

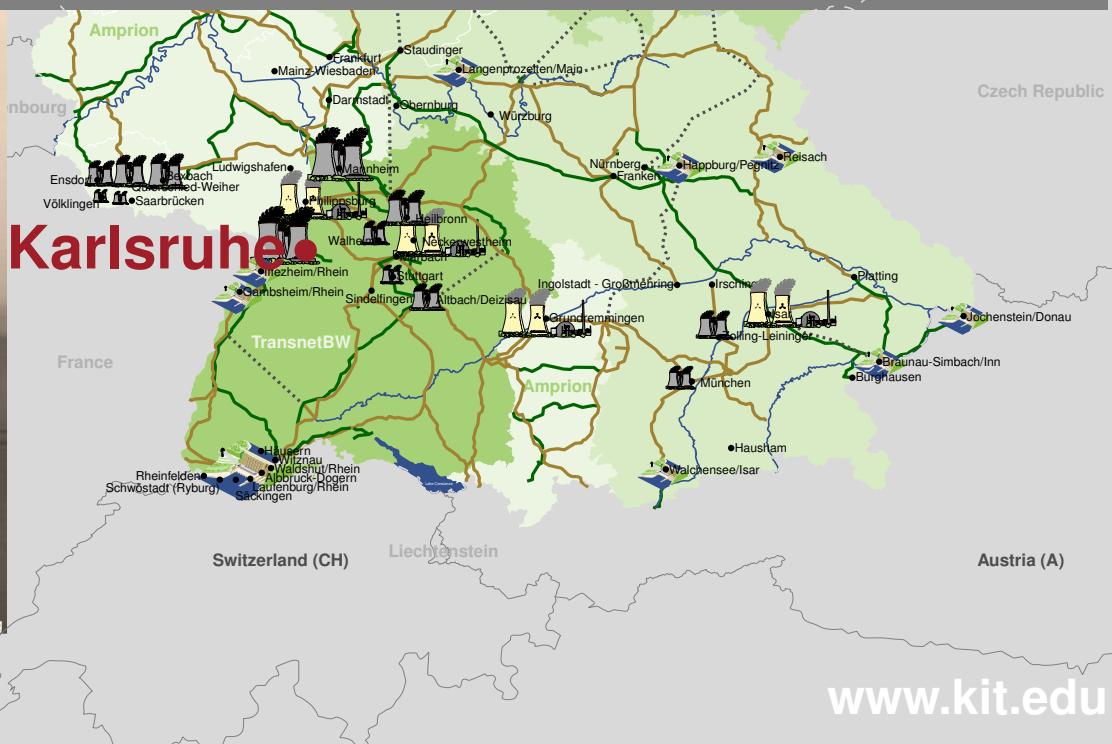
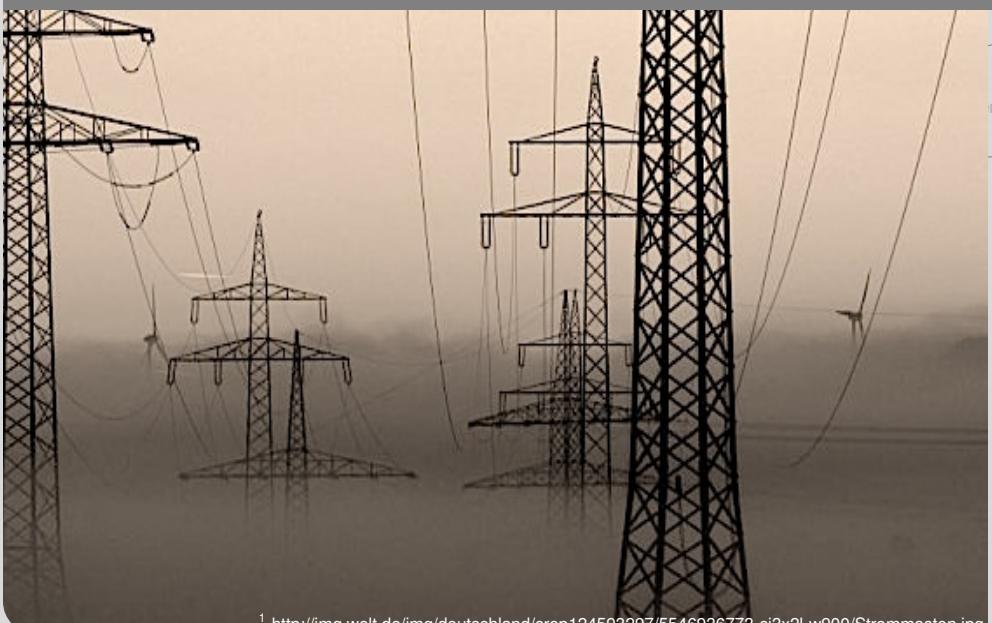
Towards Realistic Flow Control in Power Grid Operation

Energy Informatics · Nov 13, 2015

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

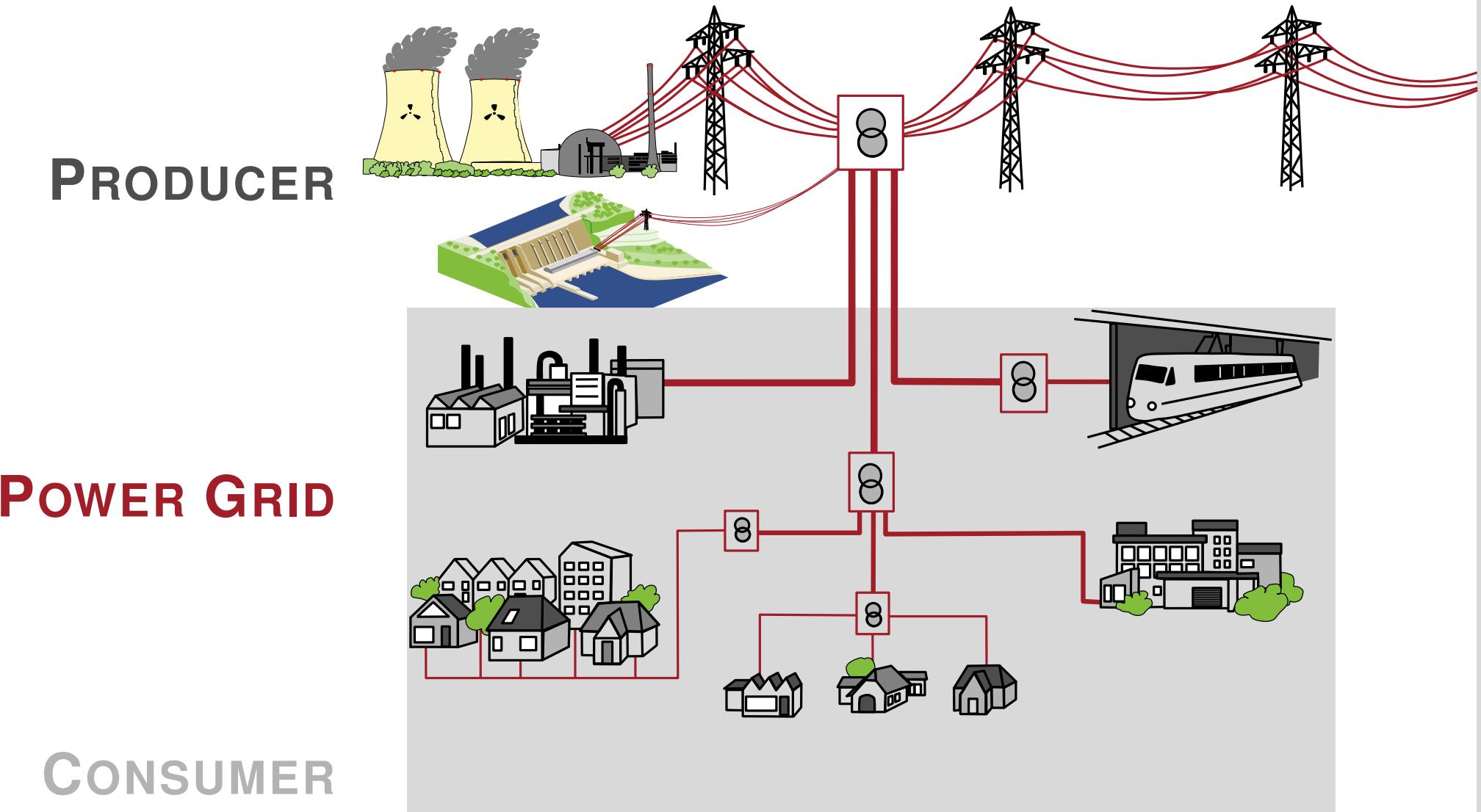


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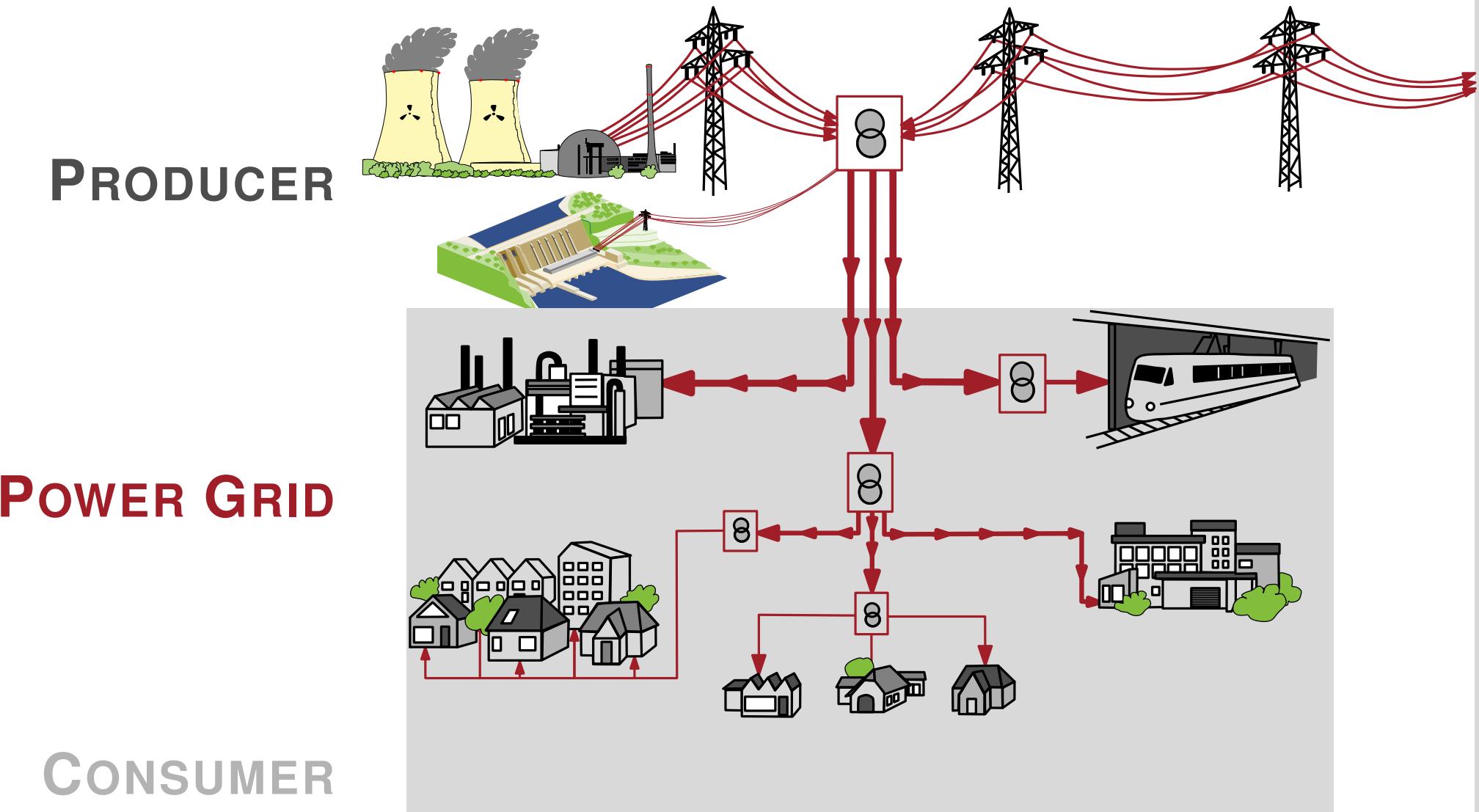


¹ <http://img.welt.de/img/deutschland/crop124593297/5546936773-ci3x2l-w900/Strommasten.jpg>

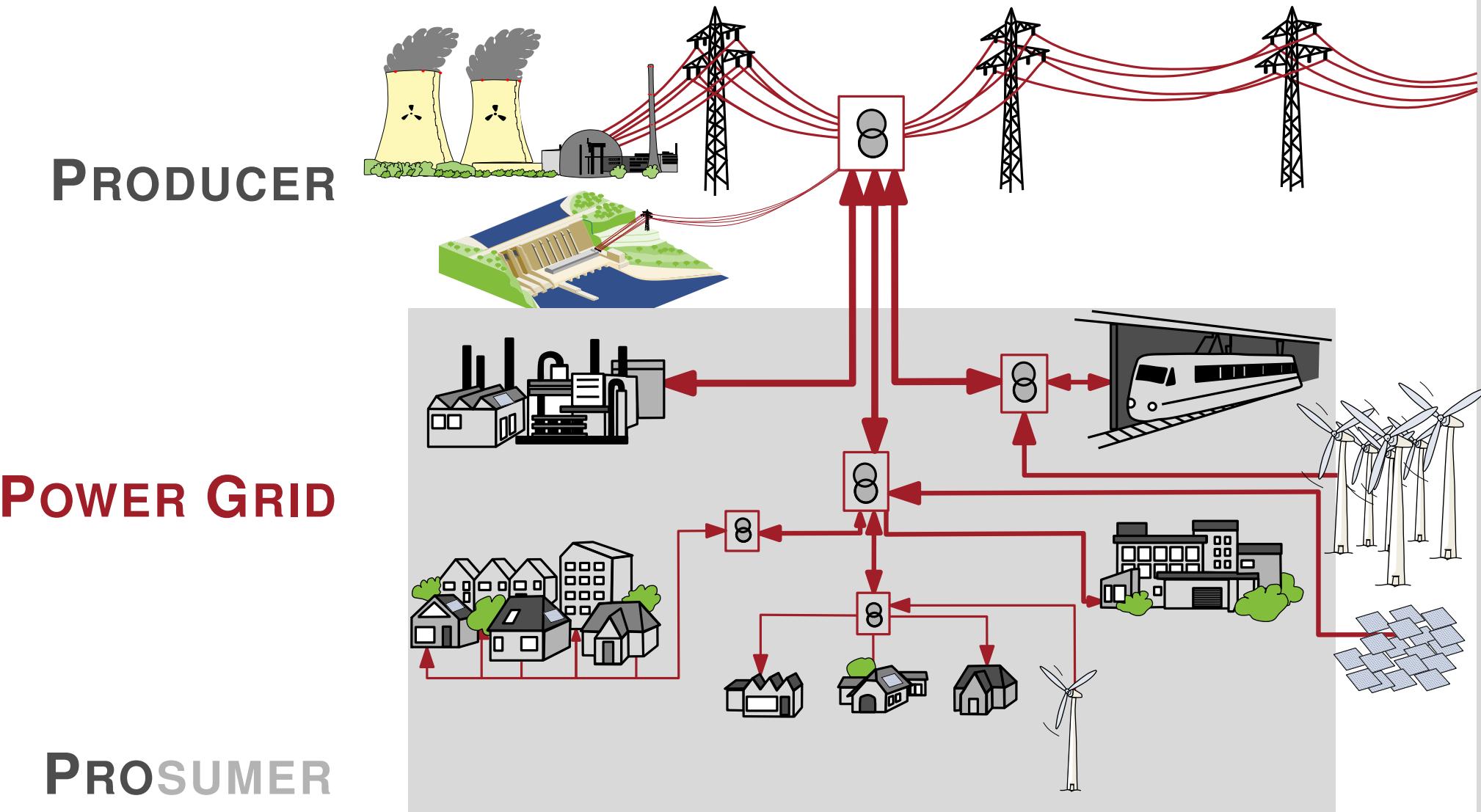
Recent Development in Power Grids



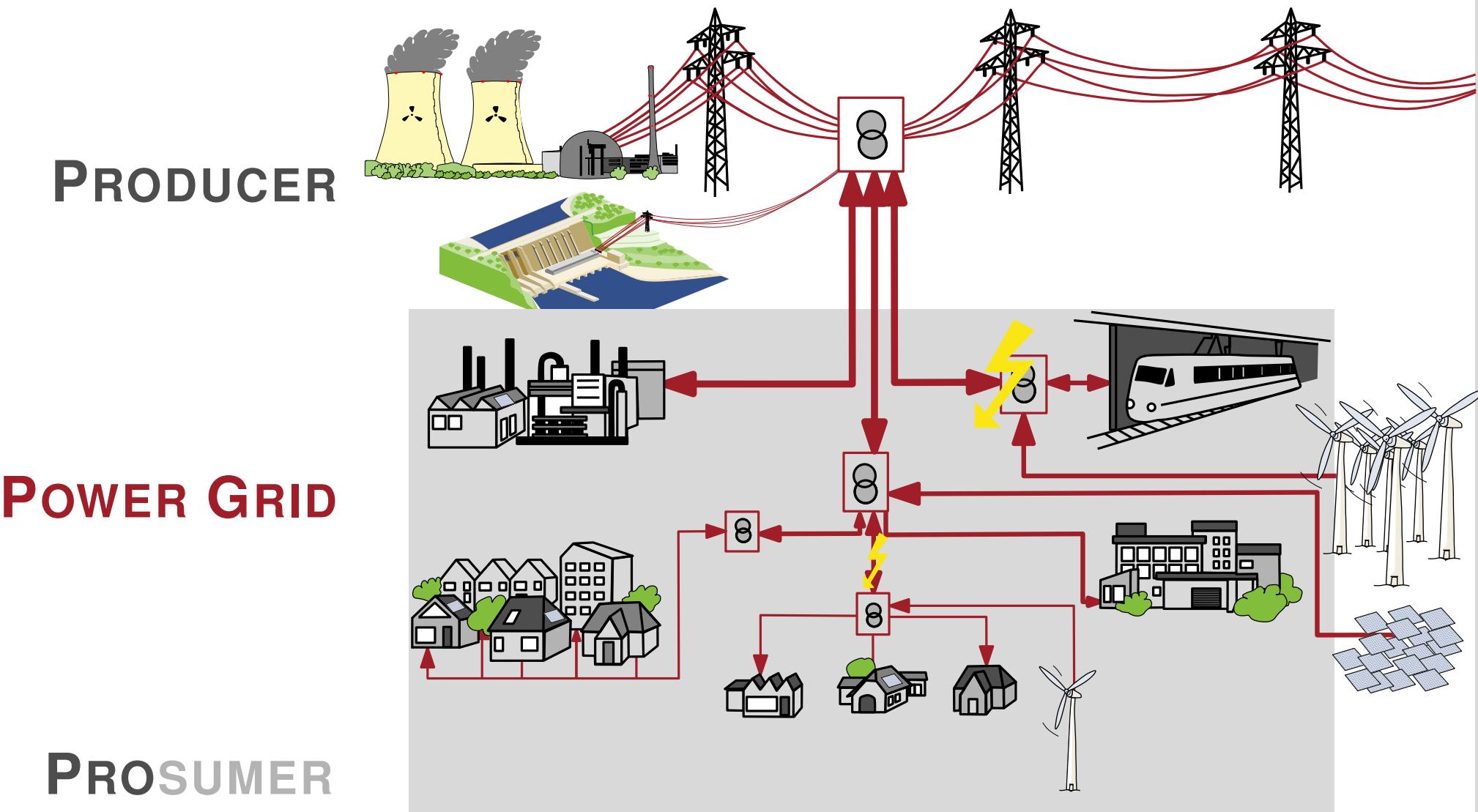
Recent Development in Power Grids



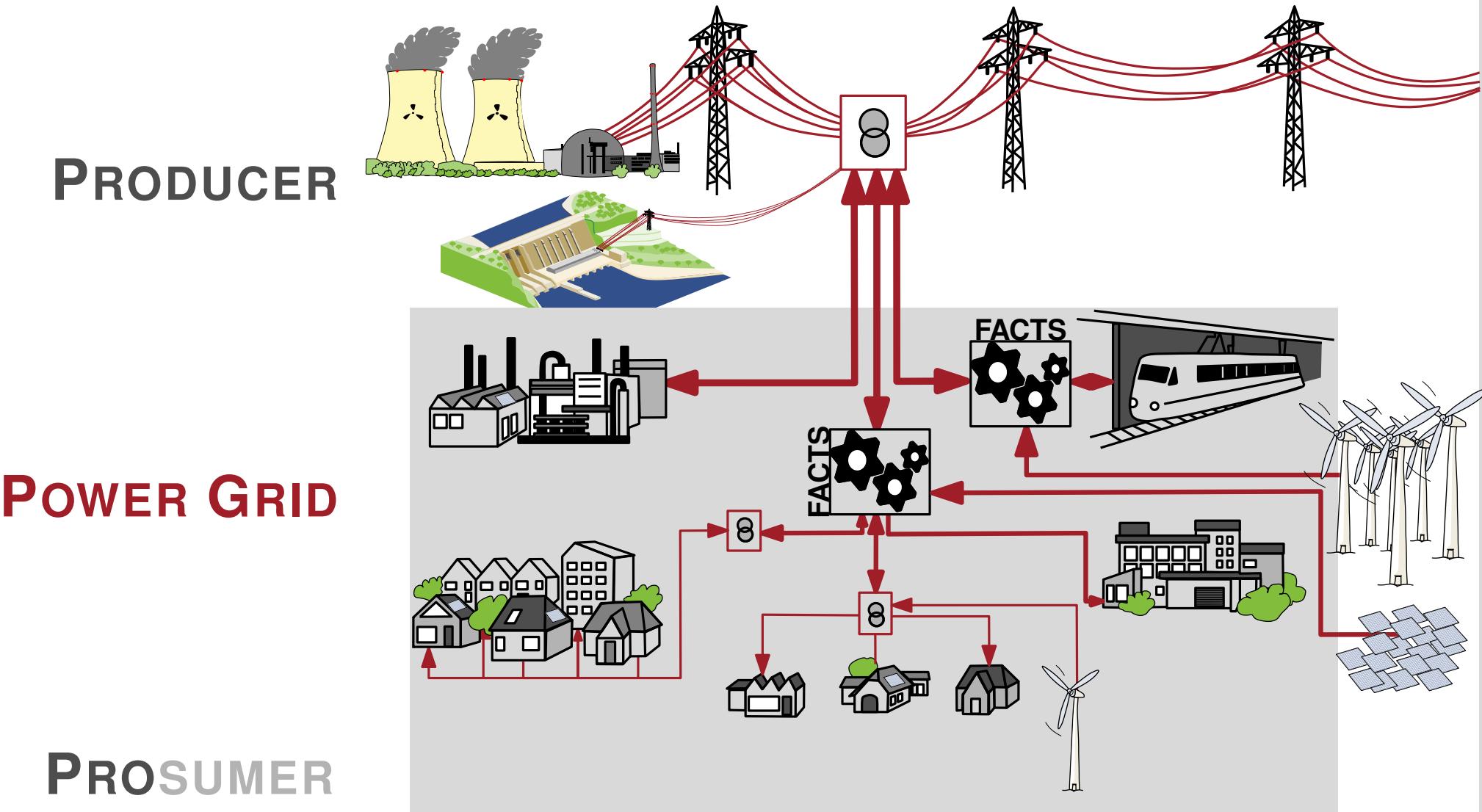
Recent Development in Power Grids



Recent Development in Power Grids



Recent Development in Power Grids



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

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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- Power grid with parameters

Find:

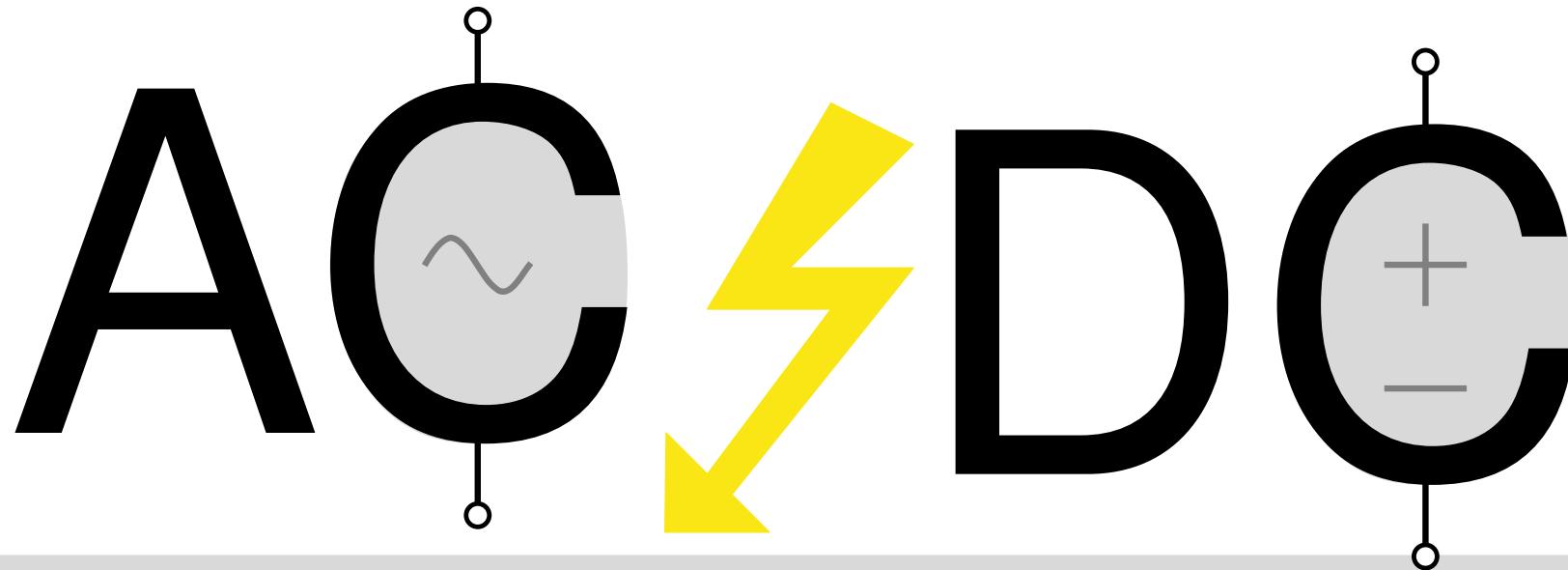
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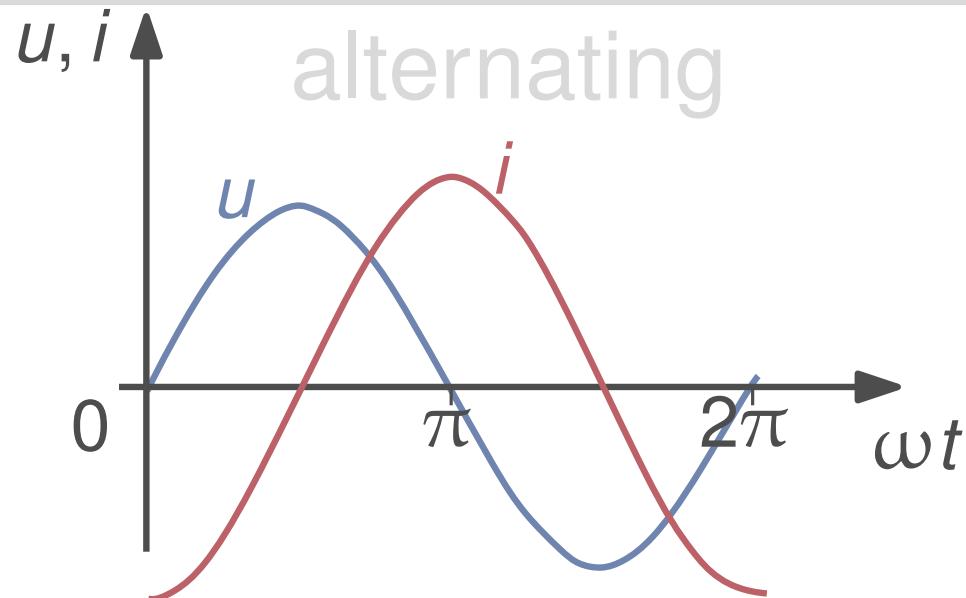
- Minimize production cost (similar to OPF)
 - Minimize branch losses
- } operation cost

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

⇒ Place FACTS to enhance controllability.



DC-based Flow Models



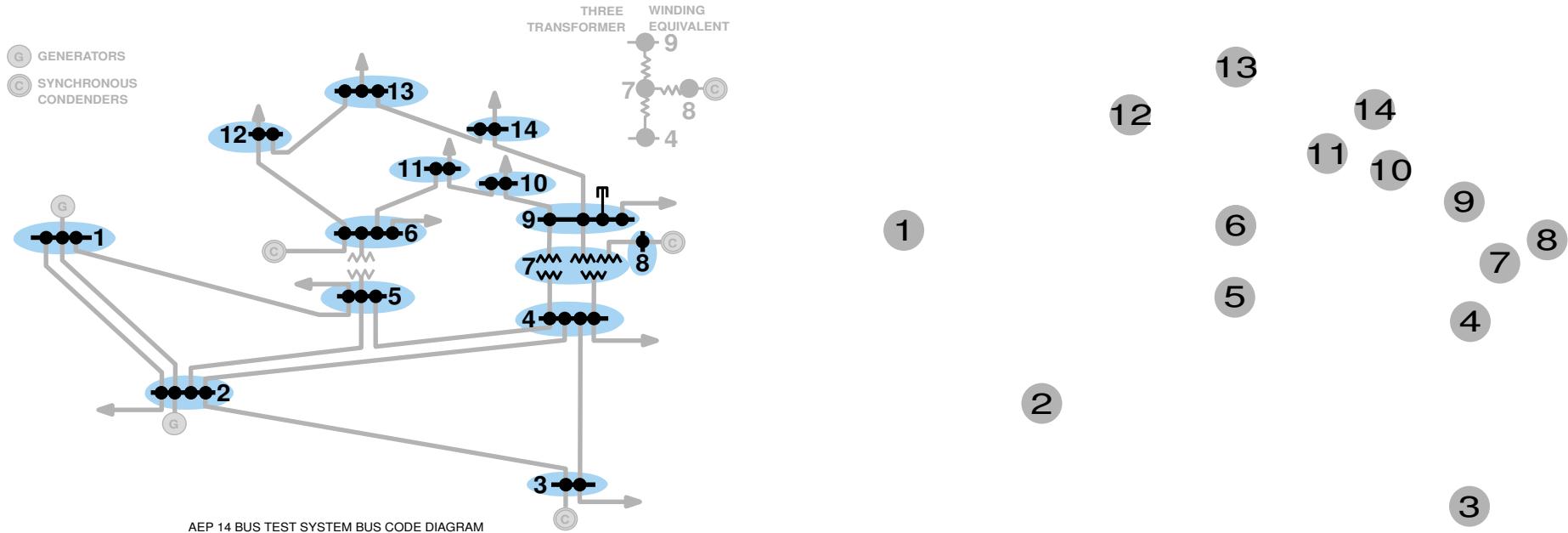
Straight-forward transformation:

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

Graph Model

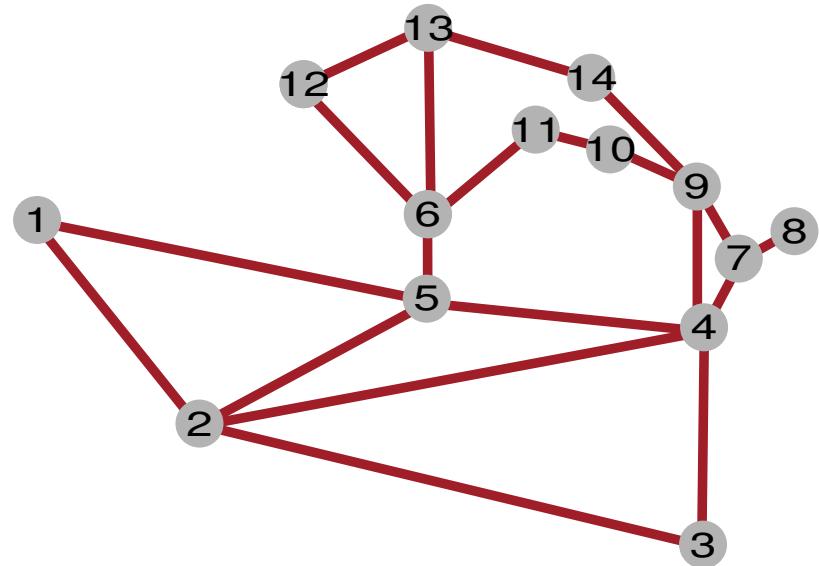
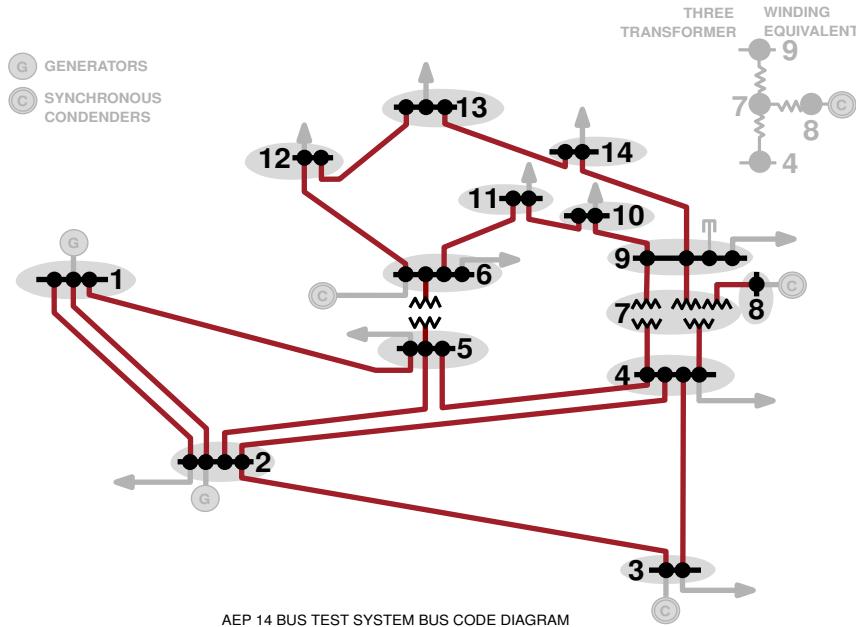
Straight-forward transformation:

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



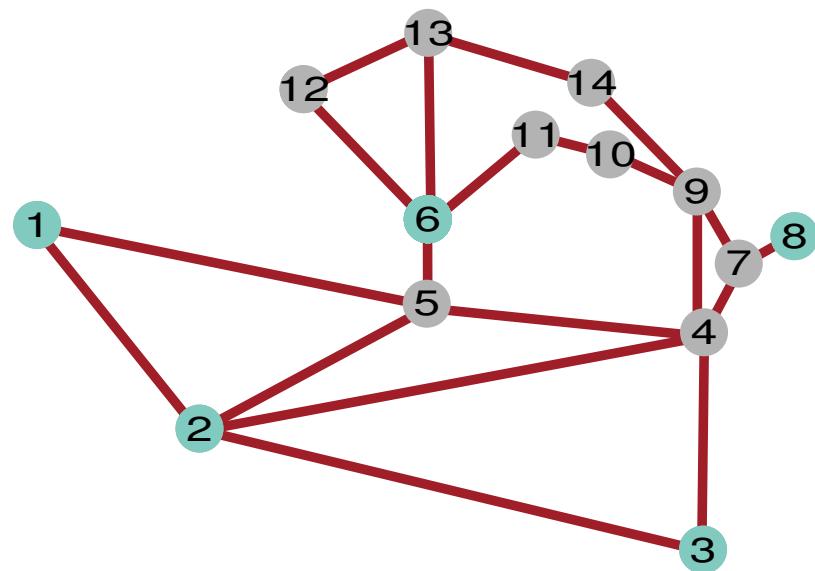
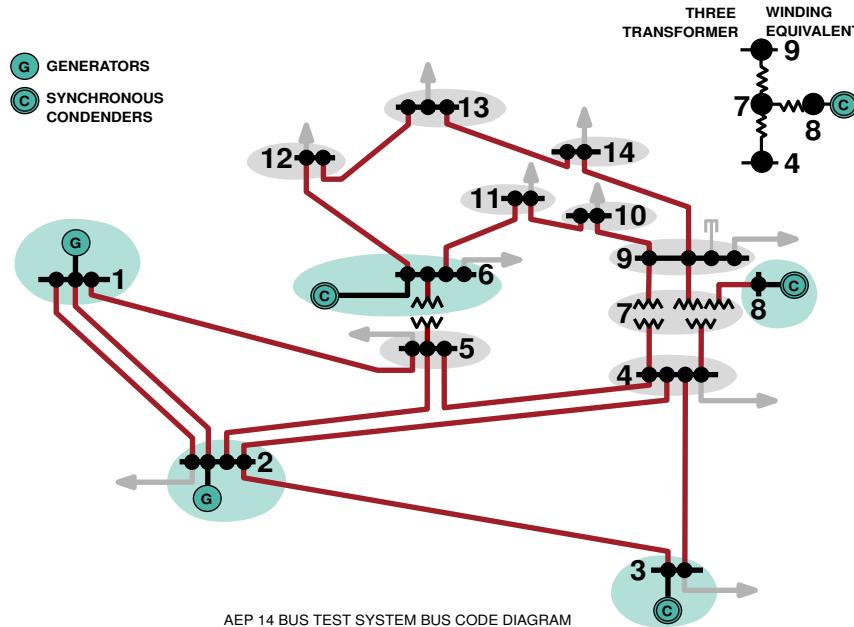
Straight-forward transformation:

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



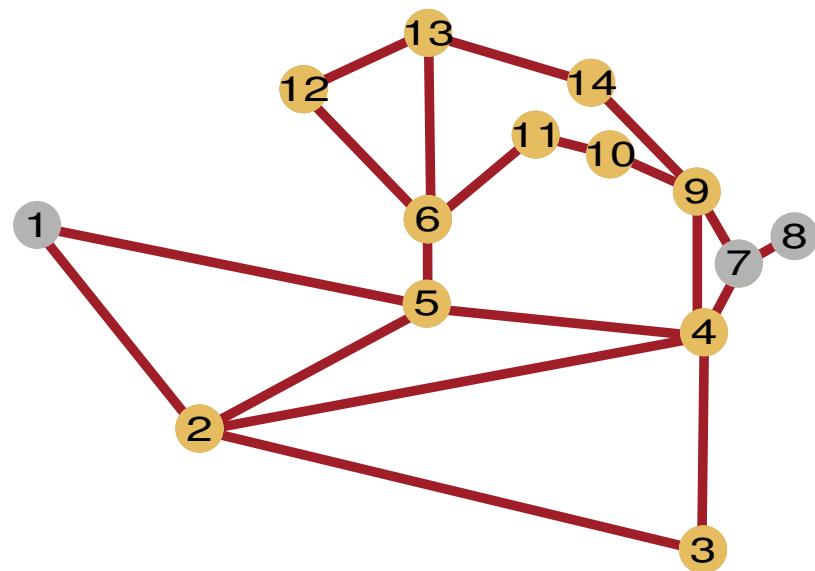
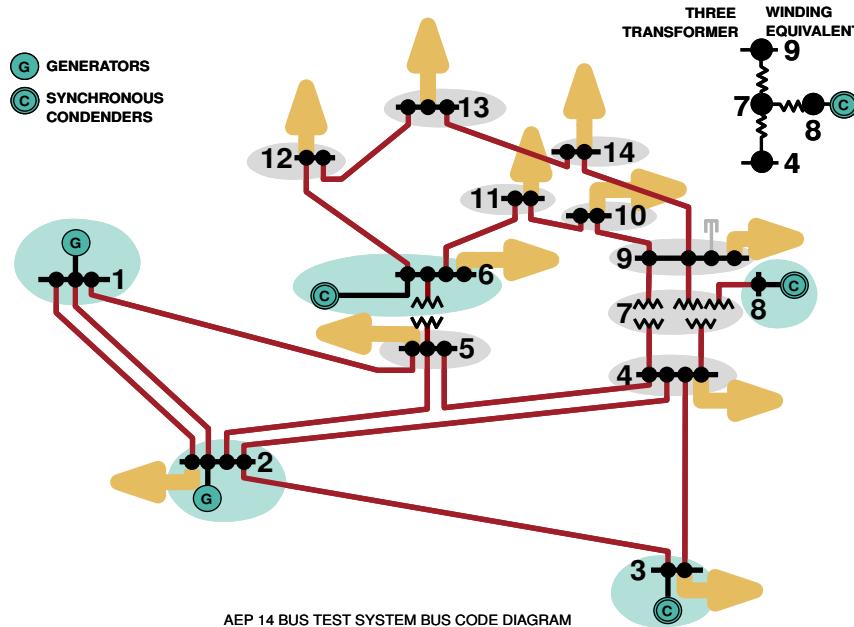
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- Generators \rightarrow set $V_G \subseteq V$ of generator buses

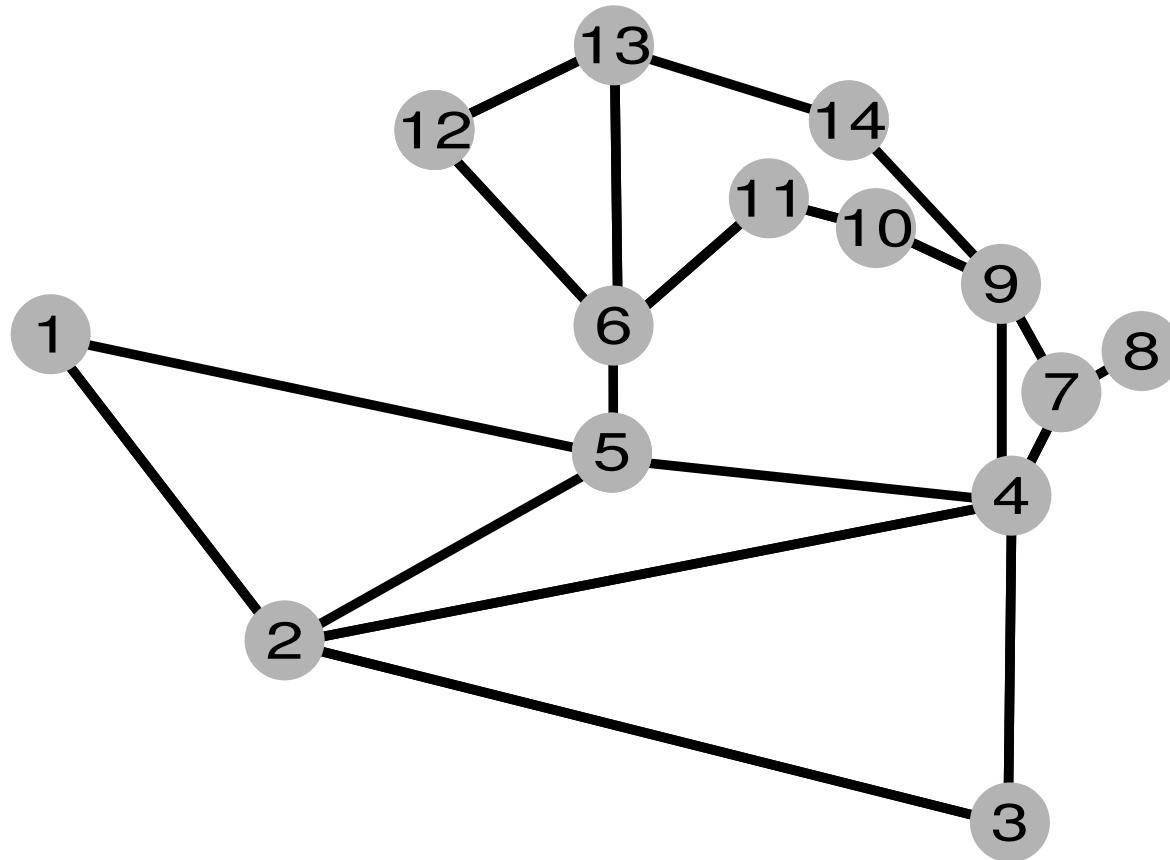


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- Generators \rightarrow set $V_G \subseteq V$ of generator buses
- Load \rightarrow set $V_L \subseteq V$ of load buses



Hybrid Flow Model



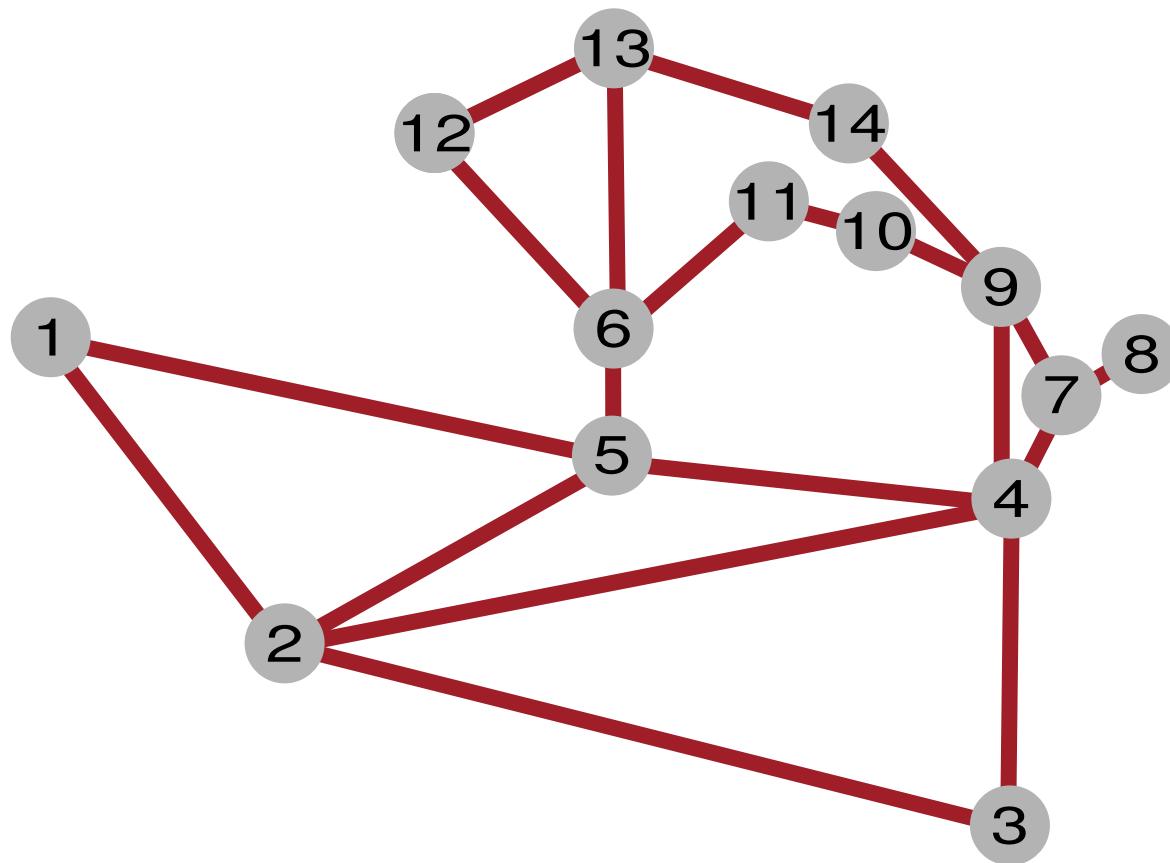
Kirchhoff's circuit laws:

Kirchhoff's current law ✓

Kirchhoff's voltage law ✓

Physical Model
(as a DC approximation)

Hybrid Flow Model



Flow Model

— control unit

Kirchhoff's circuit laws:

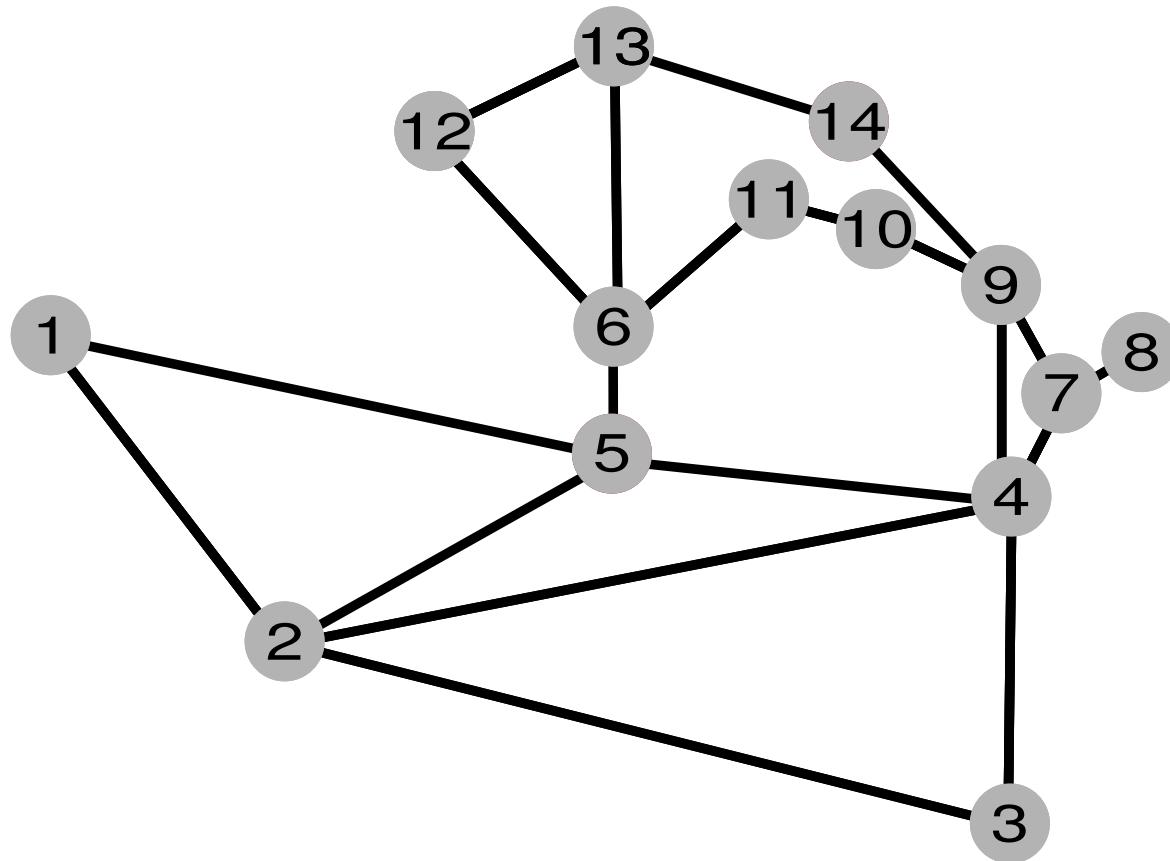
Kirchhoff's current law

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Hybrid Flow Model



— control unit

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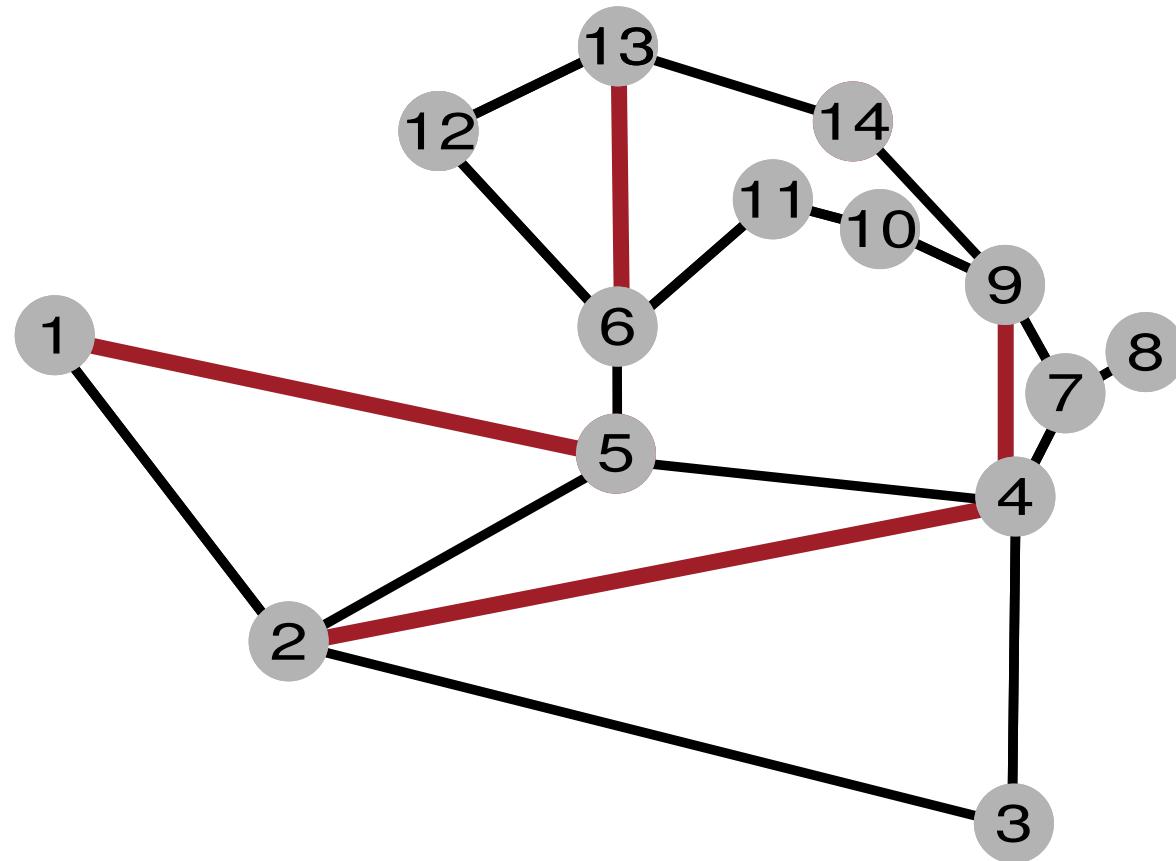
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Hybrid Model = Flow Model + Physical Model

Hybrid Flow Model



— control unit

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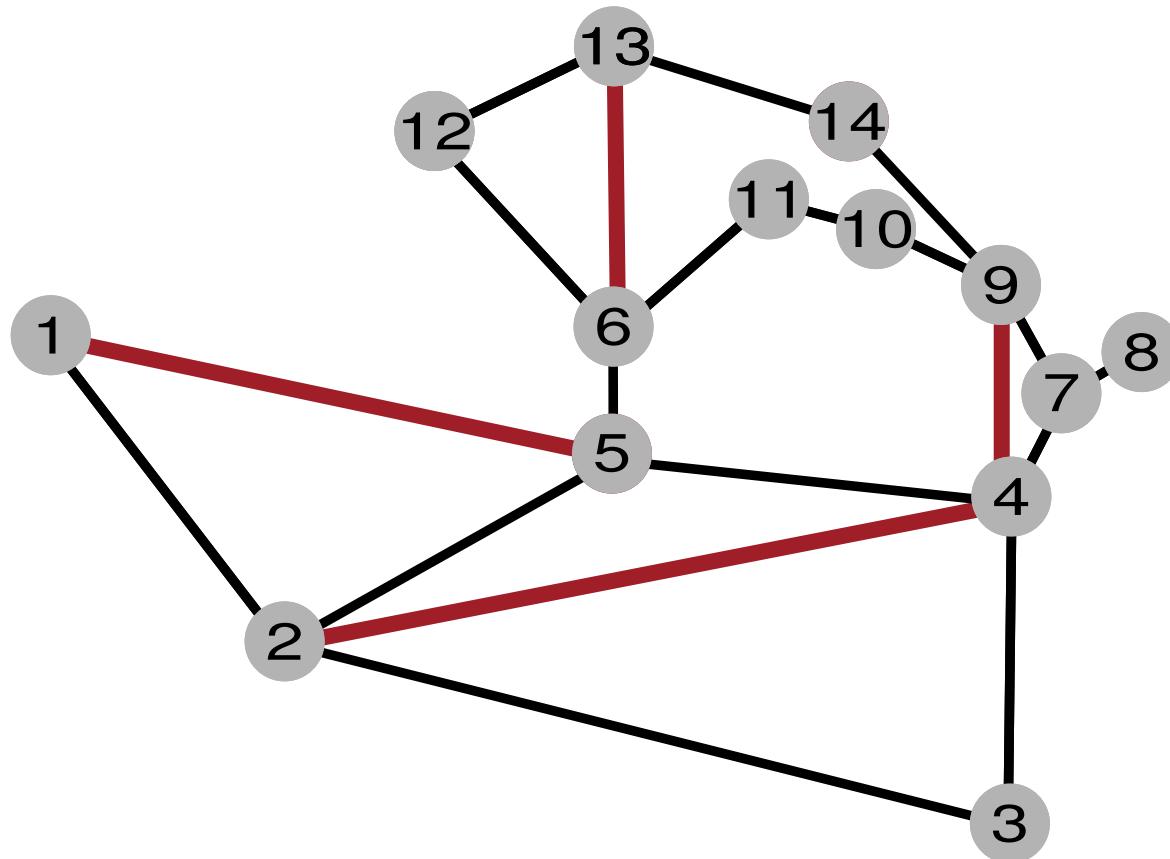
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Hybrid Flow Model



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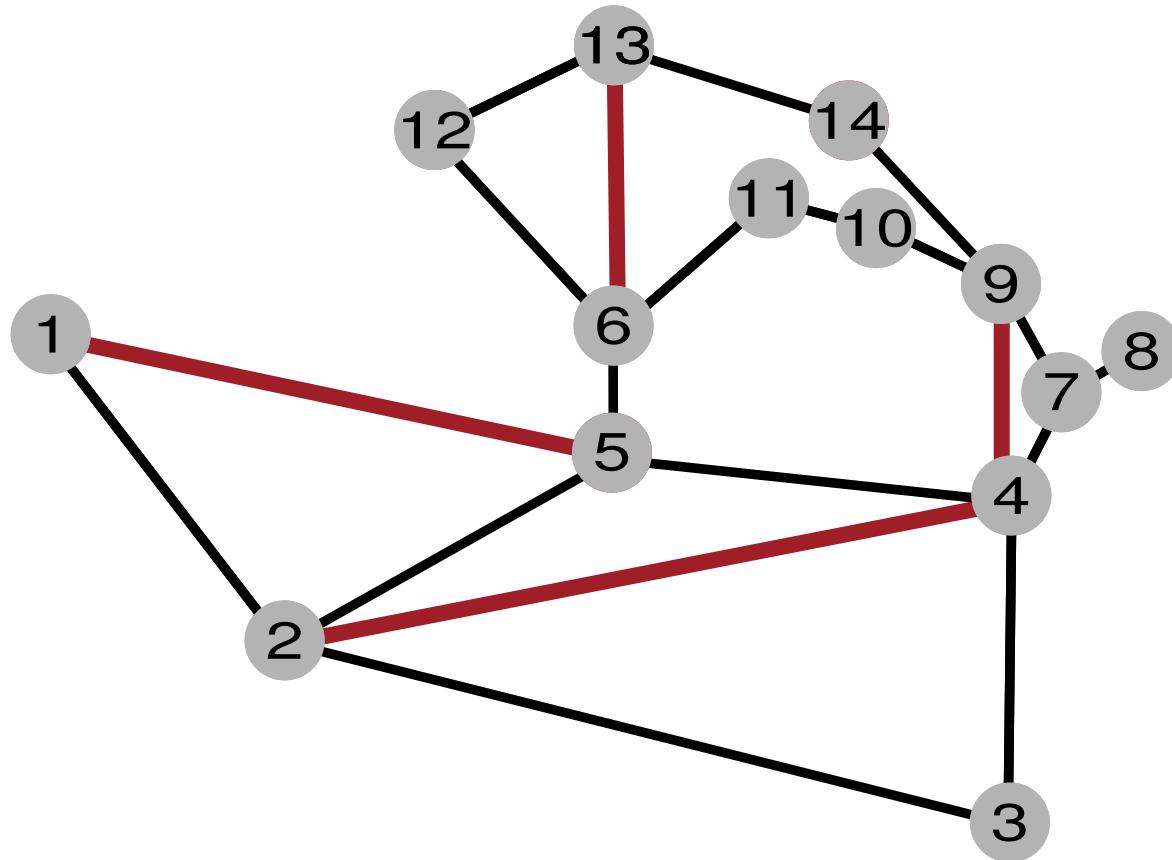
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Hybrid Model = Flow Model + Physical Model



Lower Bound

Hybrid Flow Model



— control unit

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Hybrid Model = **Flow Model** + Physical Model



Lower Bound



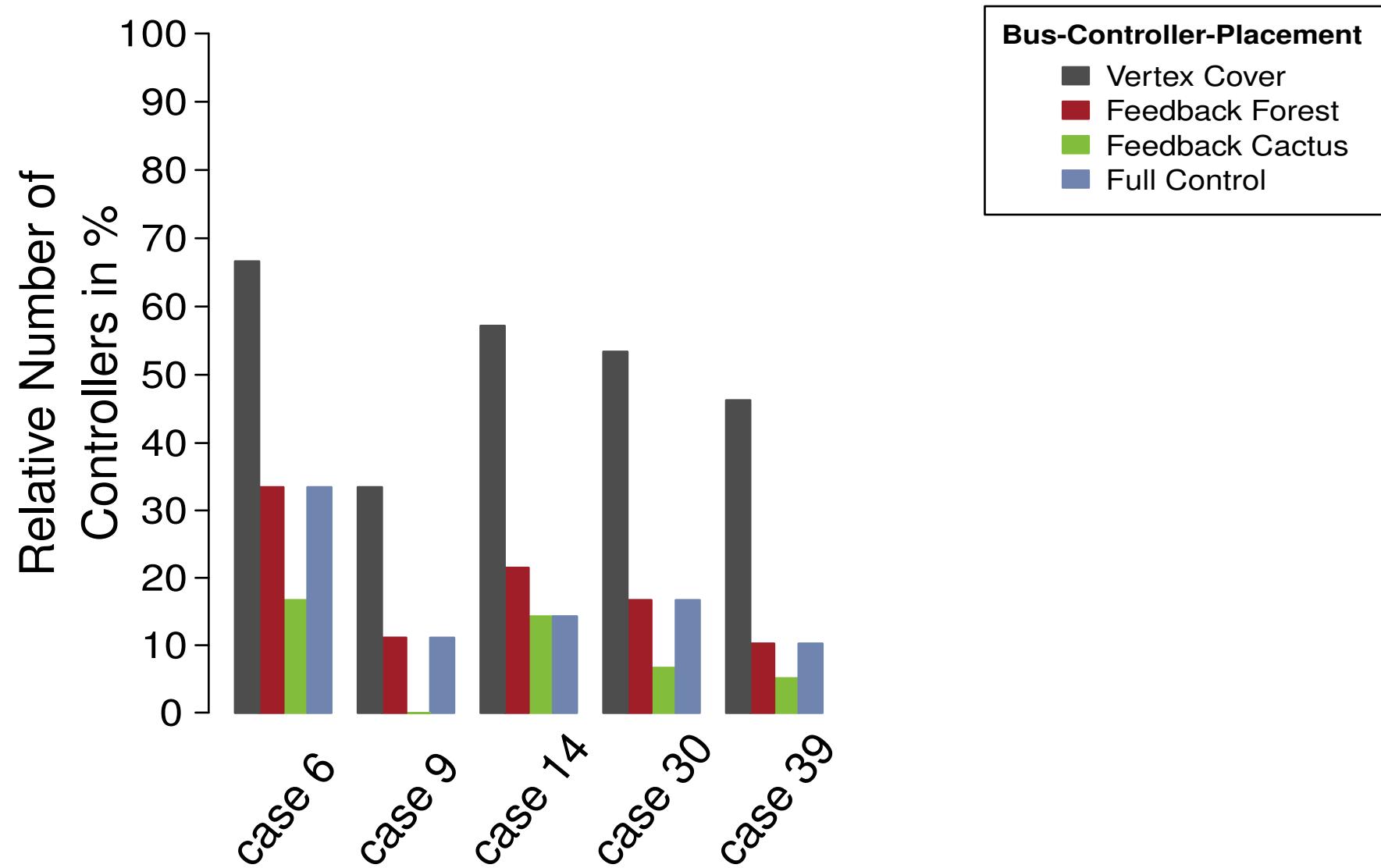
Upper Bound

Research Questions

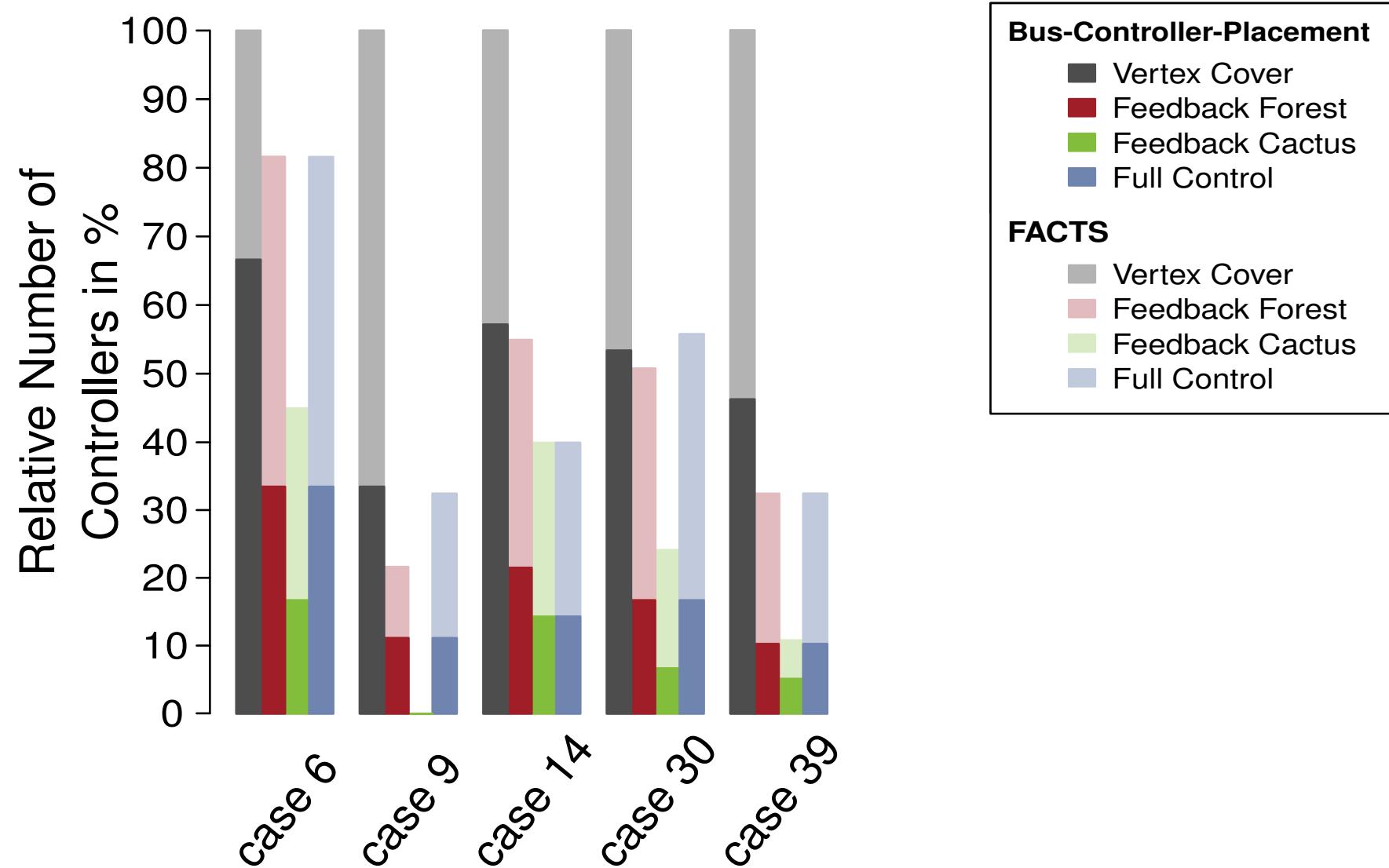
Control units are expensive – how many do we need?

- (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?

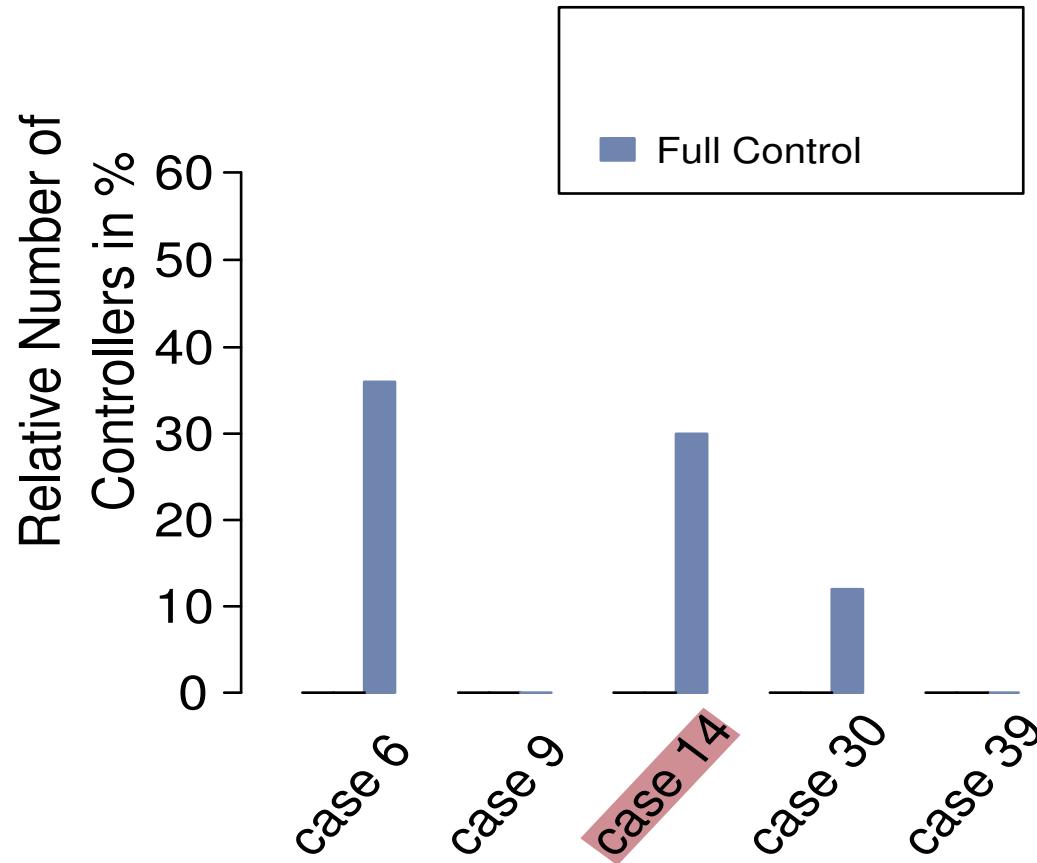
Controller Placement on Buses [Leibfried et al., 2015]



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



Number of Control Branches



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



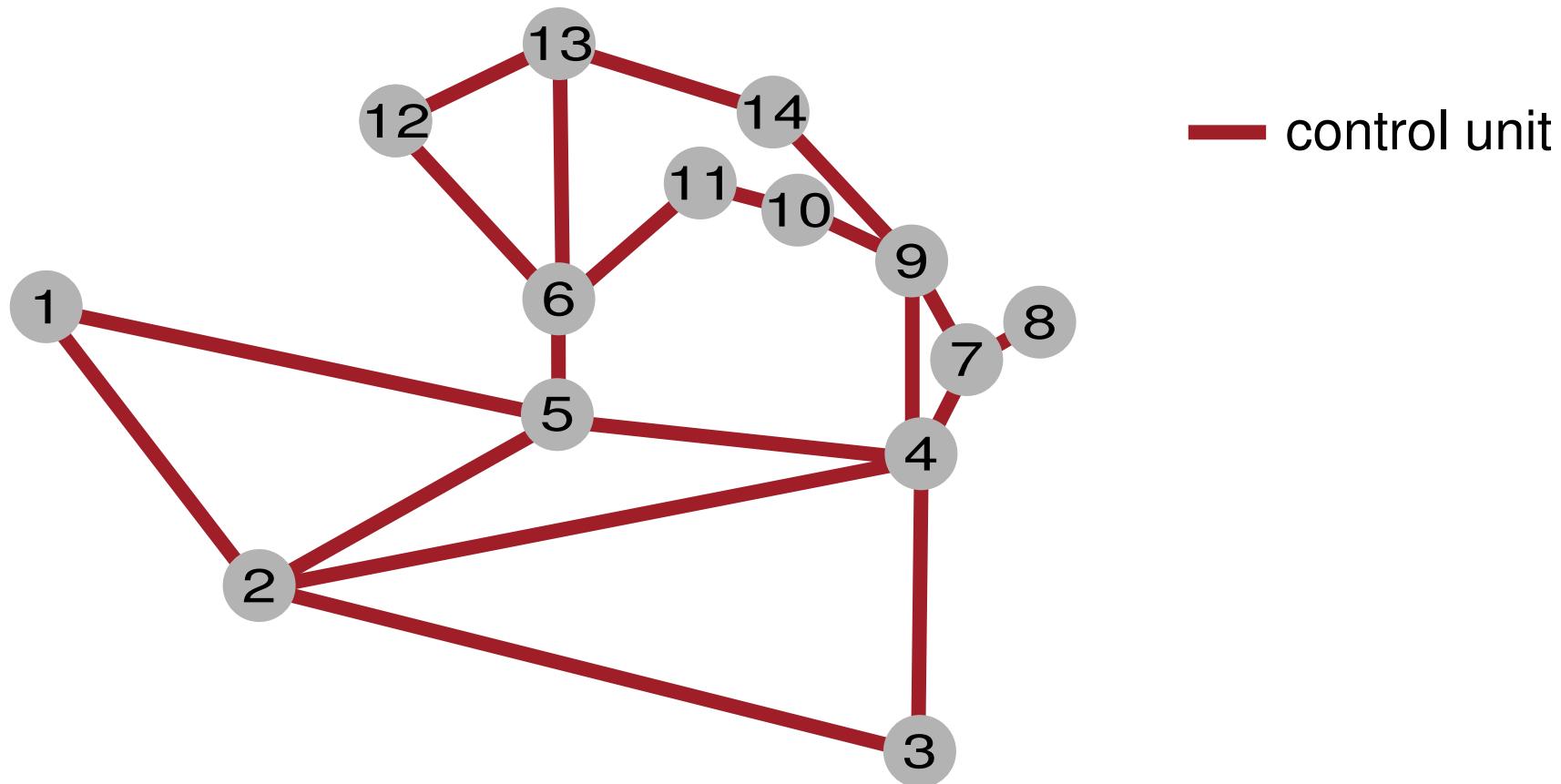
Matching the Flow Model (Q1)

- 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

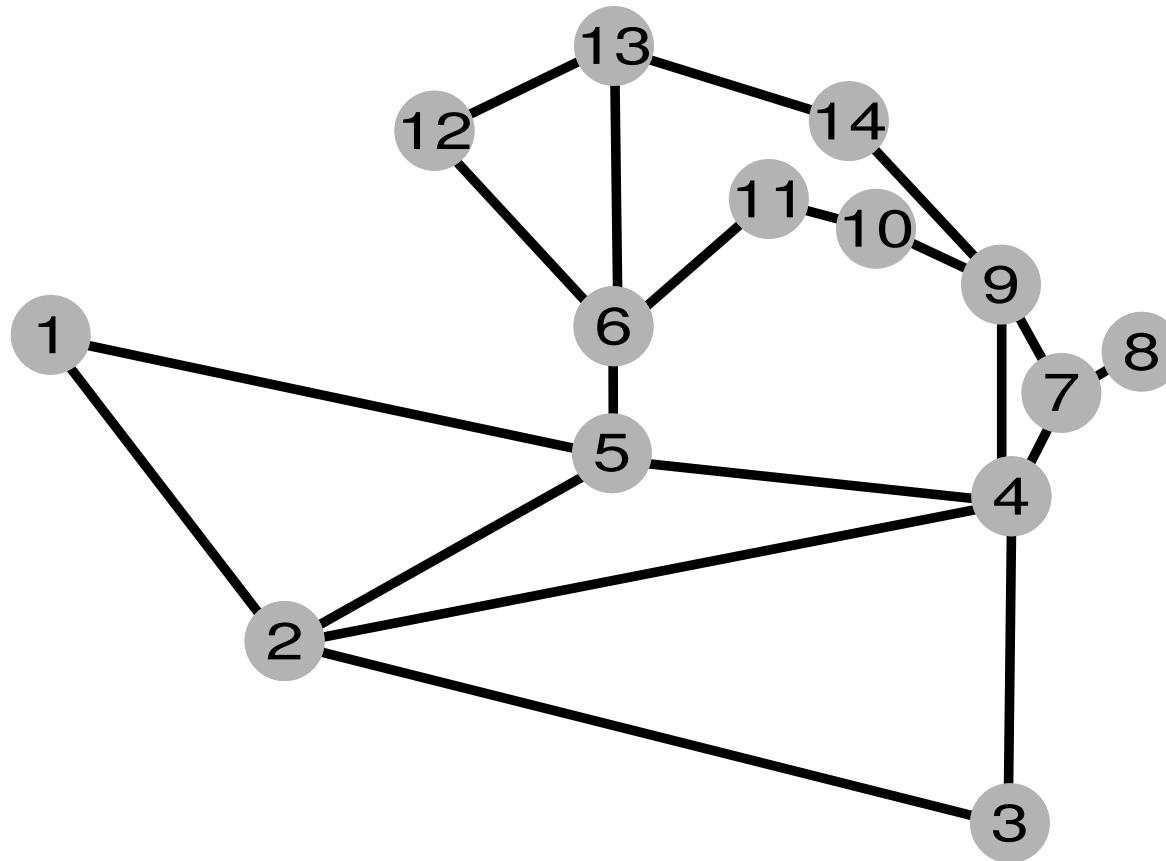


Can we become as good as the Flow Model
with fewer control branches?

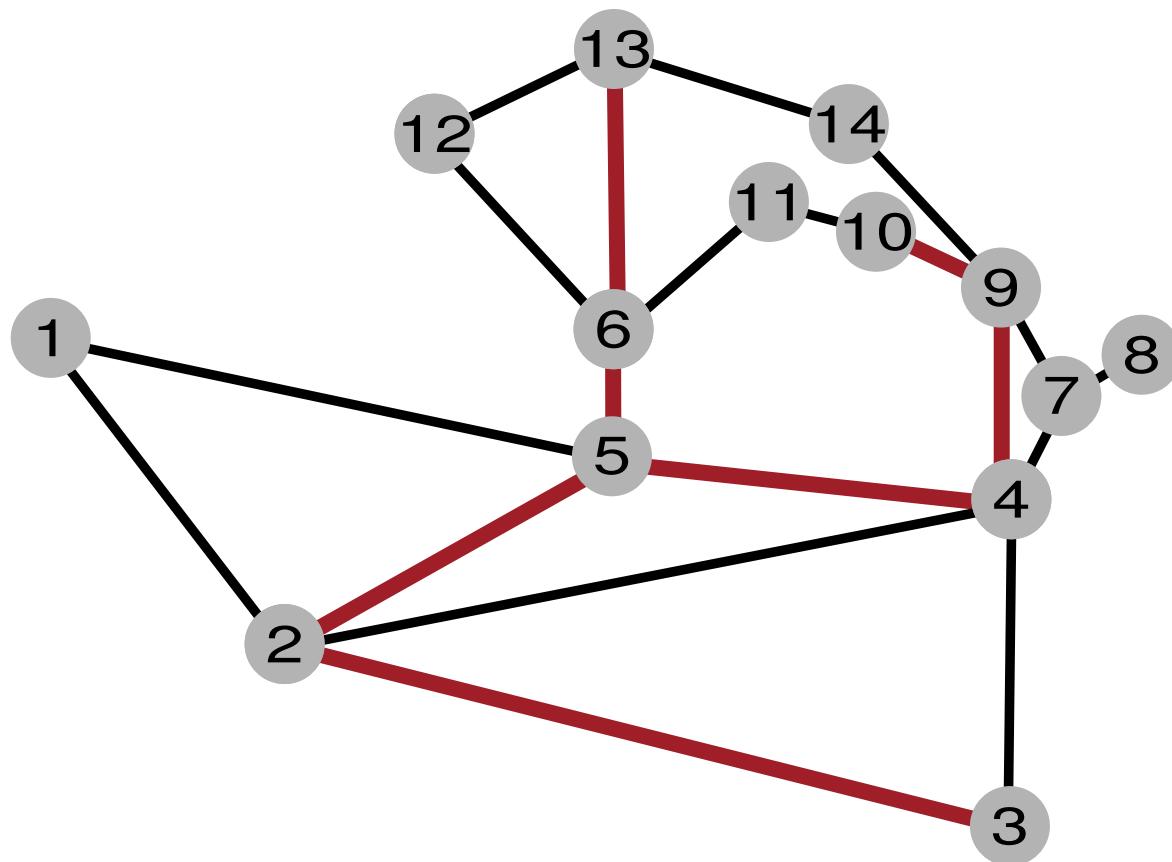
Feedback Forest Set



feedback forest set



Feedback Forest Set

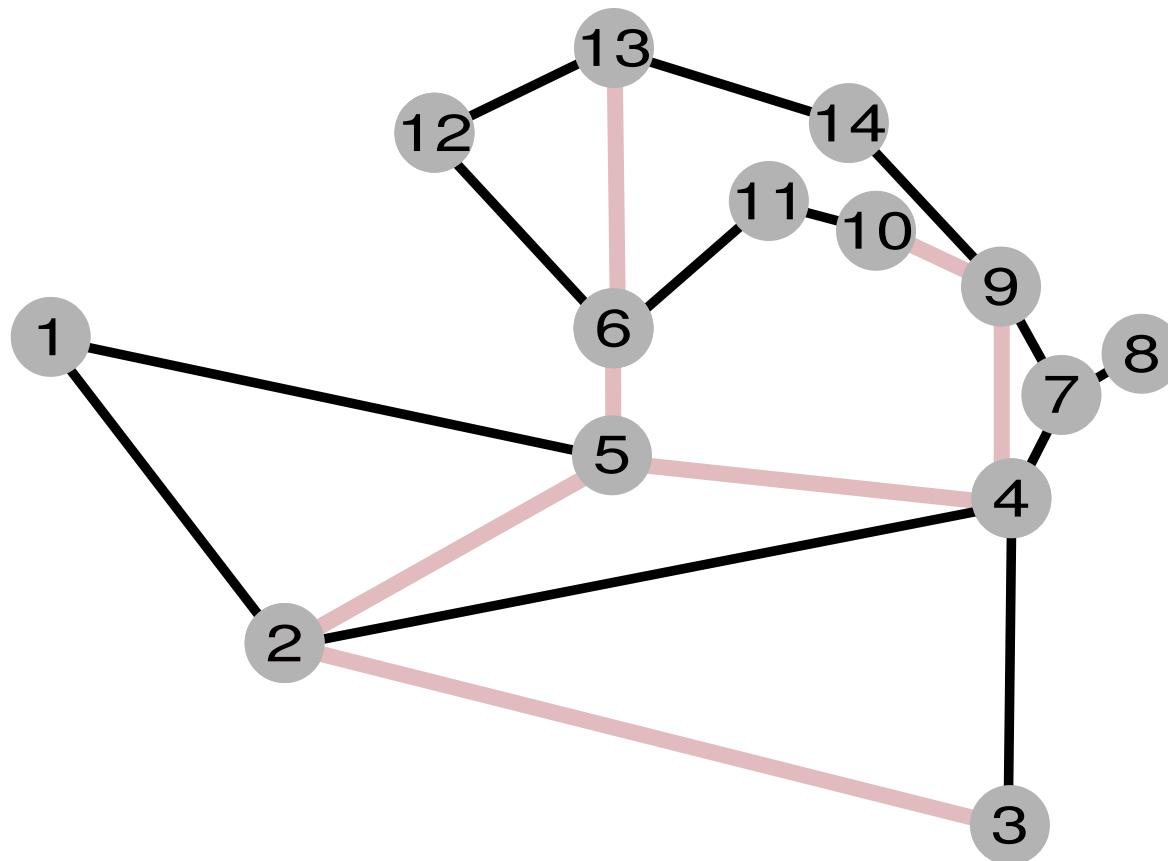


 *feedback forest set*

↓

A set of trees (*forest*) remains!

Feedback Forest Set



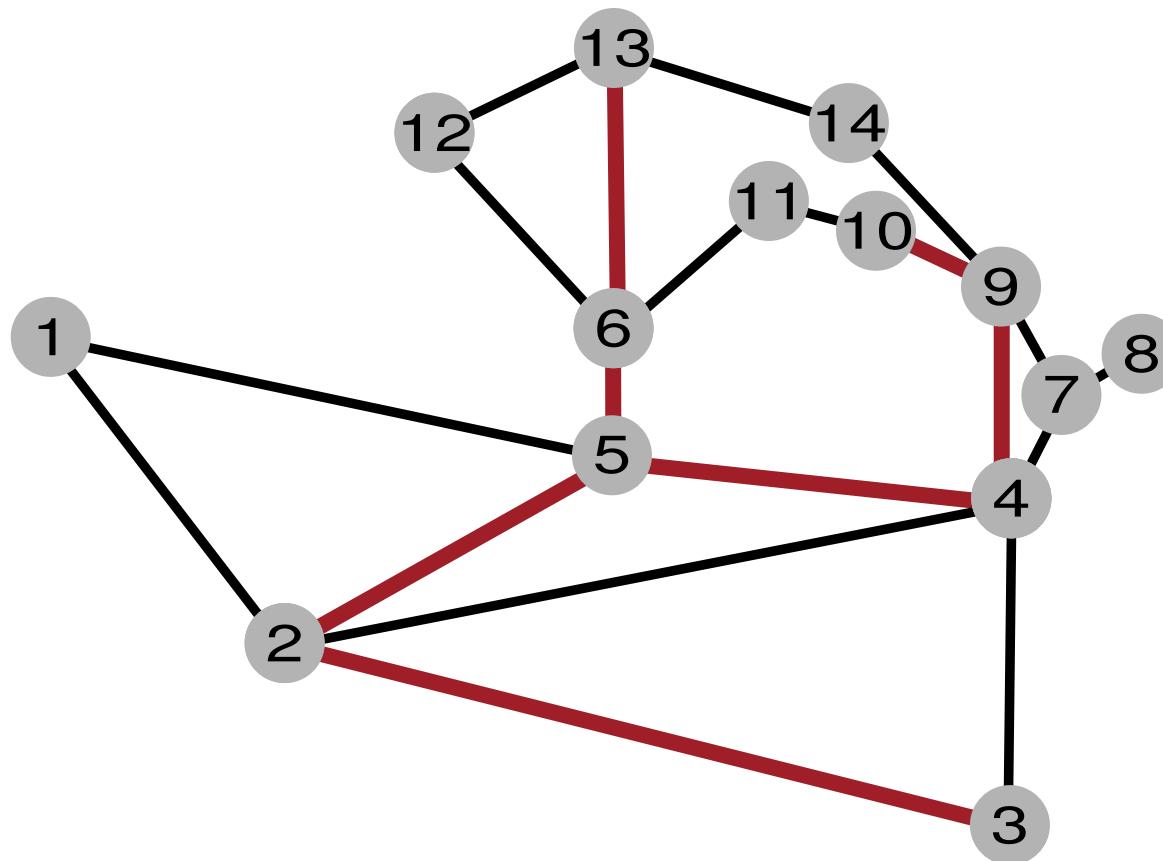
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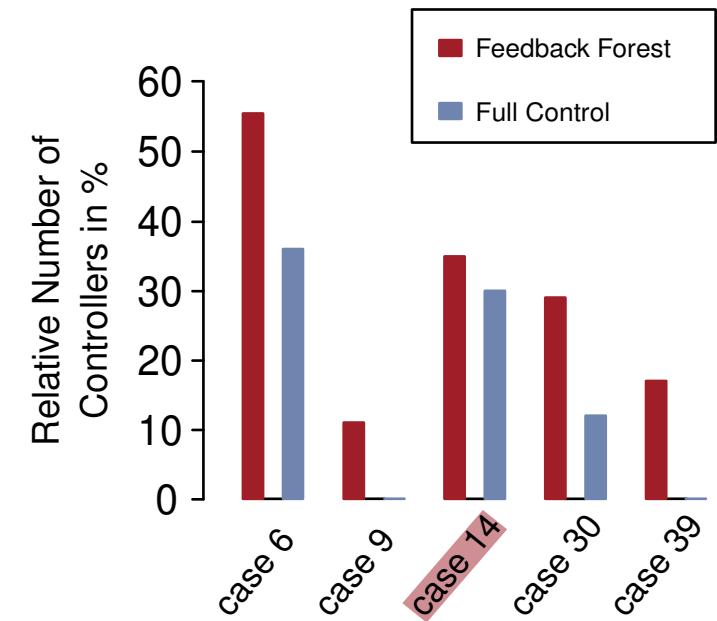
Theorem 1

Physical subgrid forest \Rightarrow All flows obey voltage laws

Feedback Cactus Set

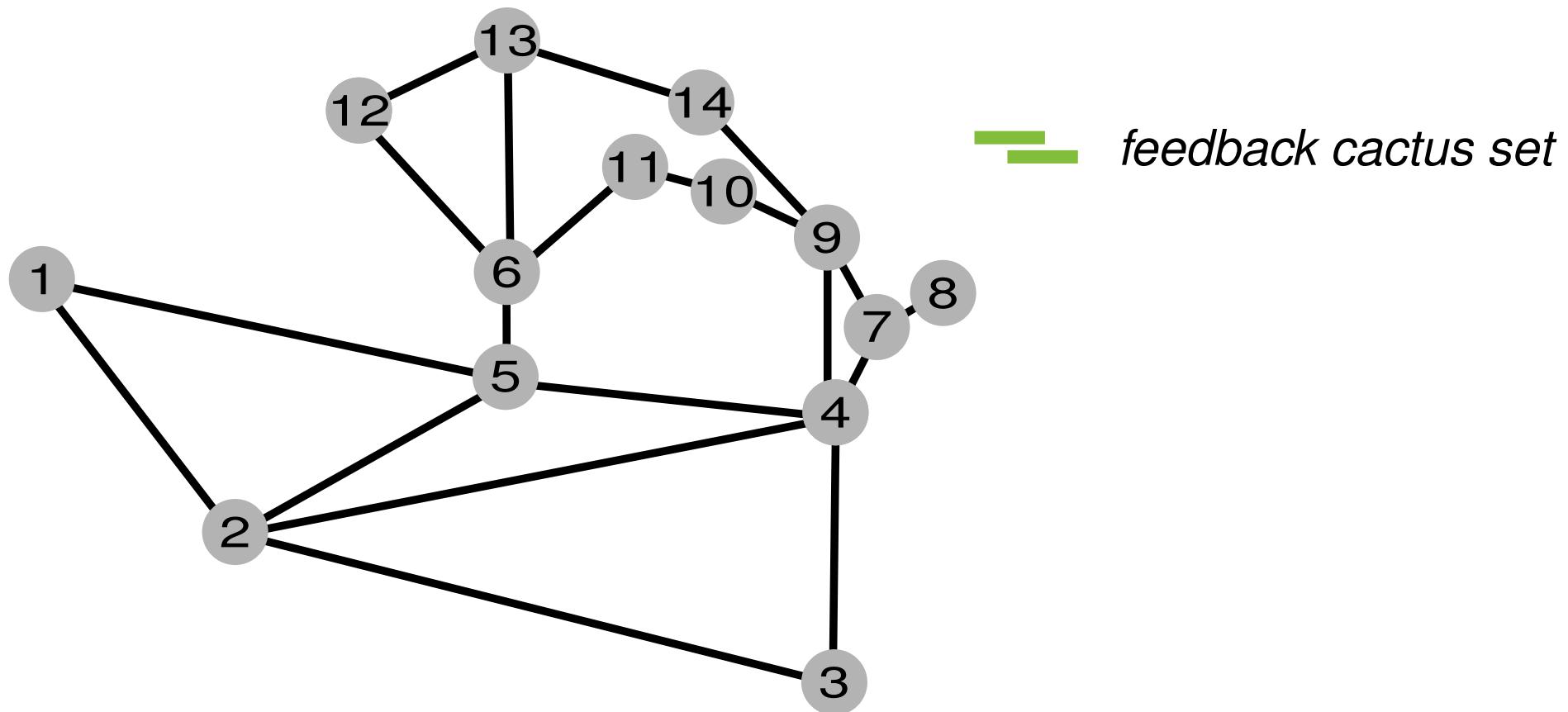


feedback forest set

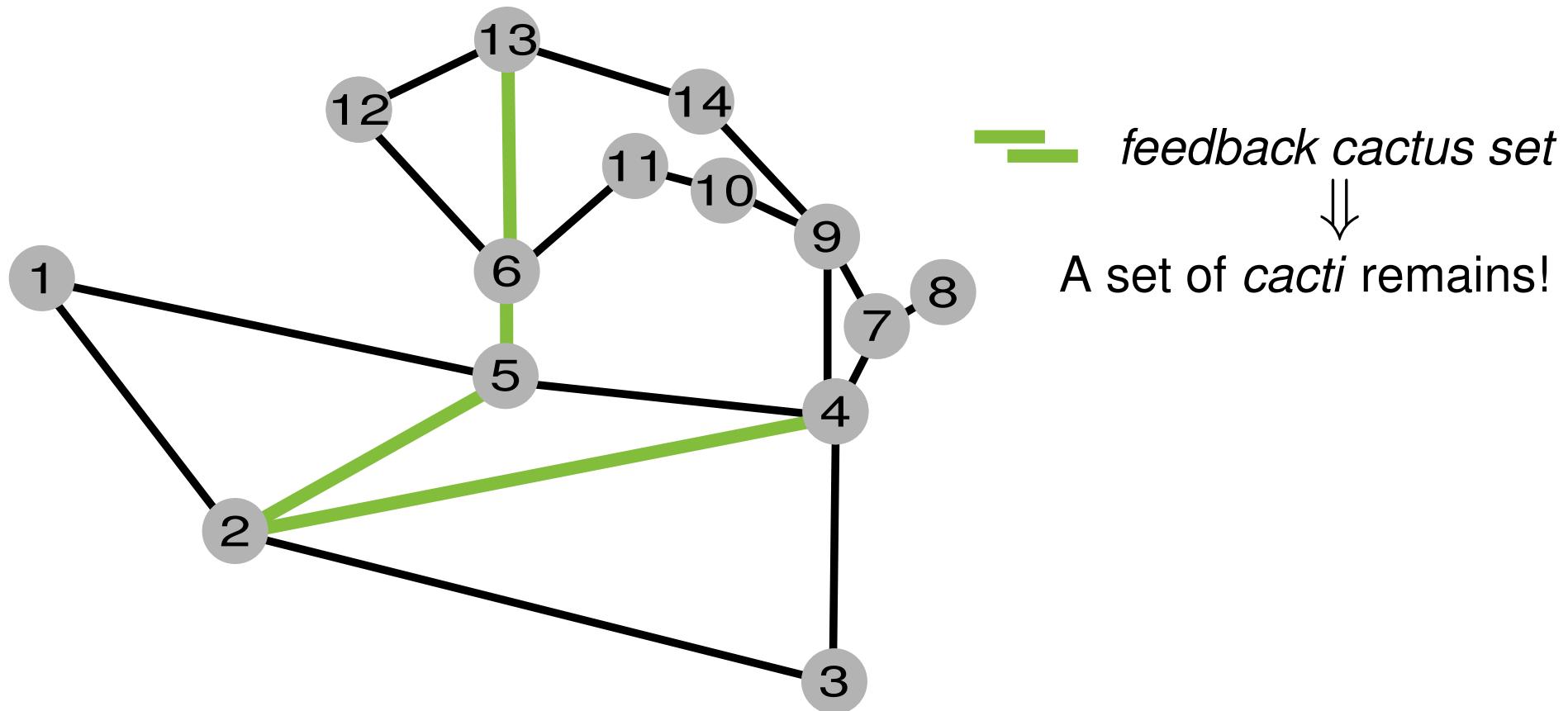


Fewer than 7 flow control buses sufficient?

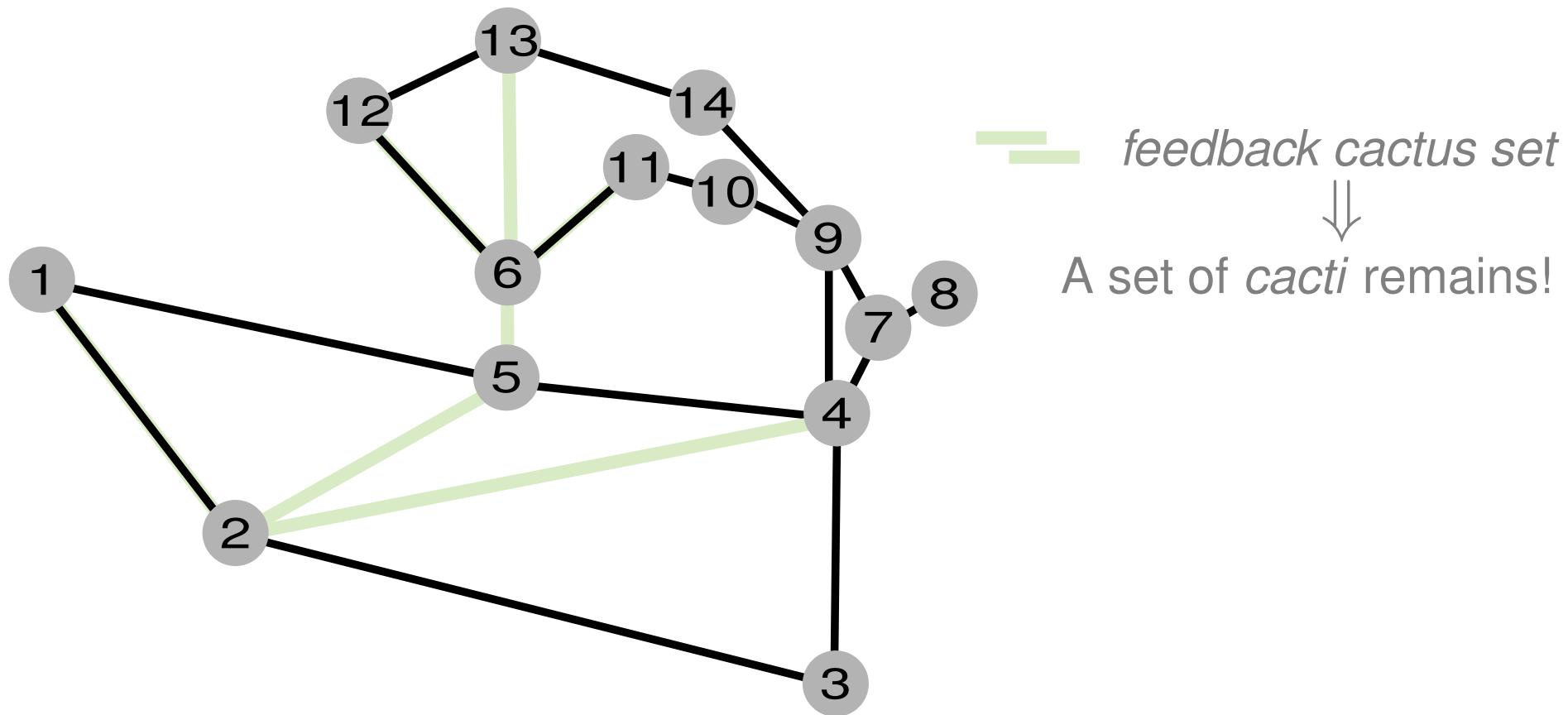
Feedback Cactus Set



Feedback Cactus Set



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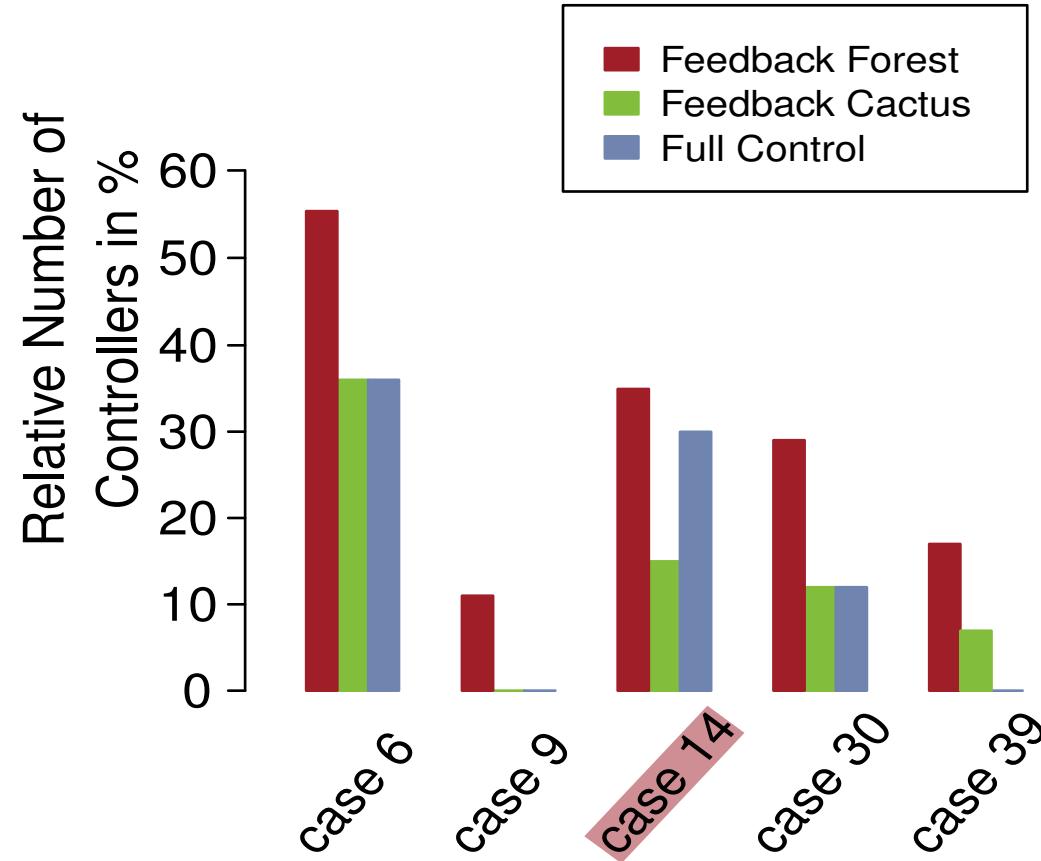
Theorem 2

Physical subgrid cactus, line limits on cactus suitably bounded.

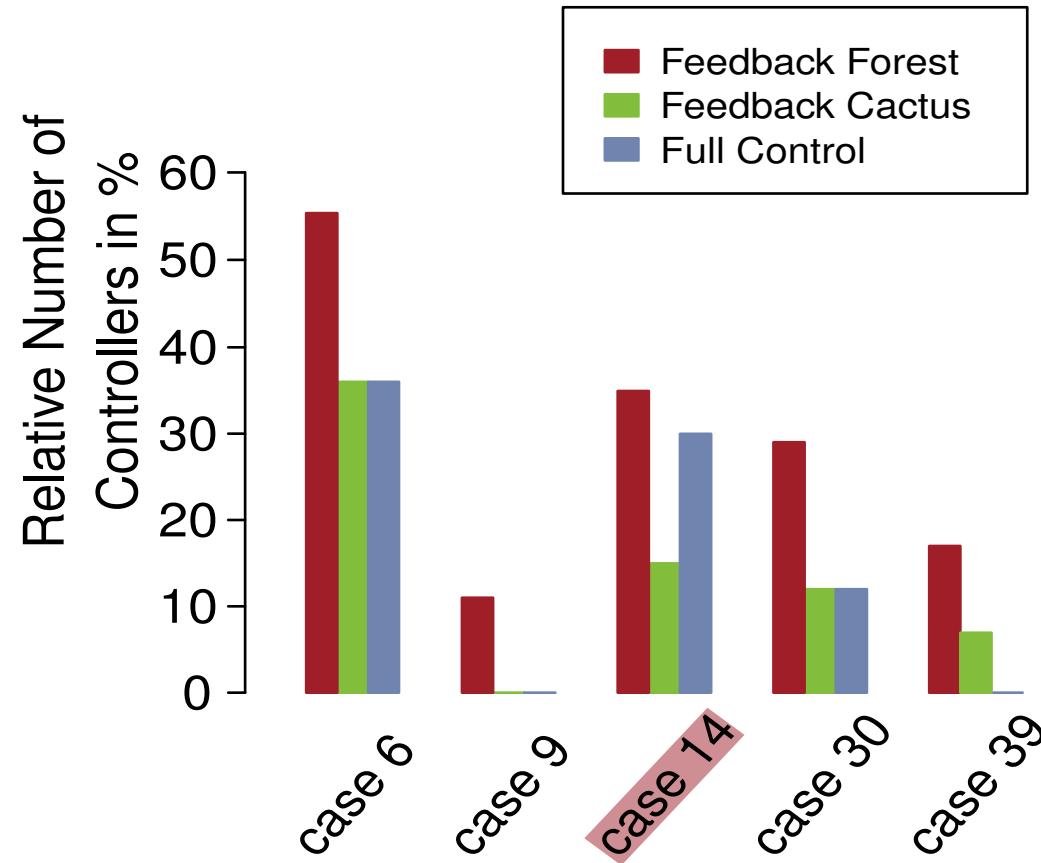


For every flow there is a cost-equivalent flow obeying voltage laws.

Number of Control Branches vs. Structural Results



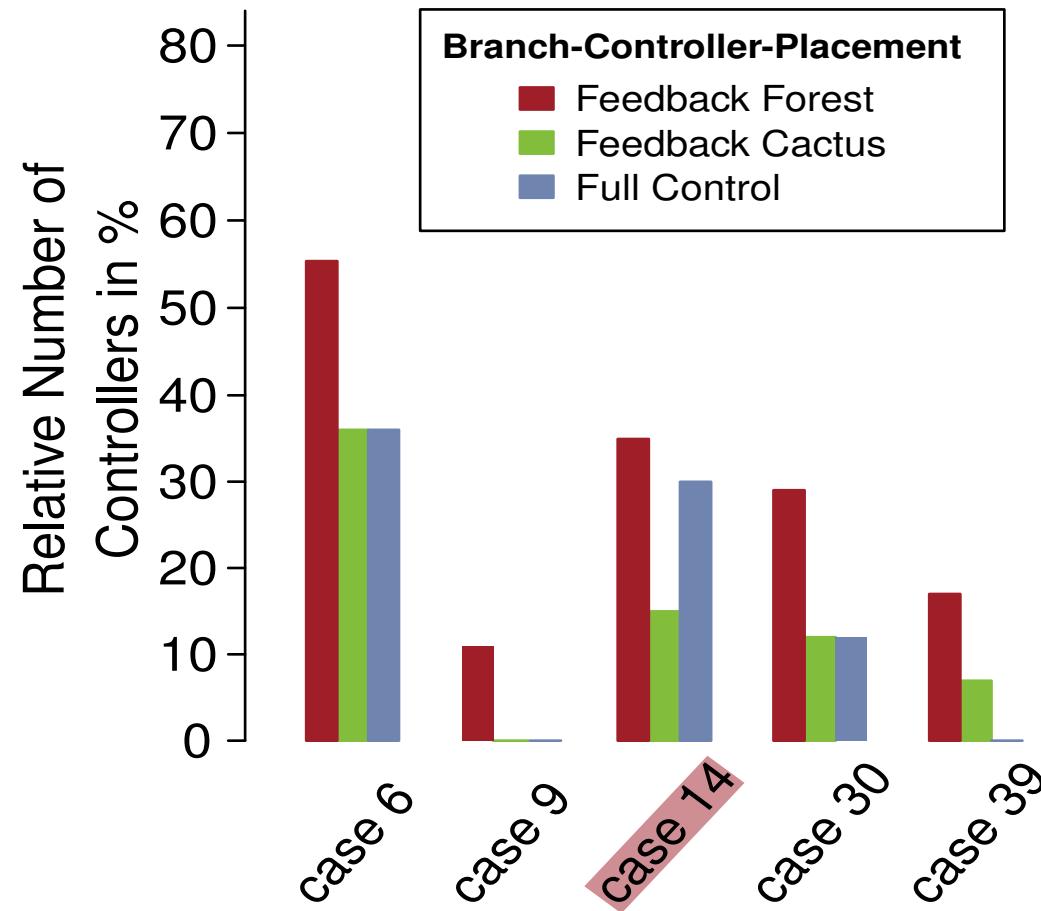
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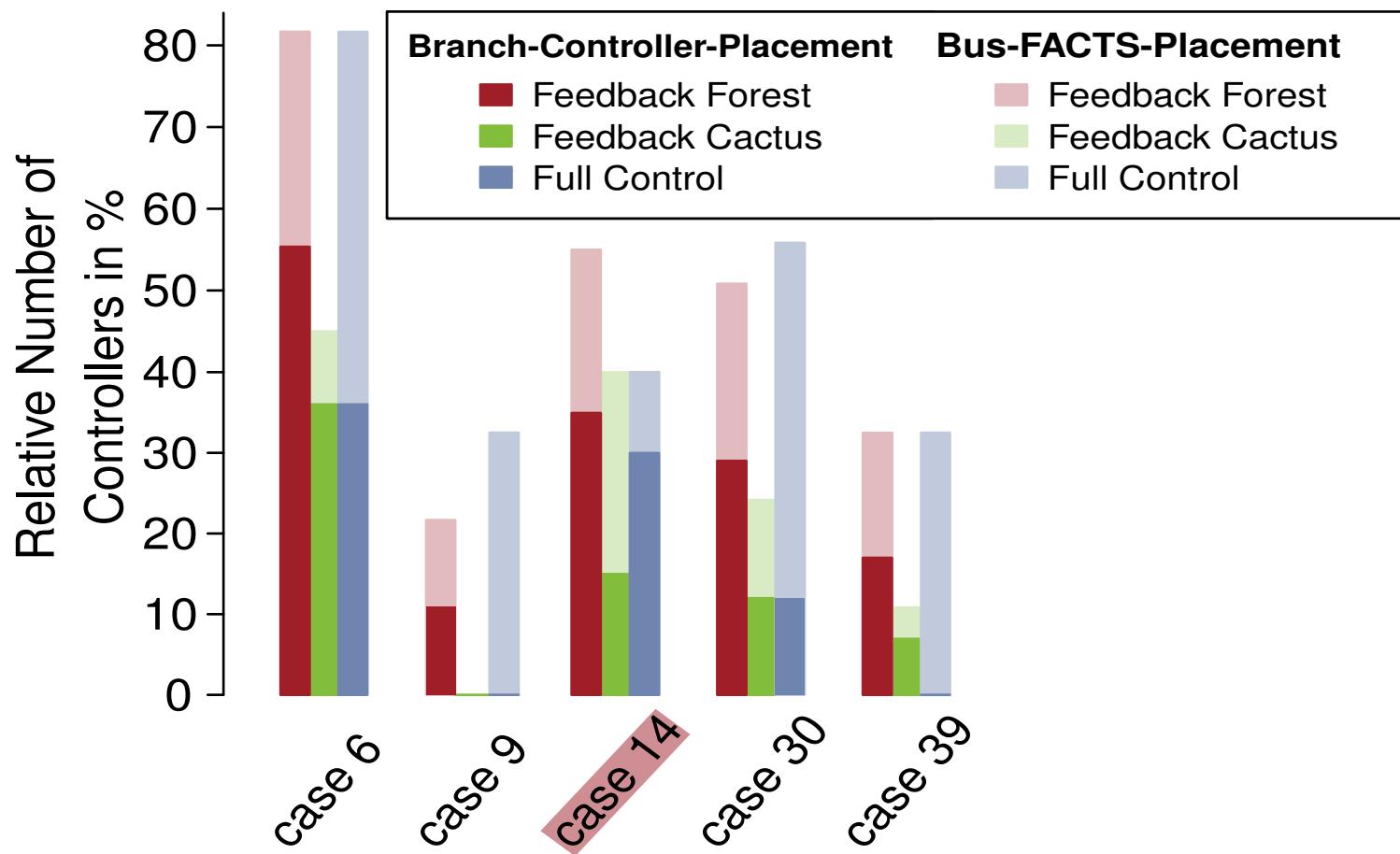
Findings

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

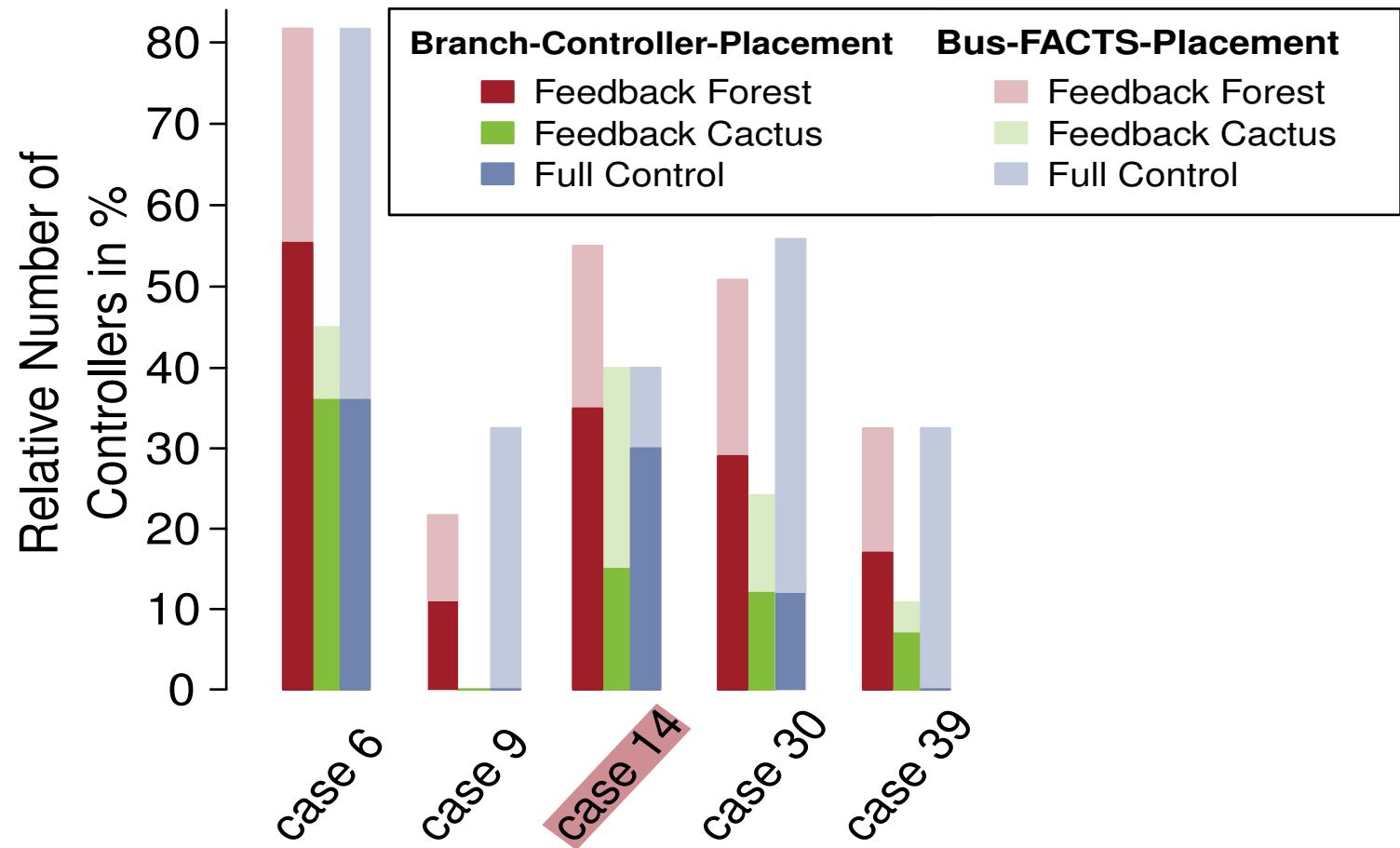
Control Branches vs. Control Buses



Control Branches vs. Control Buses



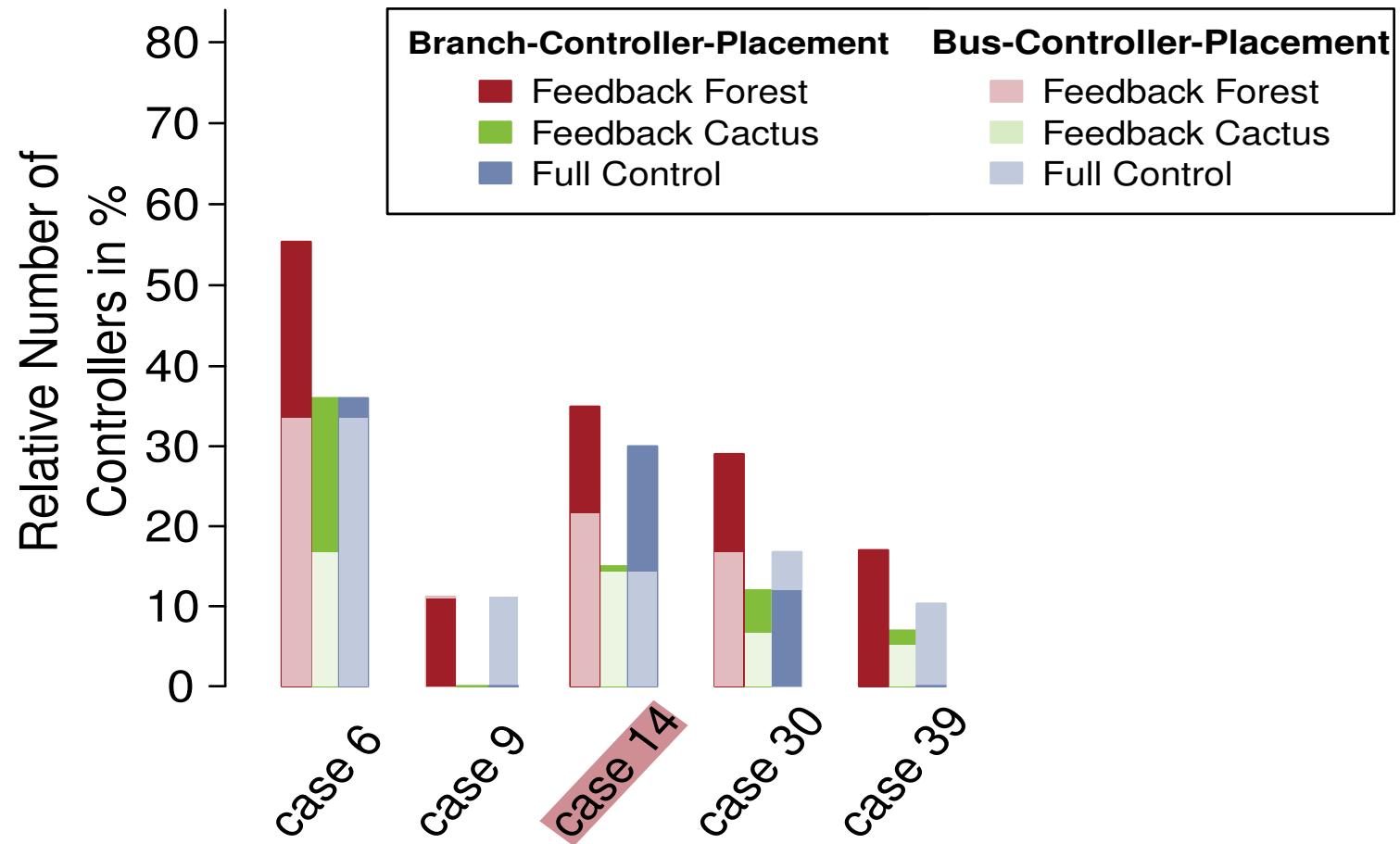
Control Branches vs. Control Buses



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 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?

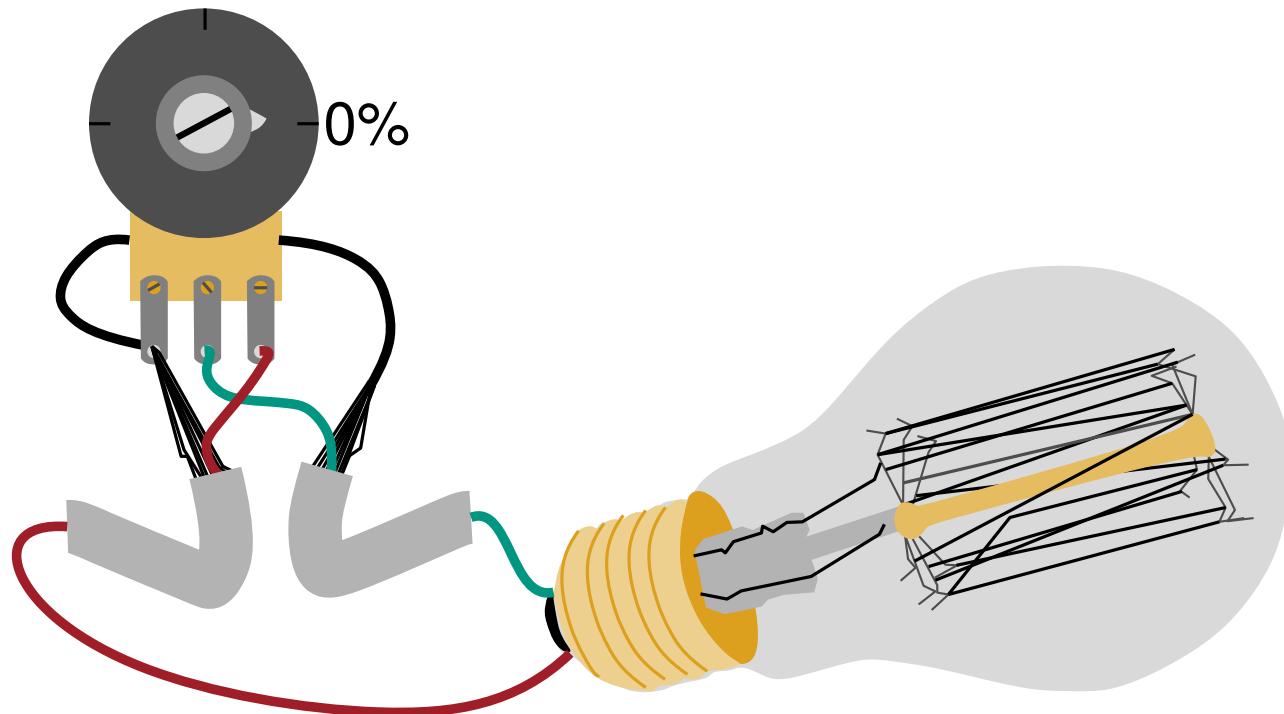
Figures FLTR:

³ <http://www.abb.com/cawp/seitp202/c36f4e62da52ab46c1257670003690d3.aspx>

⁴ <http://electrical-engineering-portal.com/facts-flexible-ac-transmission-systems>

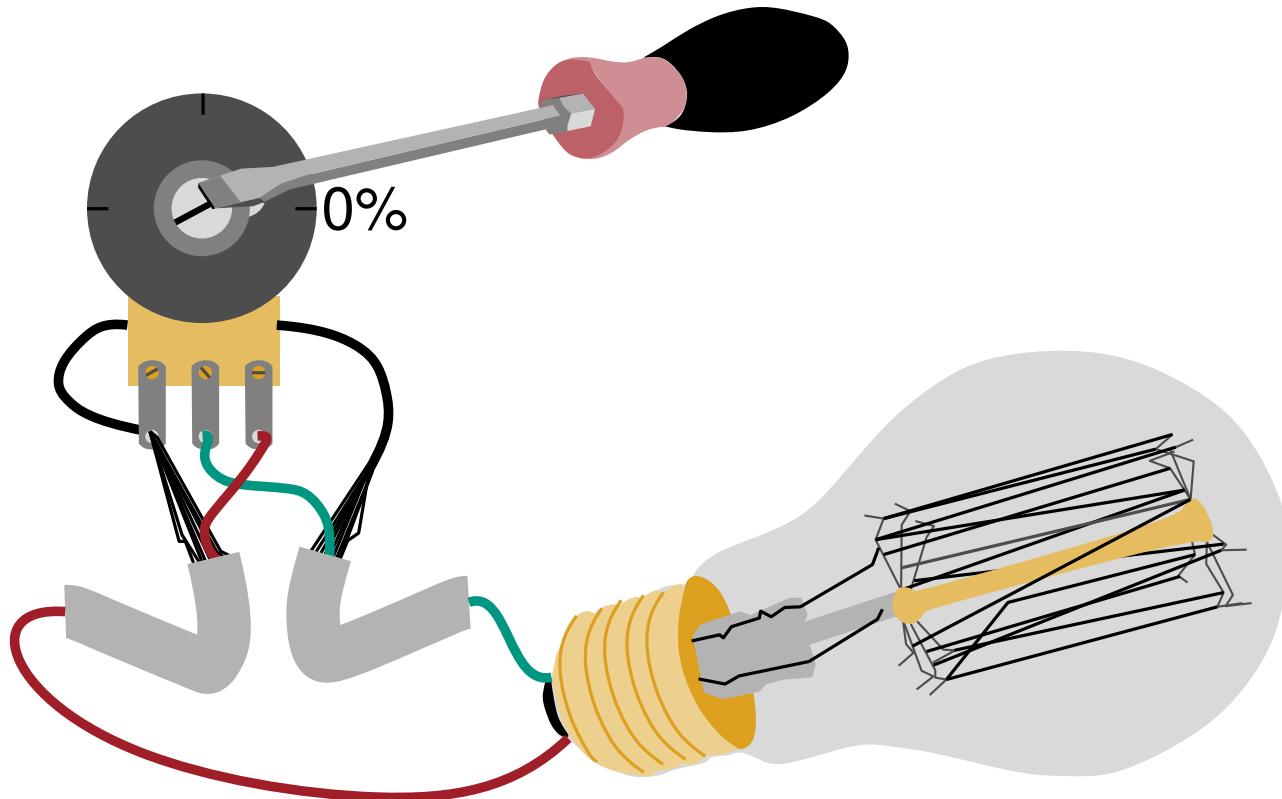
Effect of Few Flow Control Branches

Simulate load increase by a load increase factor ρ ,



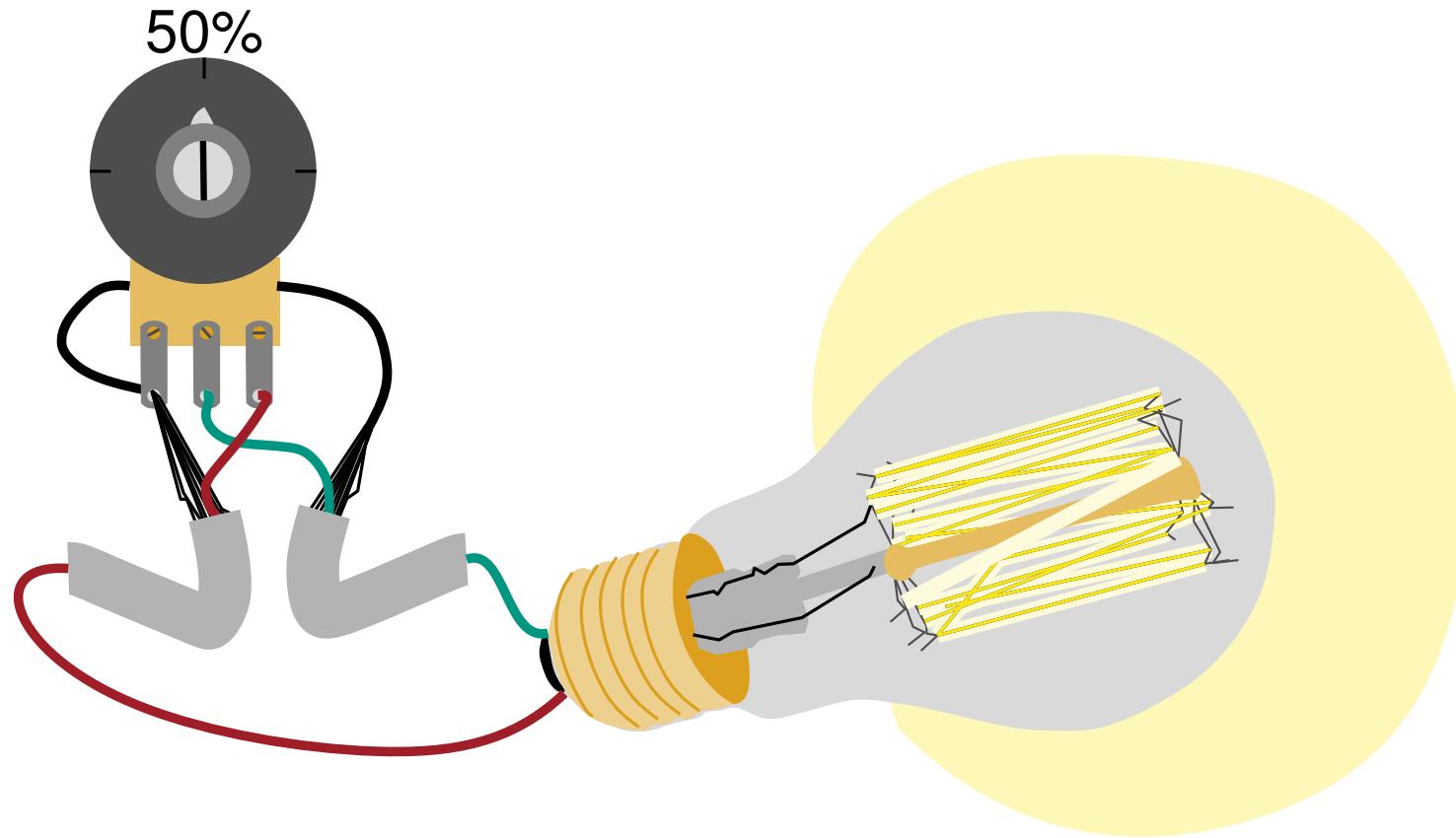
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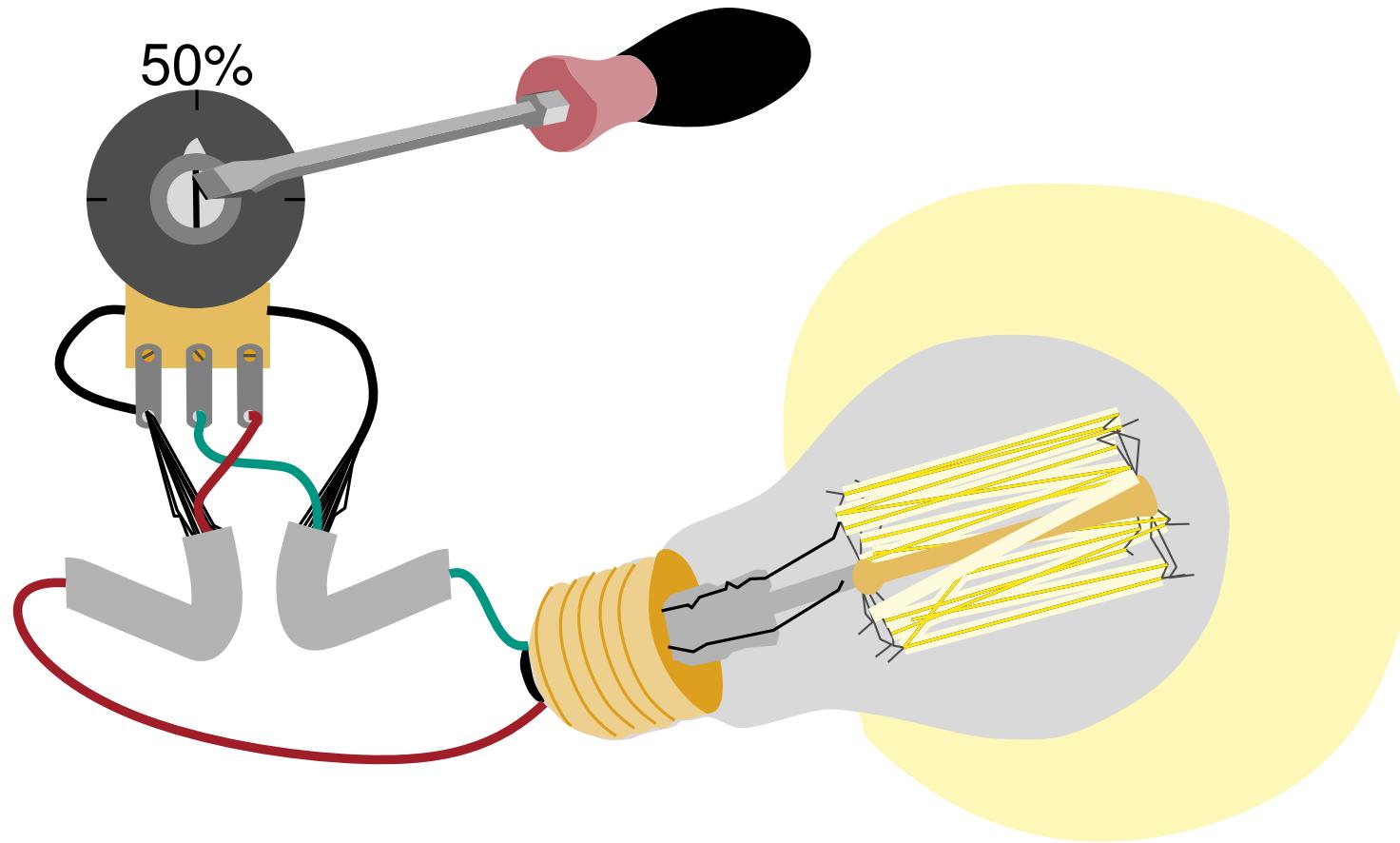
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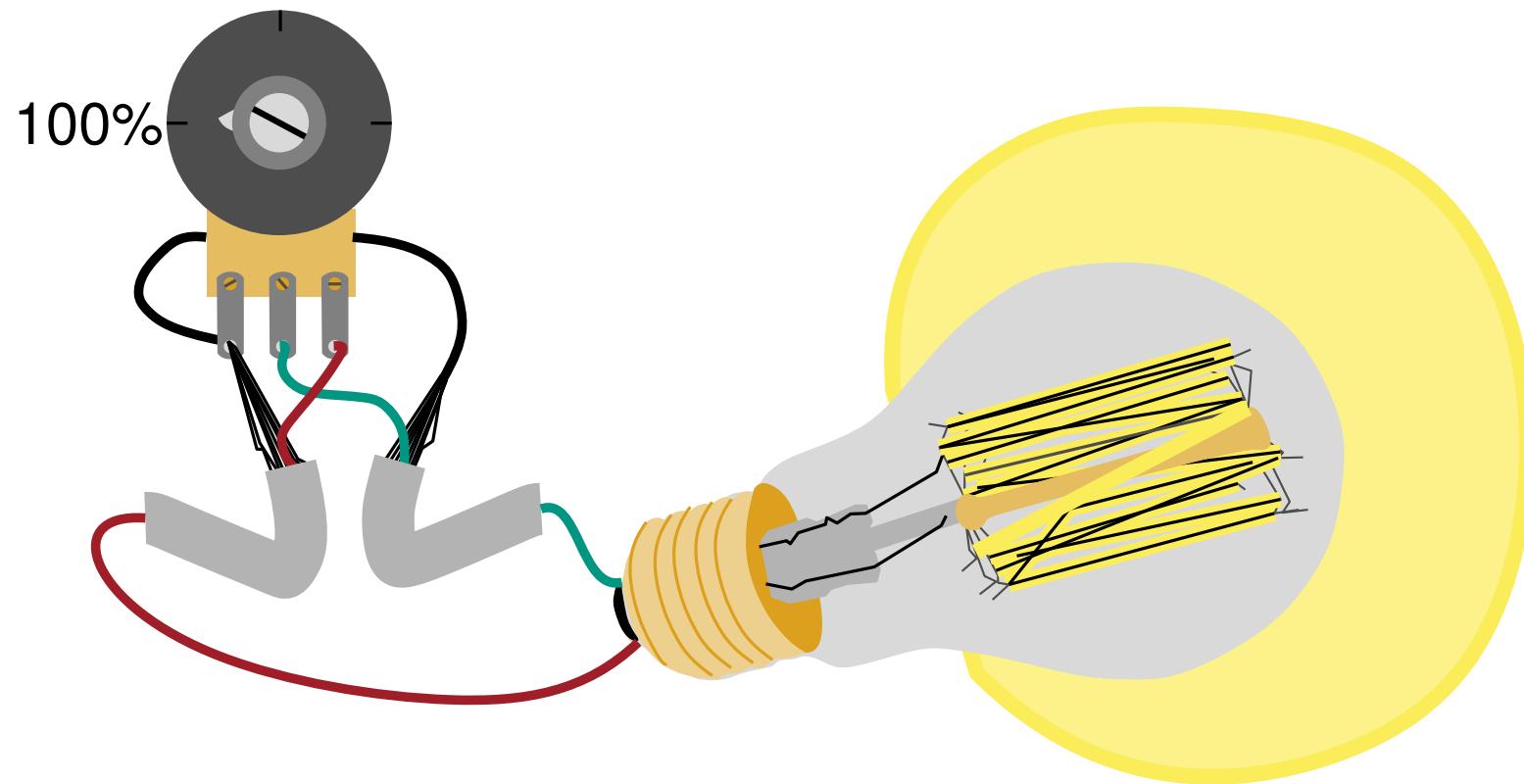
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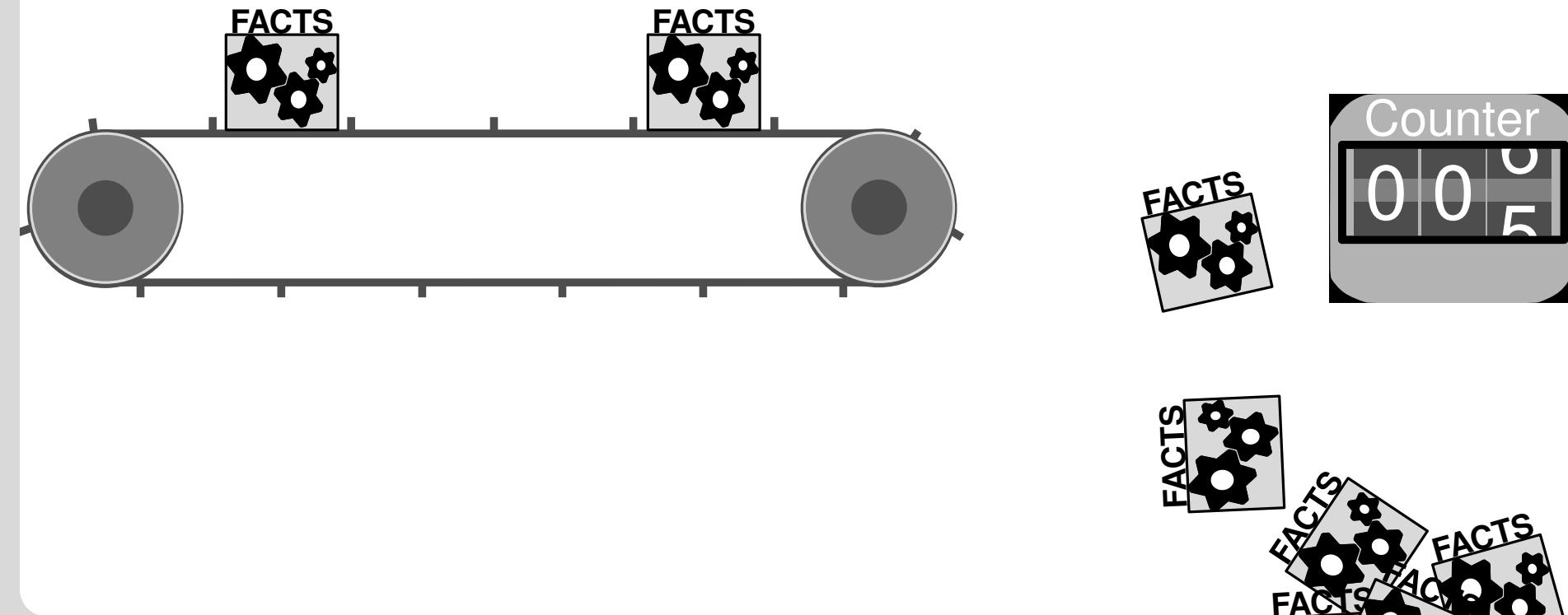
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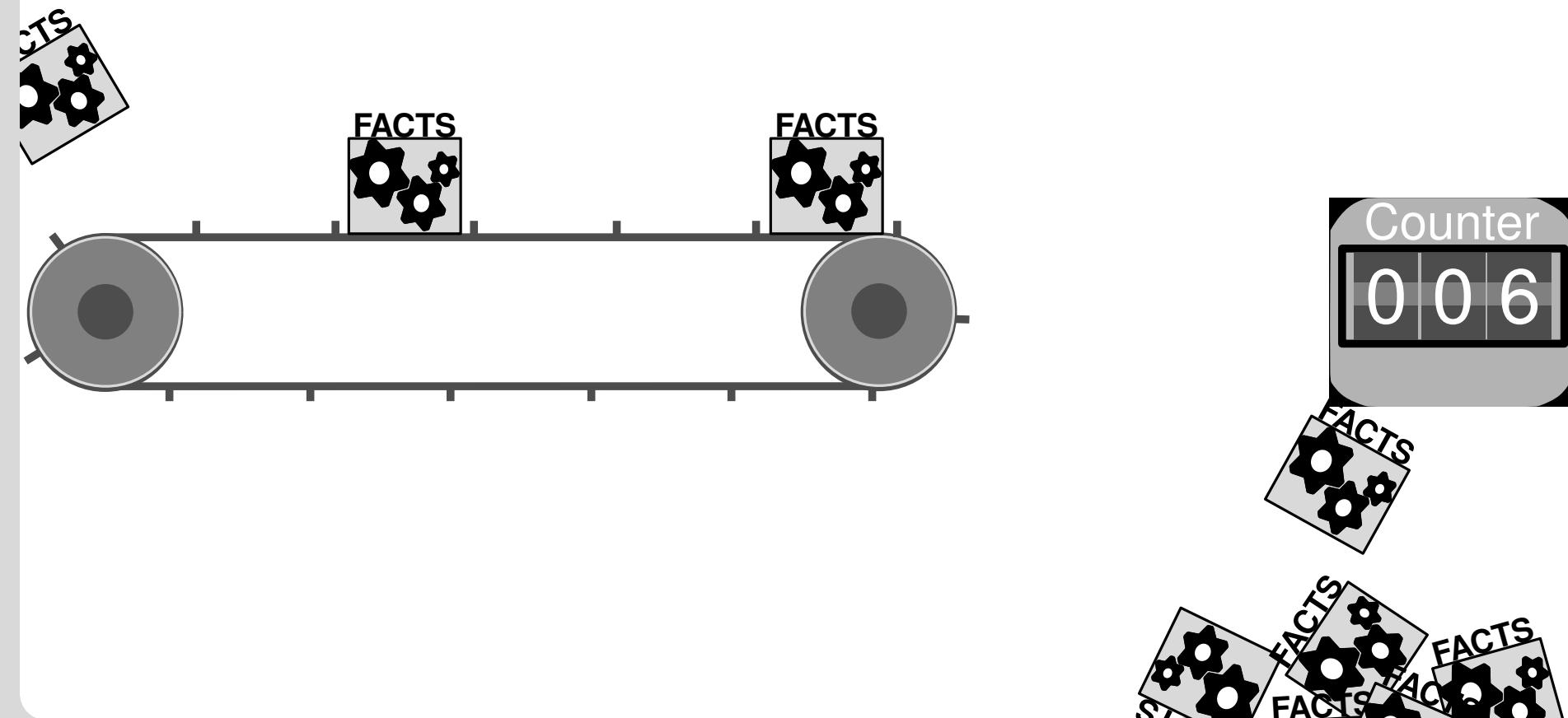
Effect of Few Flow Control Branches

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



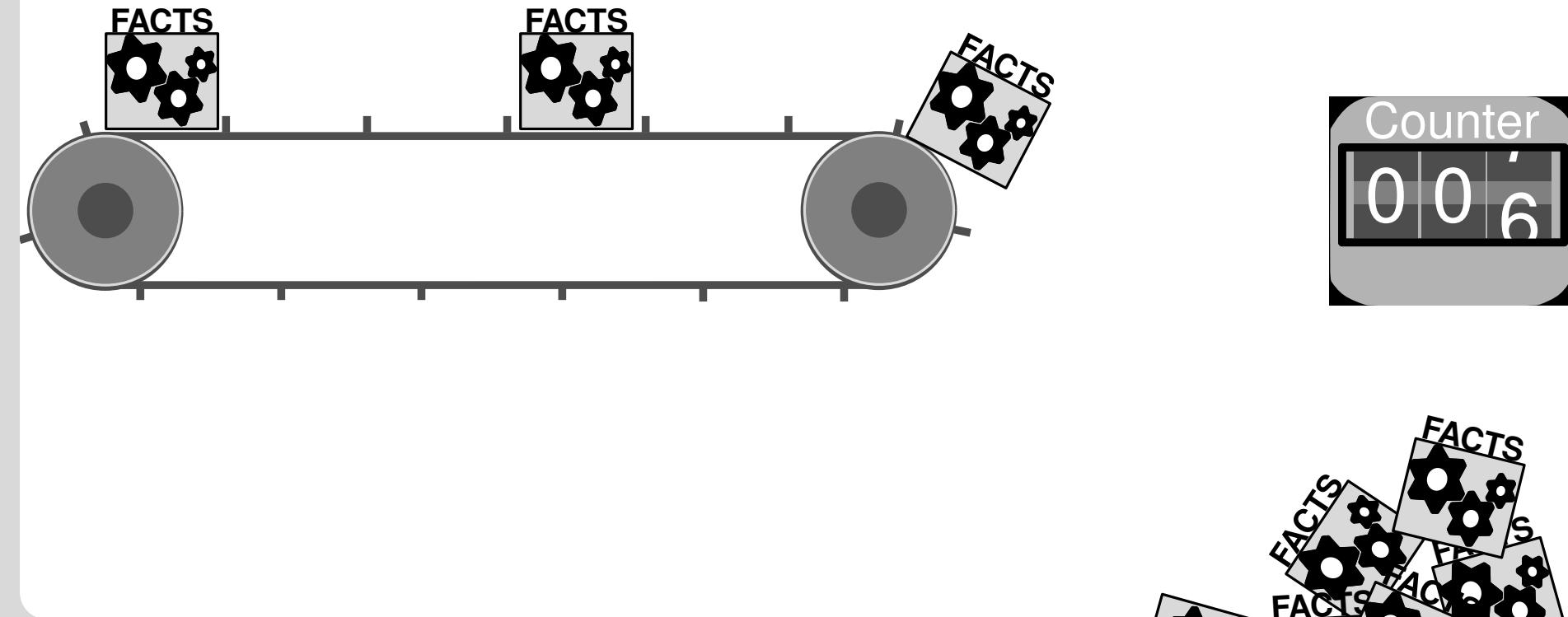
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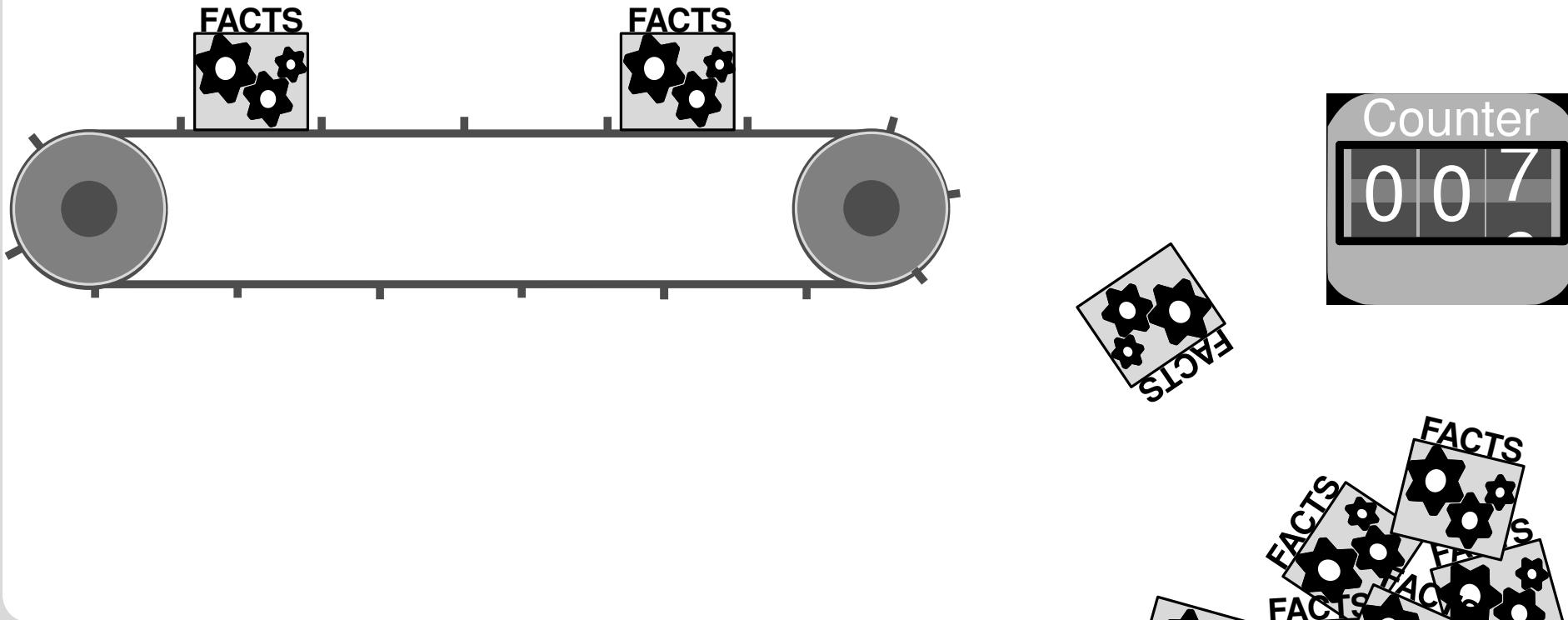
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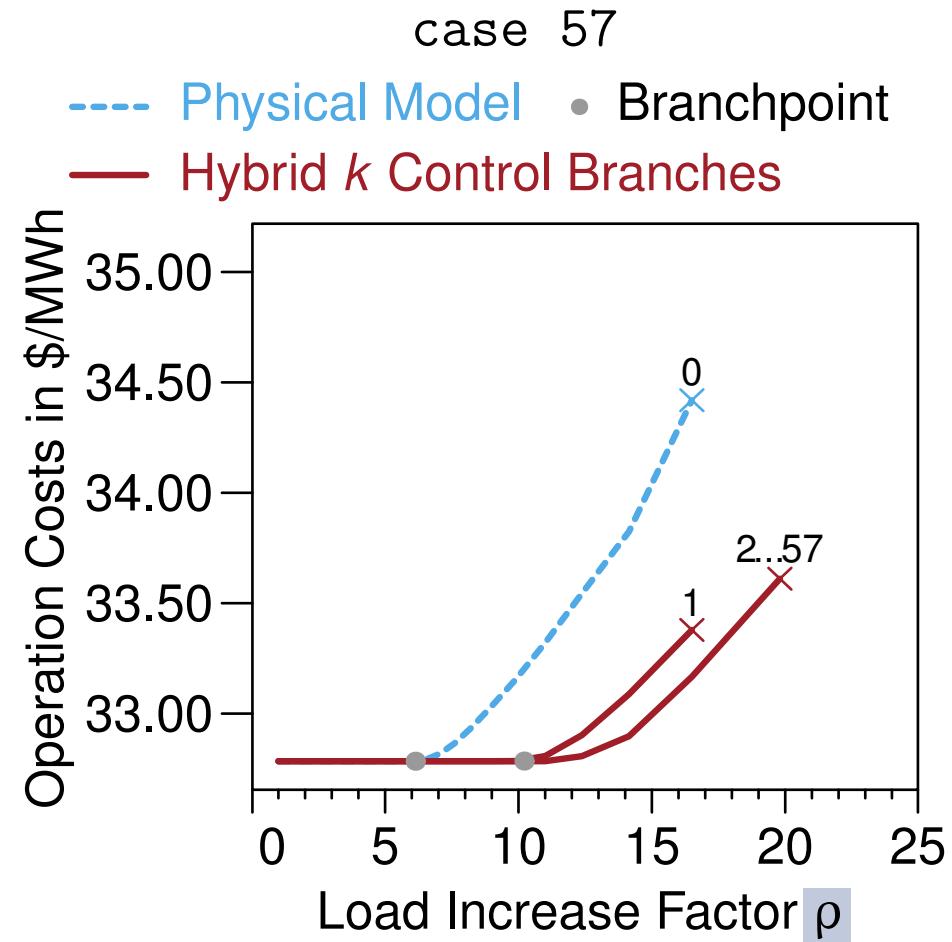
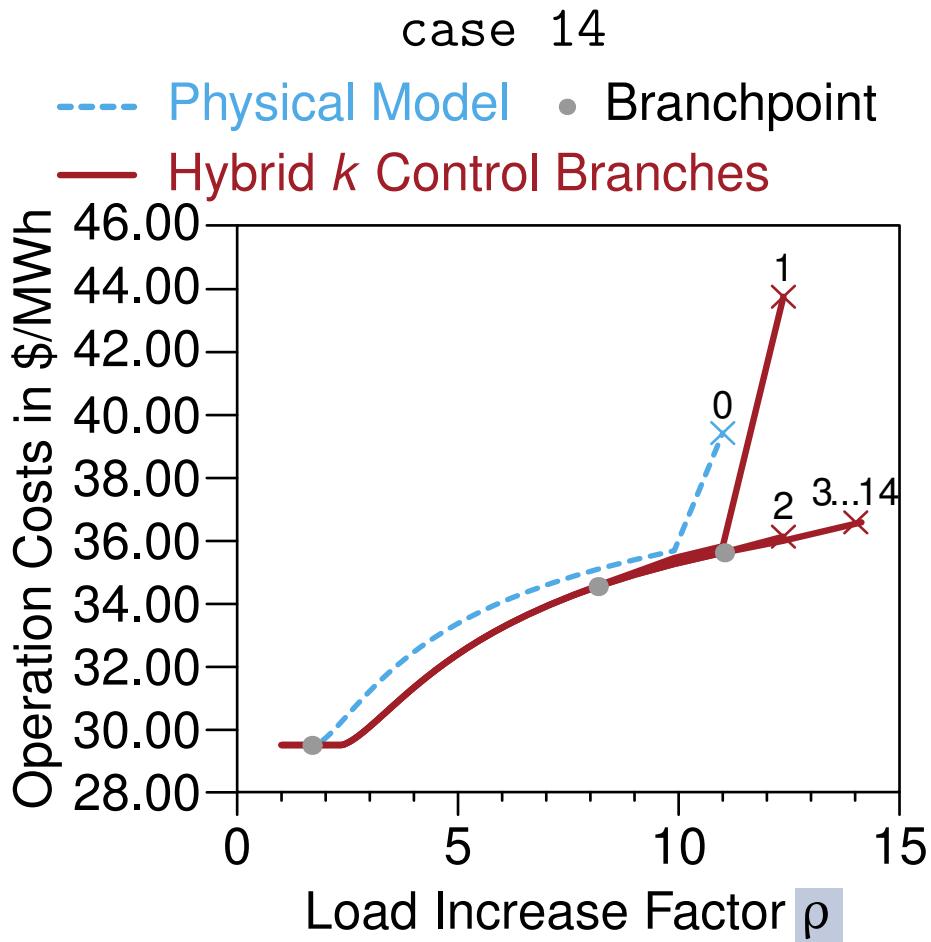


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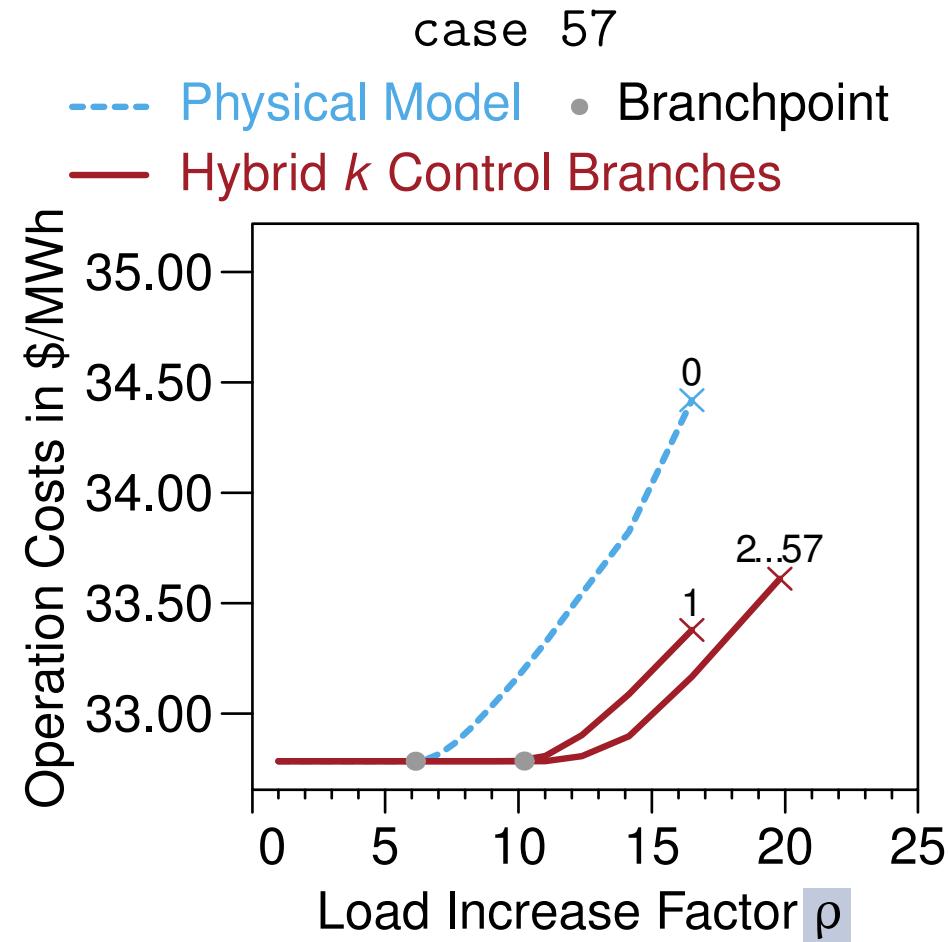
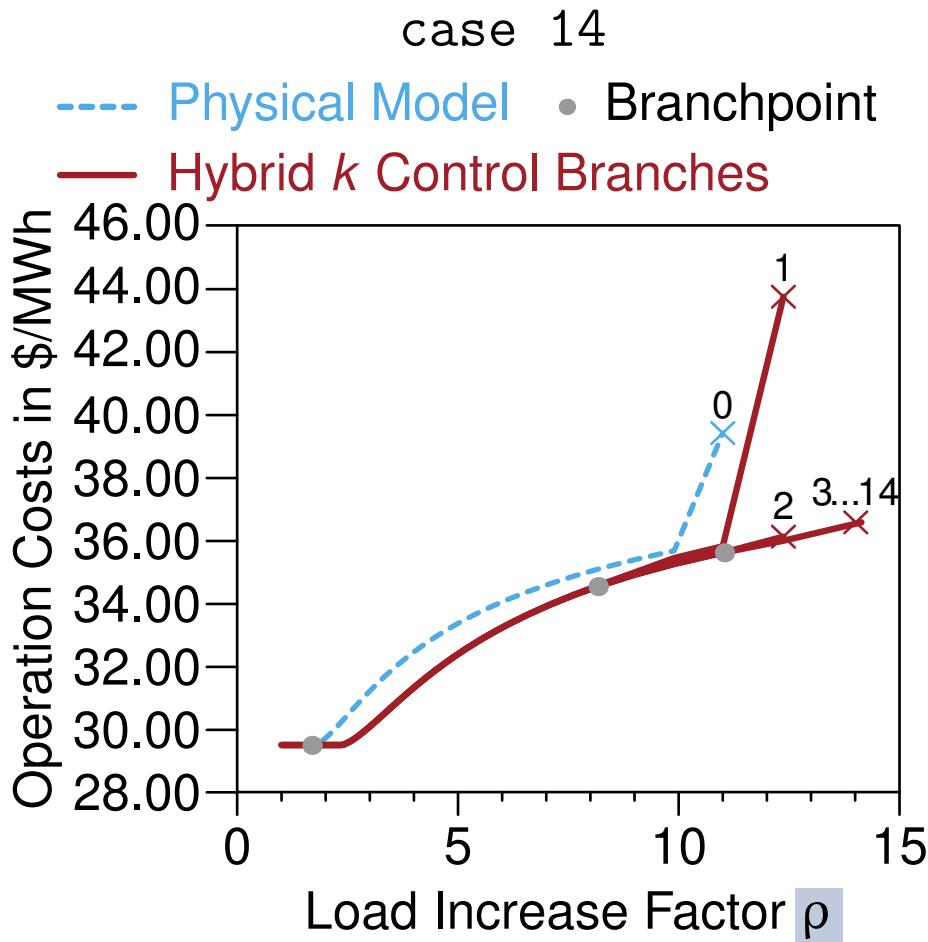
Test Data:

- 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 branches extend operation point at lower cost.

Summary & Future Work

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

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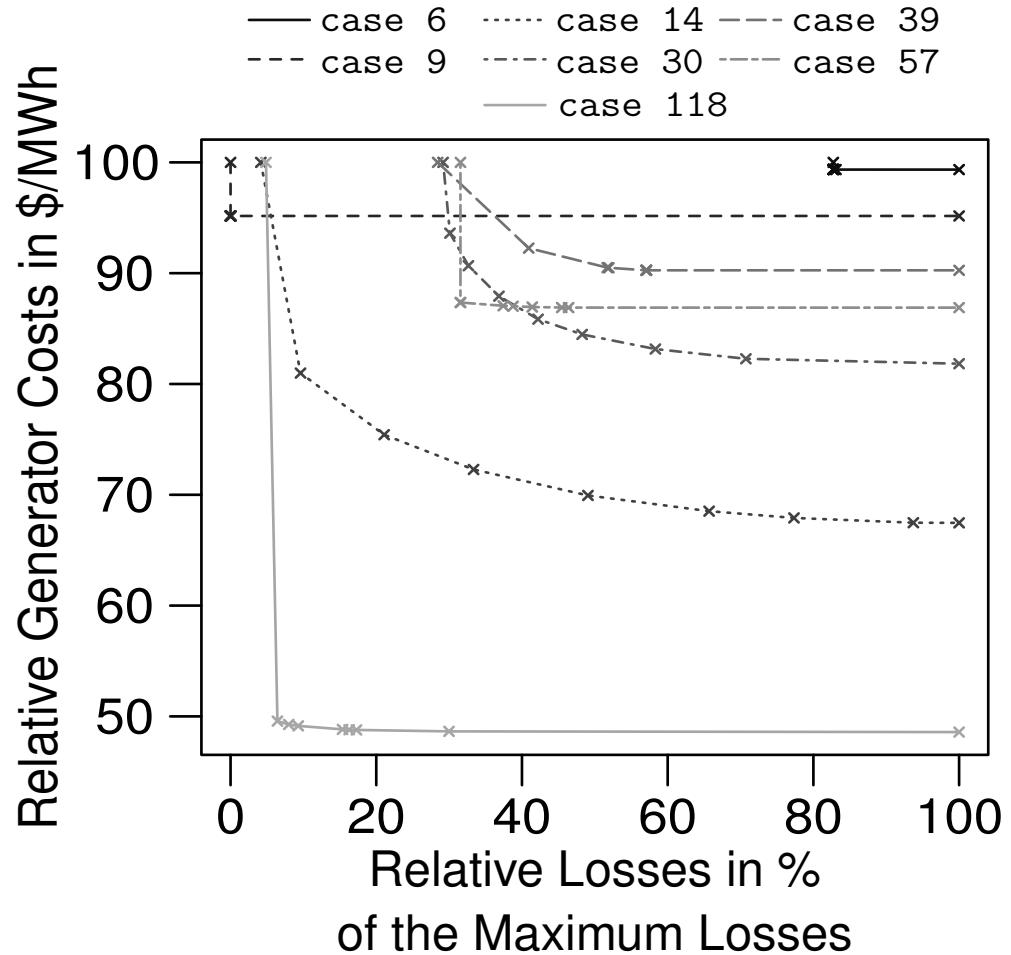
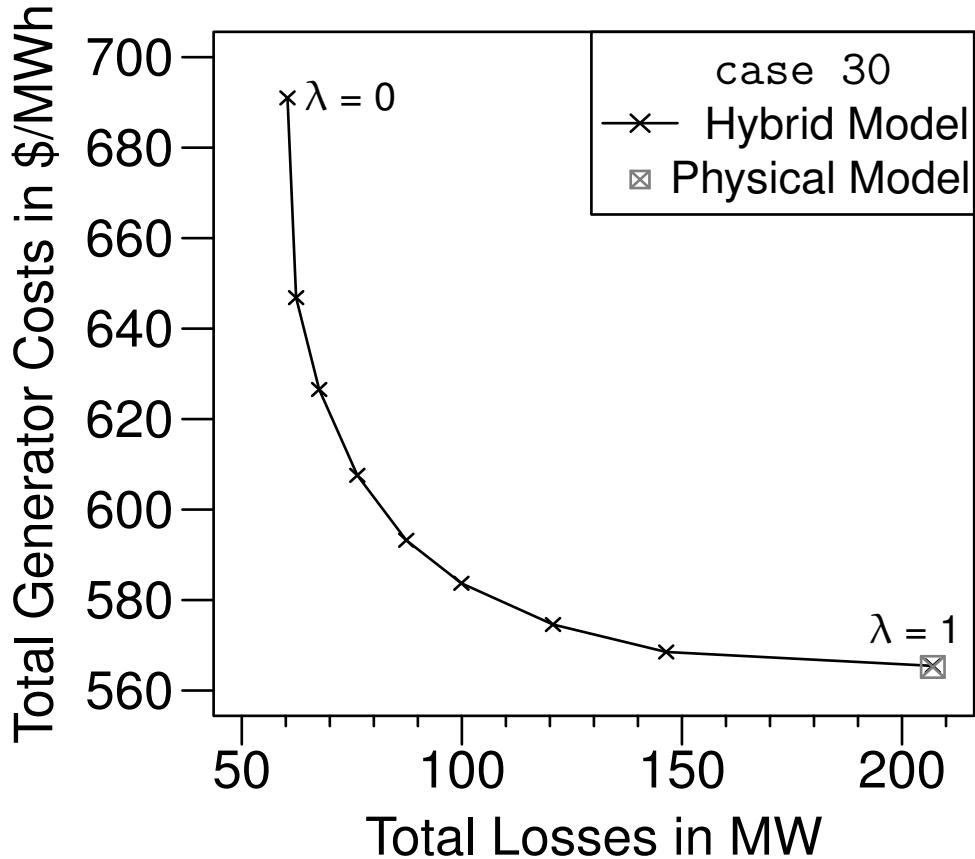
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Findings

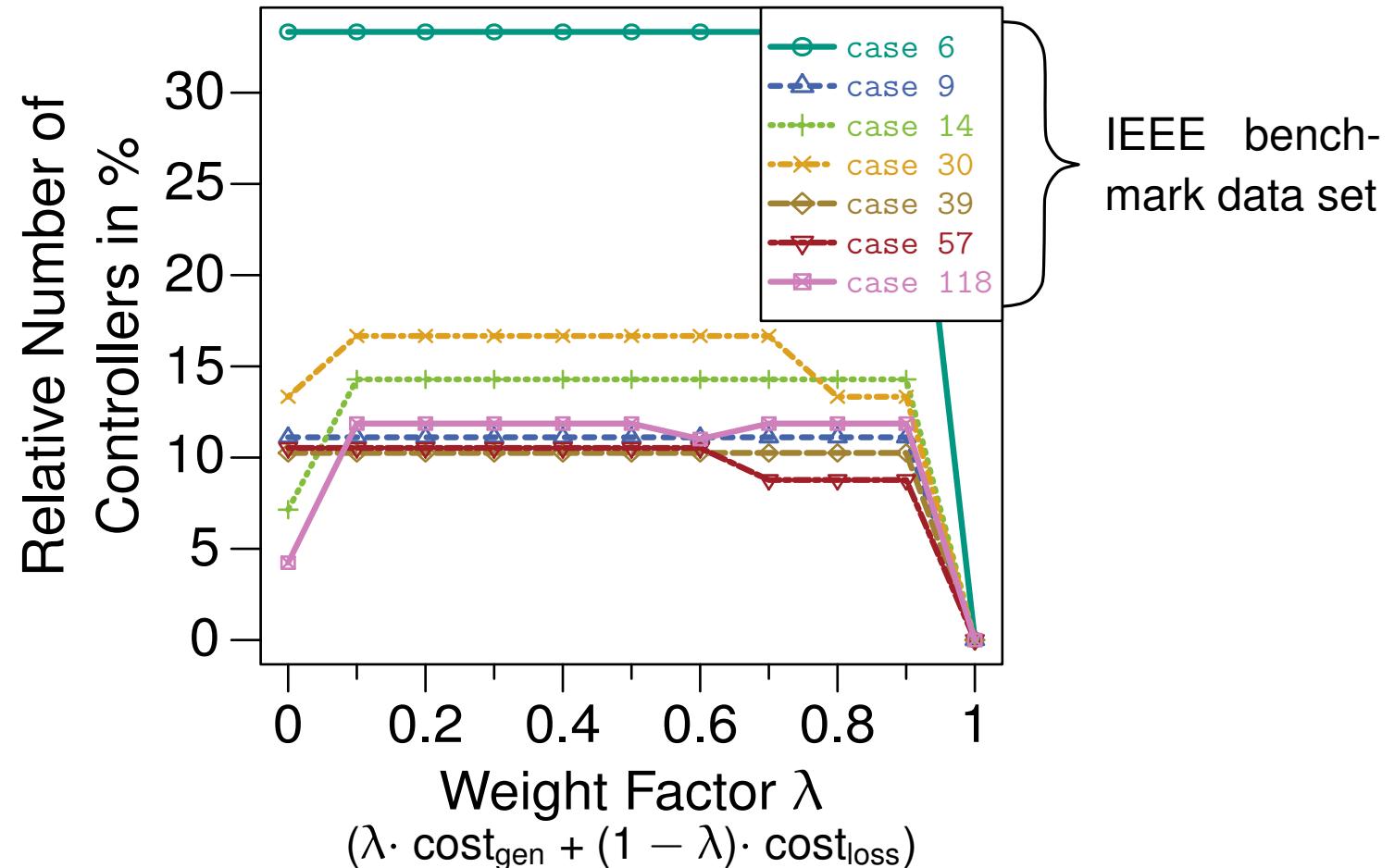
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Backup 1: Control Buses

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



Backup 2: Number of Control Buses



Observation from experiments:

- Few control buses suffice for obtaining optimal solutions

Backup 3



Backup 4

