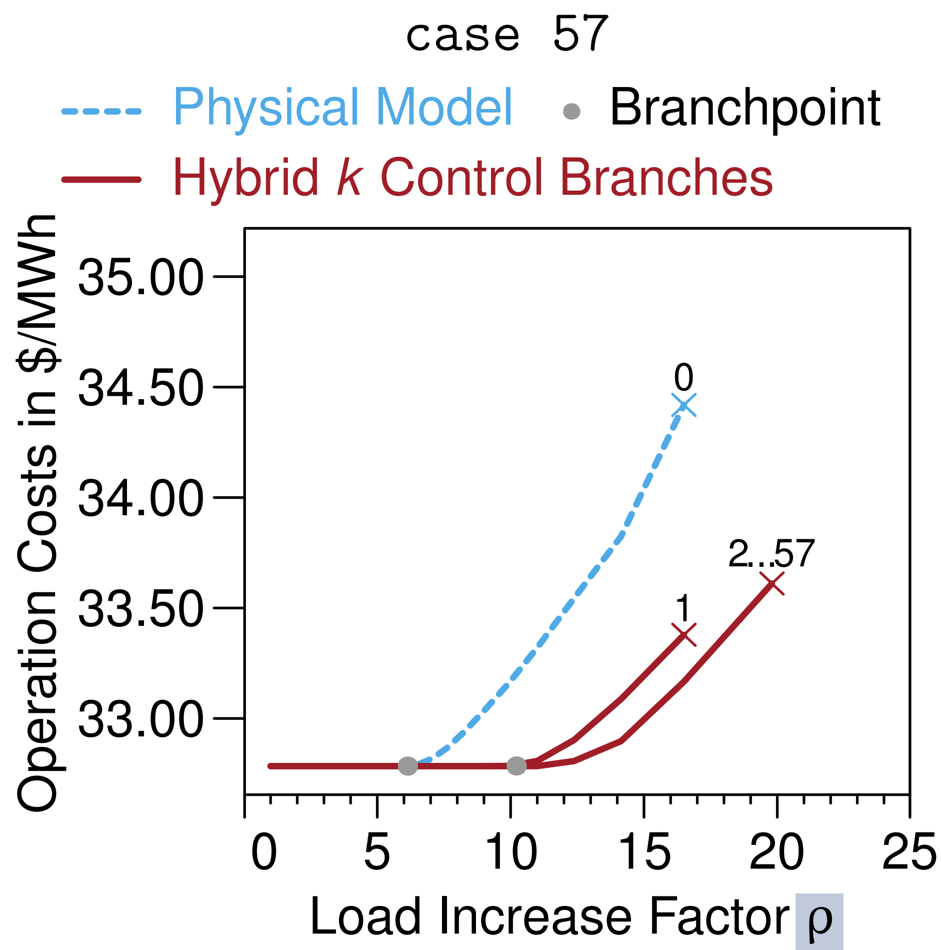
Simulate load increase by a load increase factor ρ,
Simulations with different numbers of flow controllers.

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





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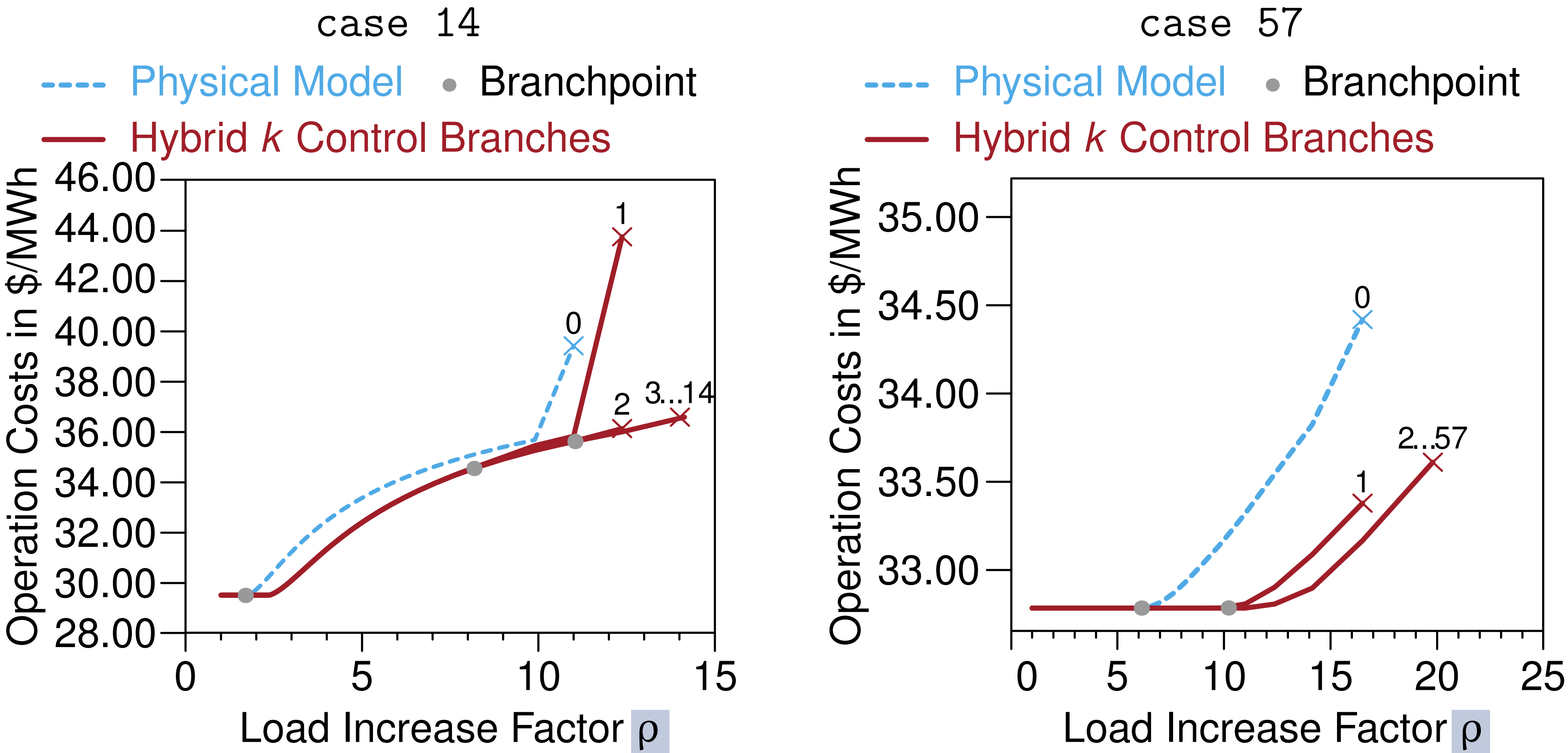

Findings

Very few flow control branches extend operation point at lower cost.

Summary & Future Work

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Hybrid Model = Flow Model + Physical Model

Question 1: Optimality

- How many controlled branches?
- Which branches need control?

Question 2: Cost & Operability

- Is there a positive effect on flow costs and operability?

Findings

- Often a small number of flow control branches suffices

Findings

- Extend the operation point
- Lower operation cost

having only very few flow control branches

Summary & Future Work

Karlsruhe Institute of Technology

Hybrid Model = Flow Model + Physical Model

Question 1: Optimality

- How many controlled branches?
- Which branches need control?

Question 2: Cost & Operability

- Is there a positive effect on flow costs and operability?

Findings

- Often a small number of flow control branches suffices

Findings

- Extend the operation point
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having only very few flow control branche