Operating Power Grids with Few Flow Control Buses

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Thomas Leibfried, Tamara Mchedlidze, Nico Meyer-Hübner, Martin Nöllenburg, Ignaz Rutter, Peter Sanders, Dorothea Wagner and Franziska Wegner

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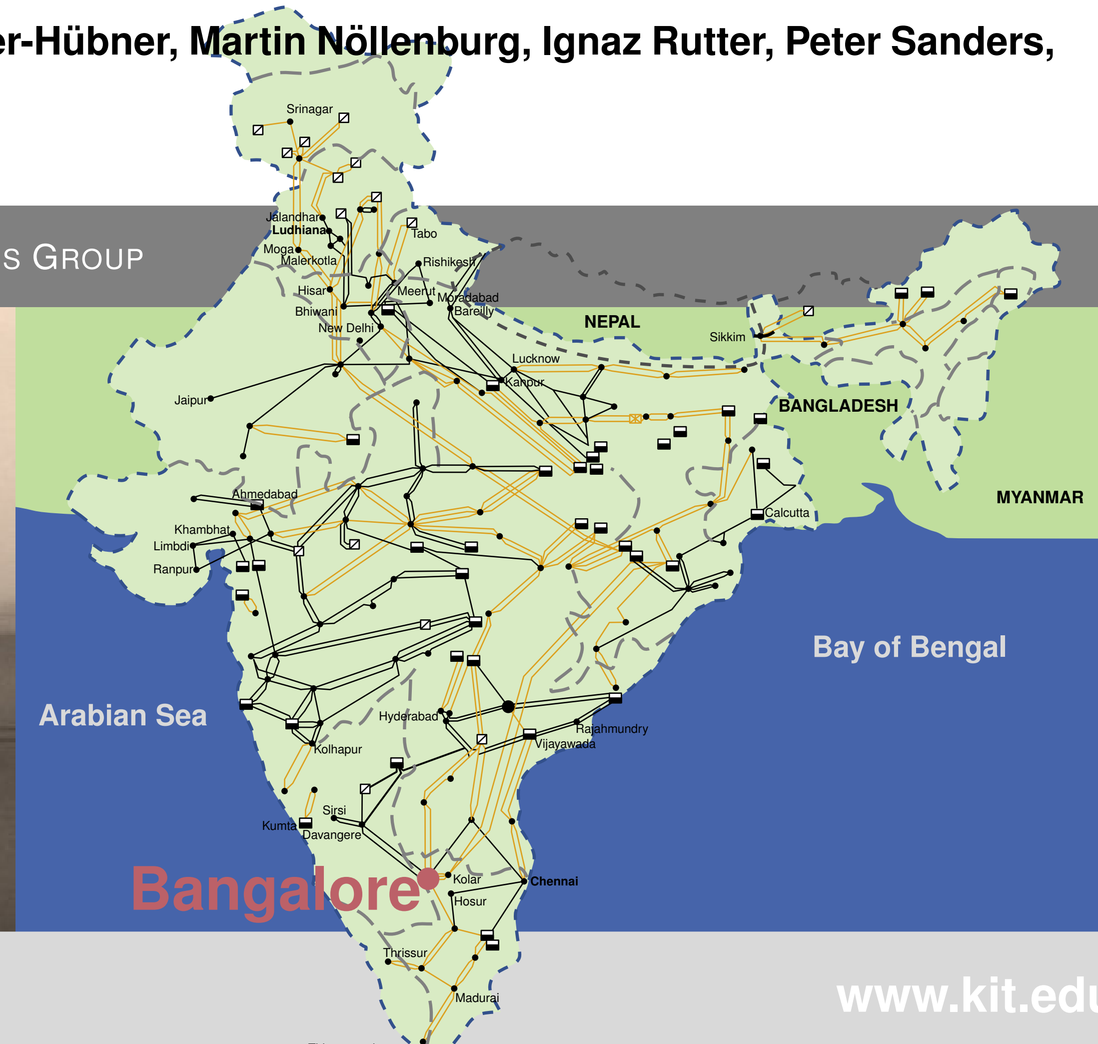
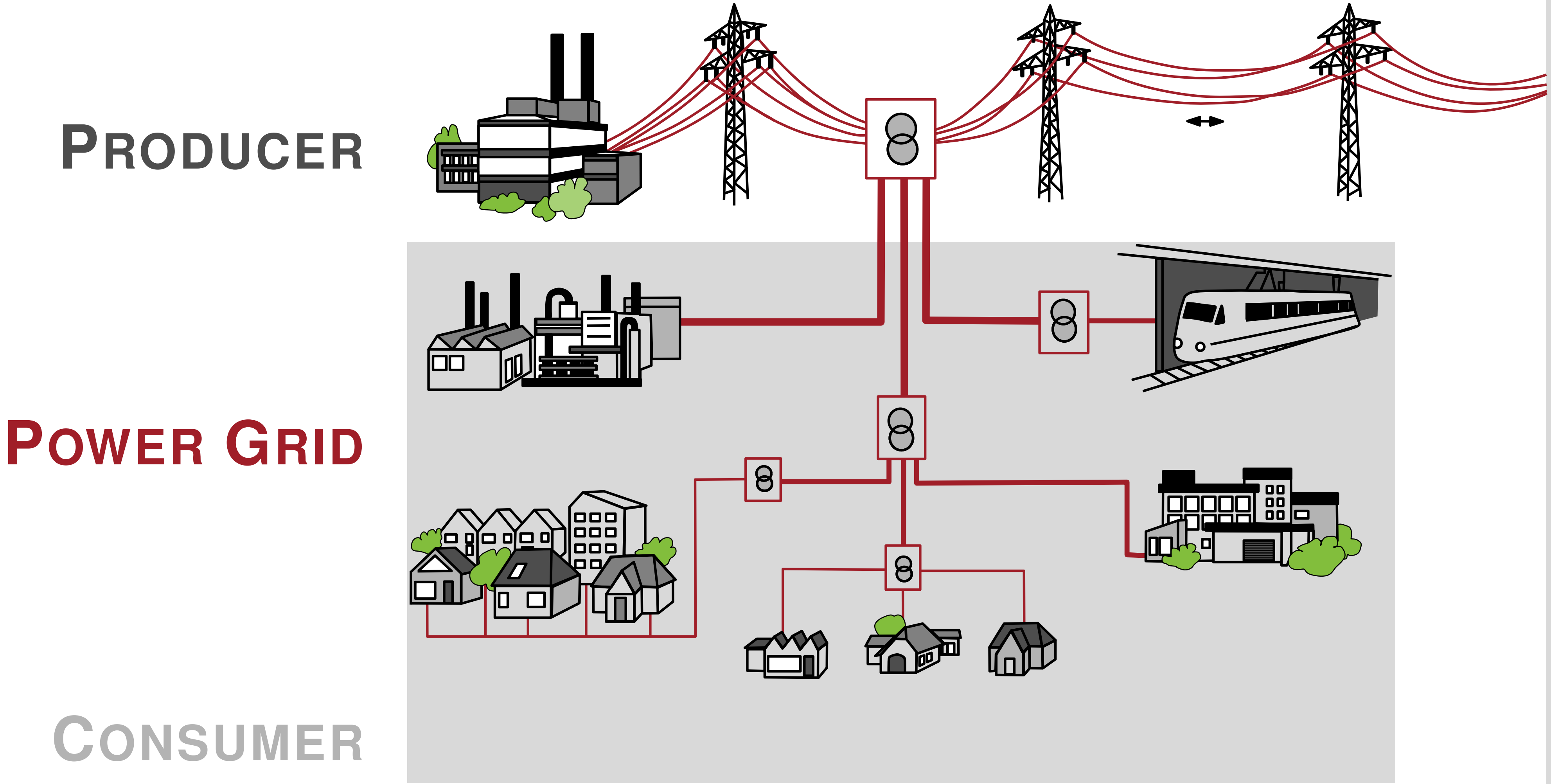


Recent Development in Power Grids



Recent Development in Power Grids

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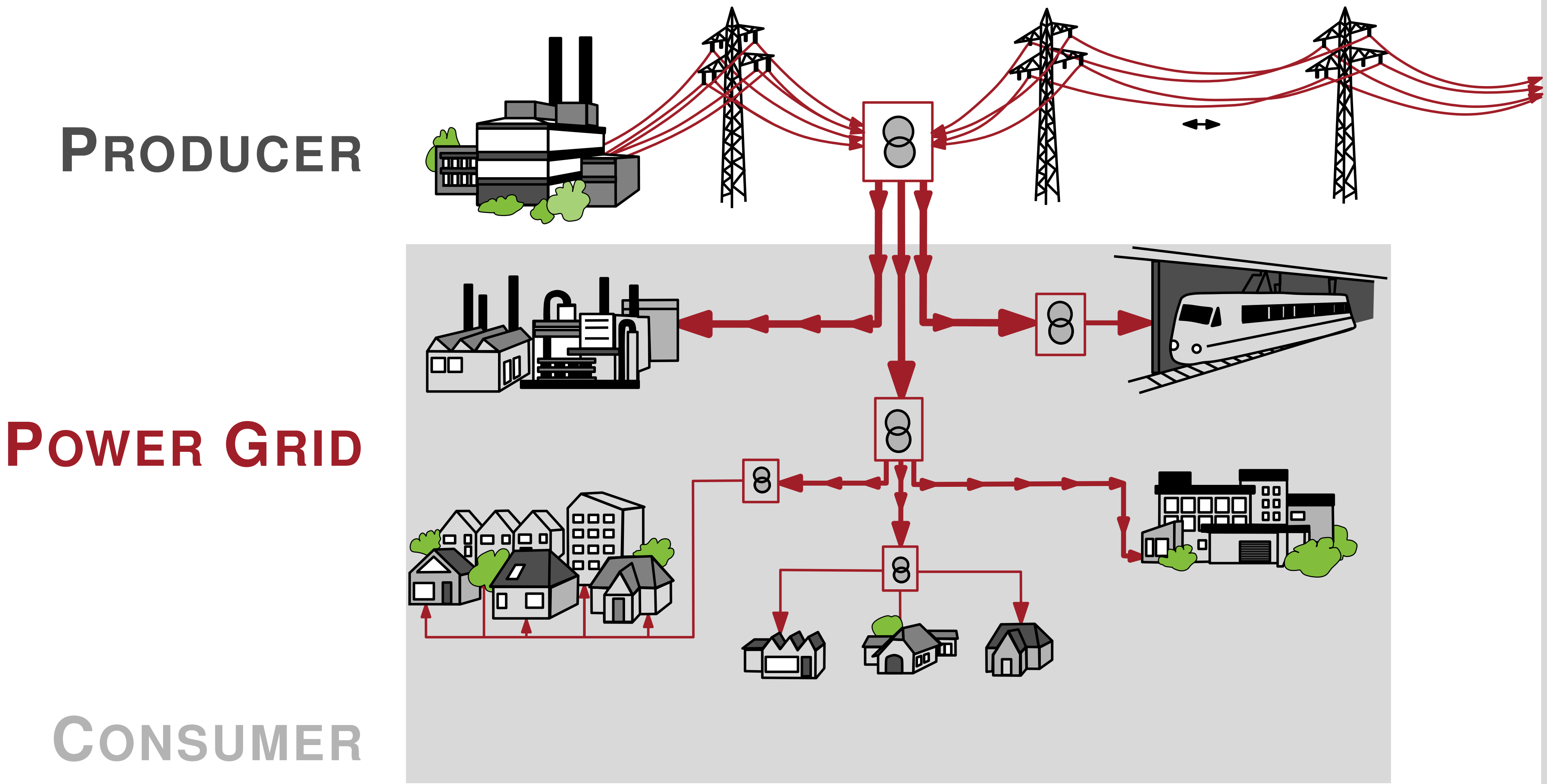

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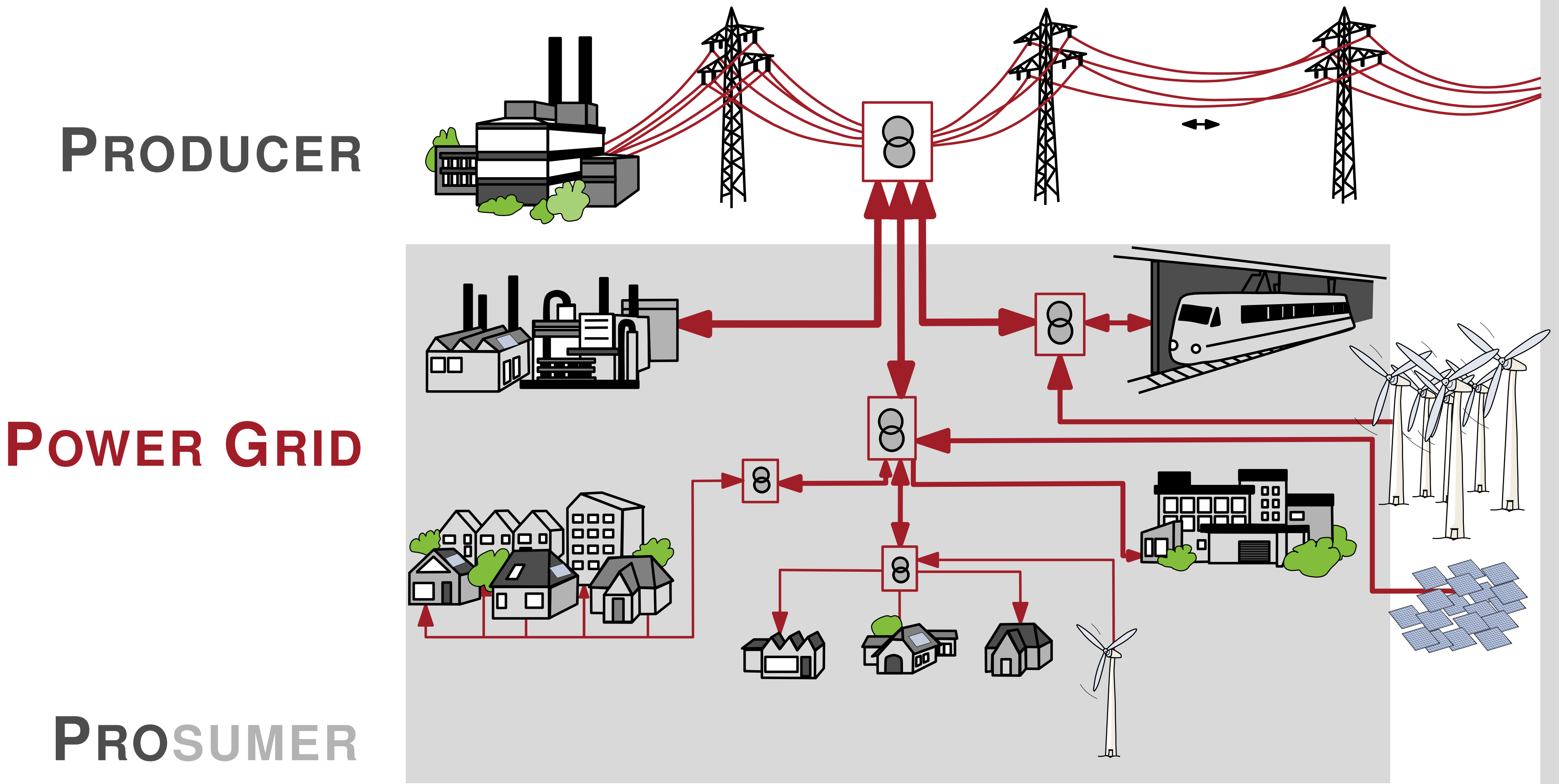

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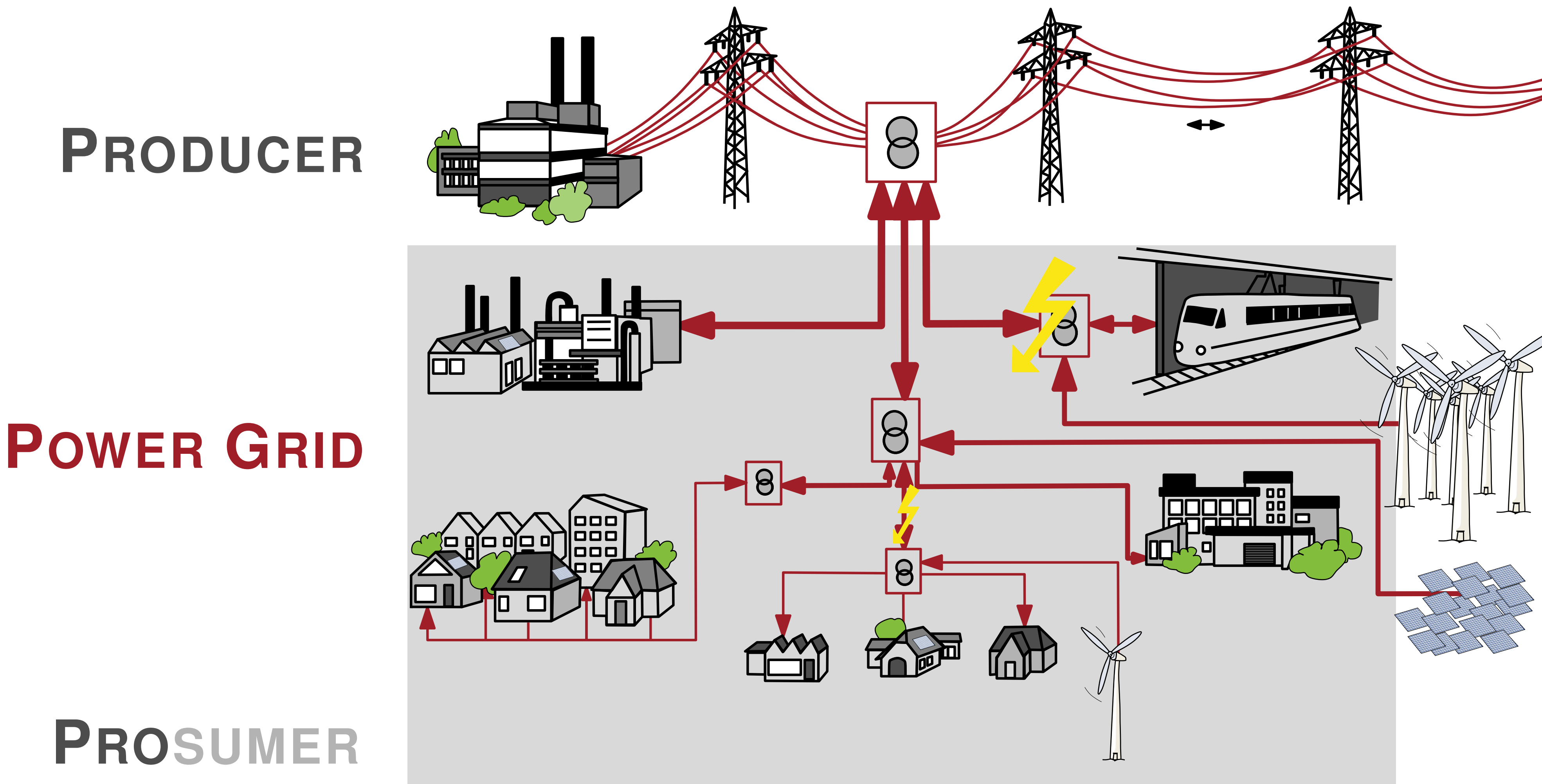
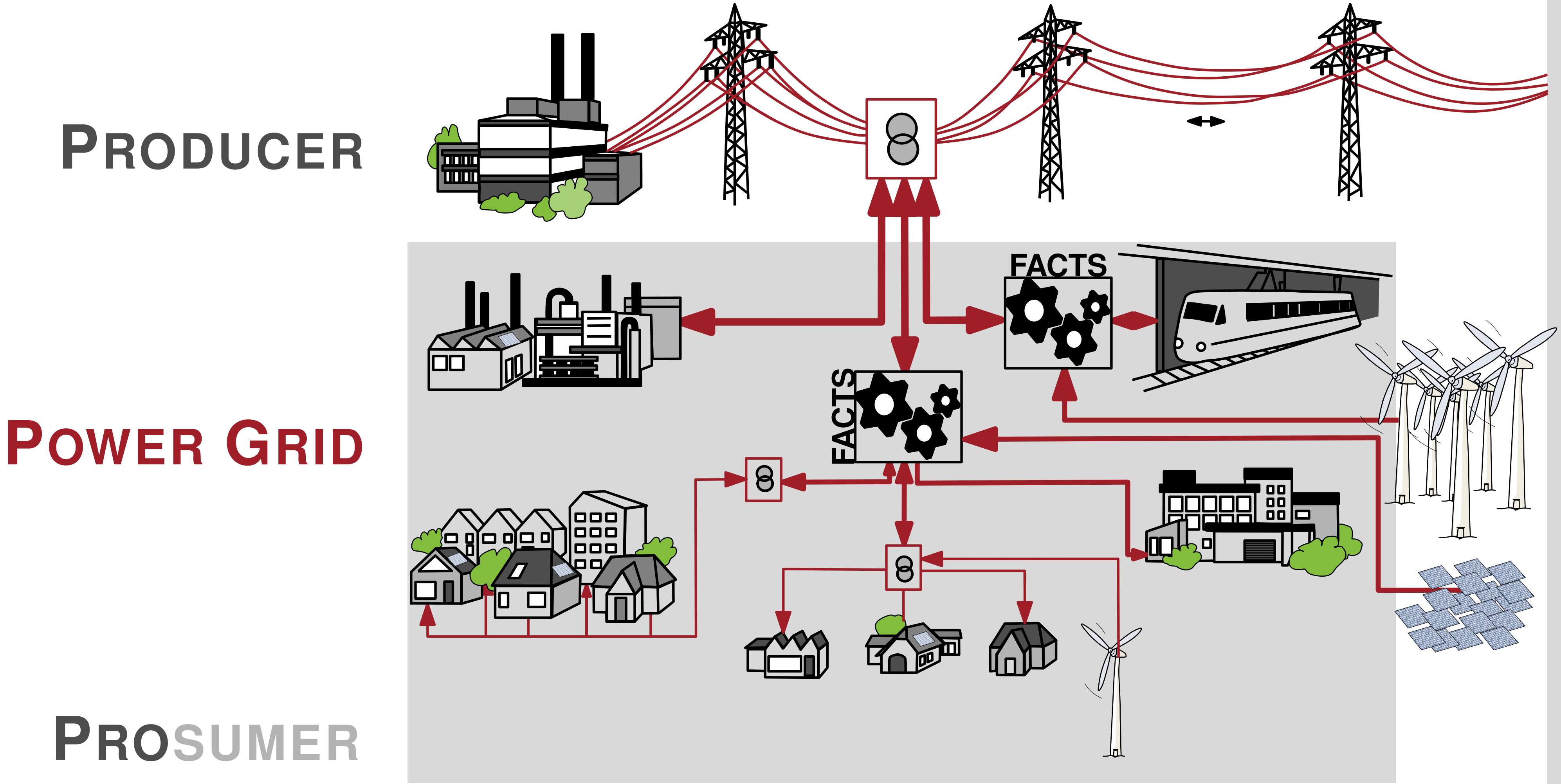


Recent Development in Power Grids



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Motivation

Challenges

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

$\Rightarrow$ 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 line limits) for power grid with control units at selected buses
- Energy production of each power generator

Goals:

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

} operation cost

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

Problem of Power Grid Operator

Given:

- Power grid with parameters

Find:

- Valid operation point (respecting thermal line limits) for power grid with control units at selected buses
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$$\left.\begin{array}{l}\text{■ Minimize production cost (similar to OPF)}\\[1em]\text{■ Minimize line losses}\end{array}\right\}\ \text{operation cost}$$

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

$\Rightarrow$ Place FACTS to enhance controllability.

AC DC

DC-based Flow Models

Graph Model

Karlsruhe Institute of Technology

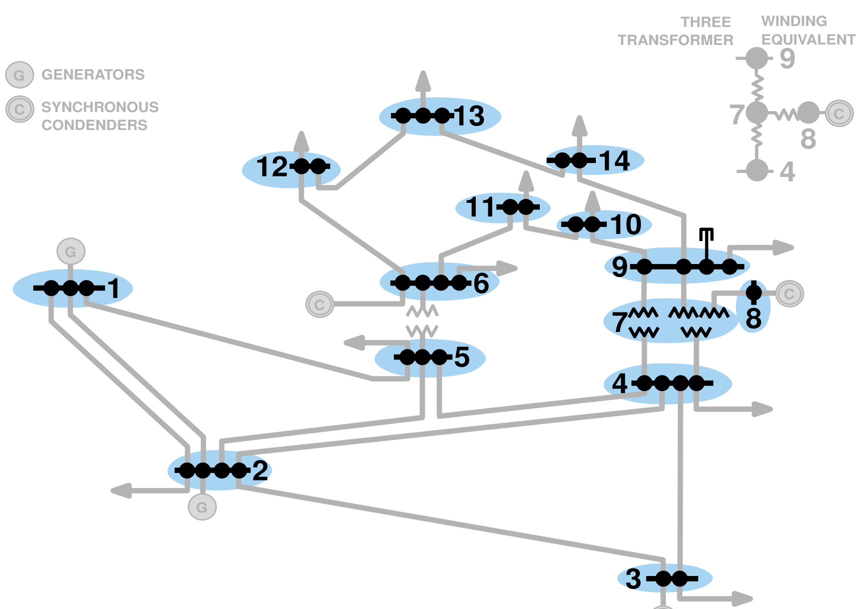
Straight-forward transformation:

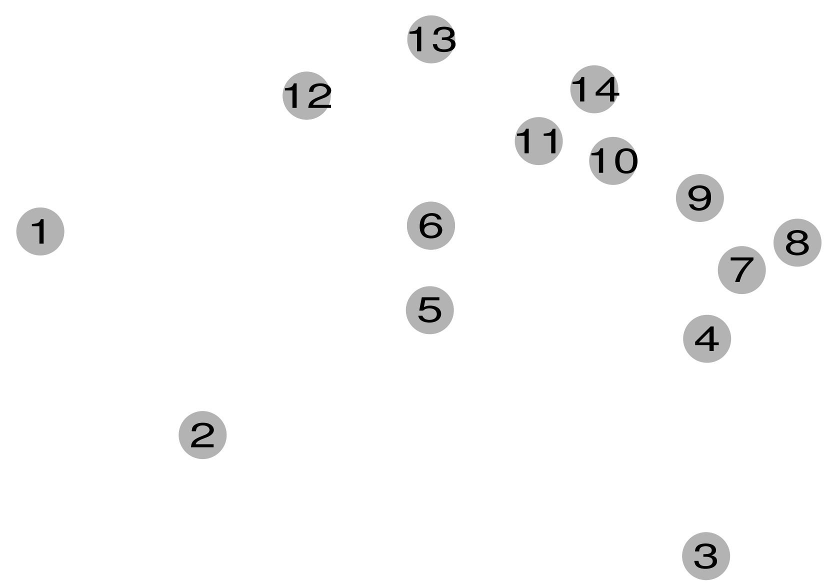
- Power grid $\longrightarrow$ graph $G = (V, E)$

Graph Model

Straight-forward transformation:

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





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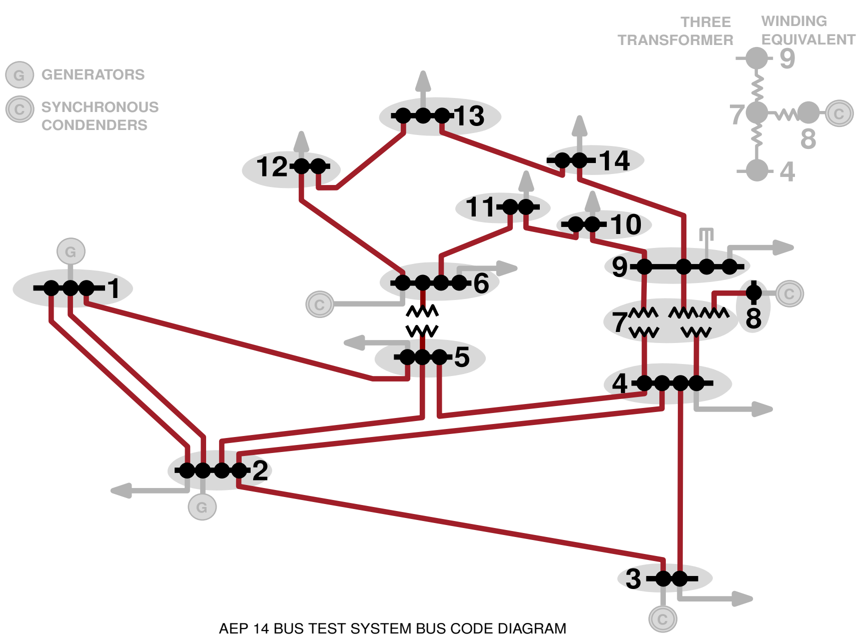
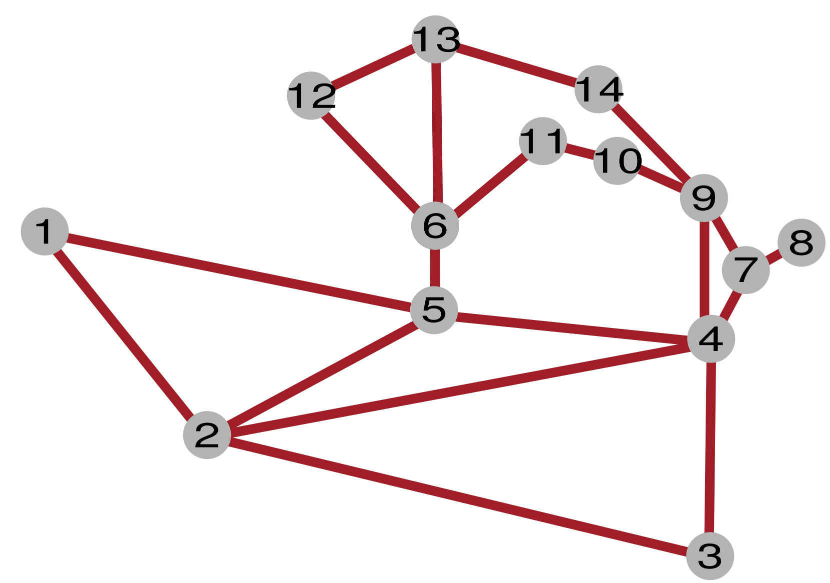
Graph Model

Straight-forward transformation:

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



AEP 14 BUS TEST SYSTEM BUS CODE DIAGRAM



Graph Model

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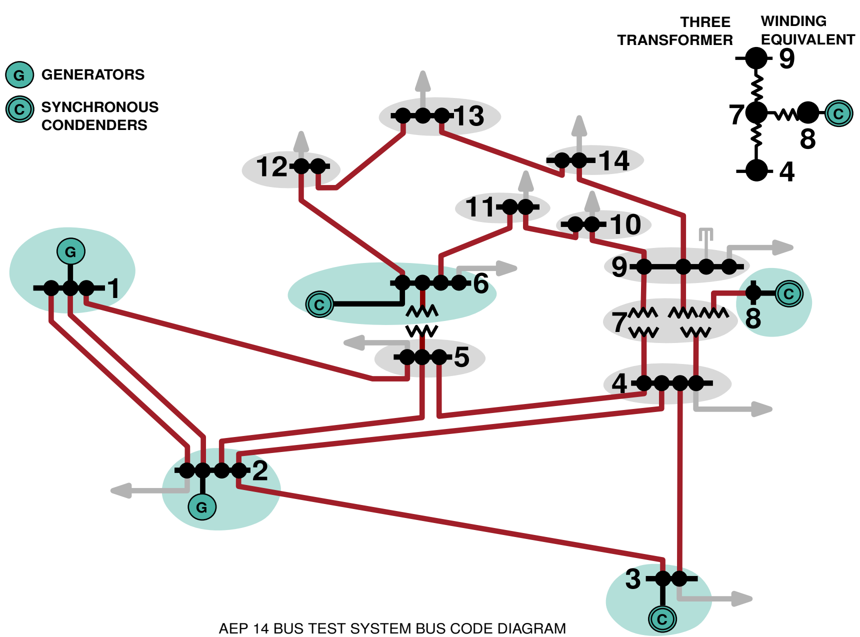
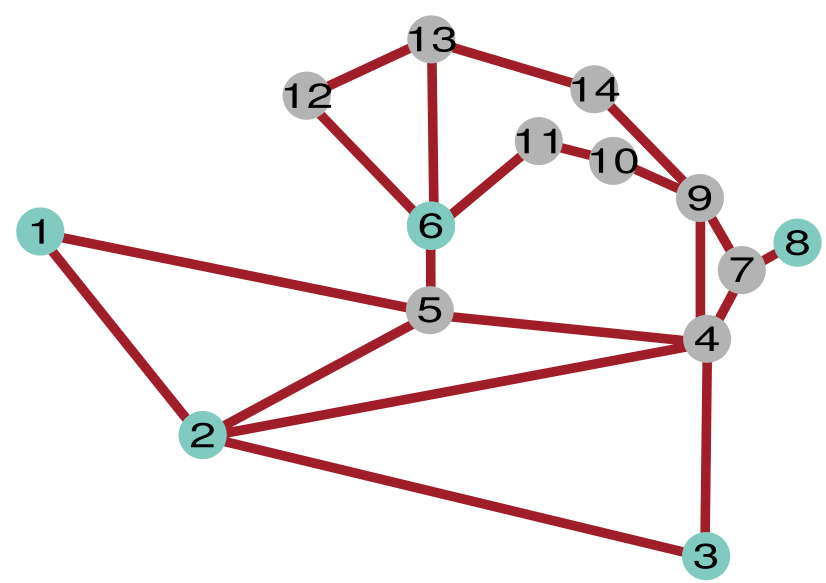
- Generators $\rightarrow$ set $V_G \subseteq V$ of generator buses





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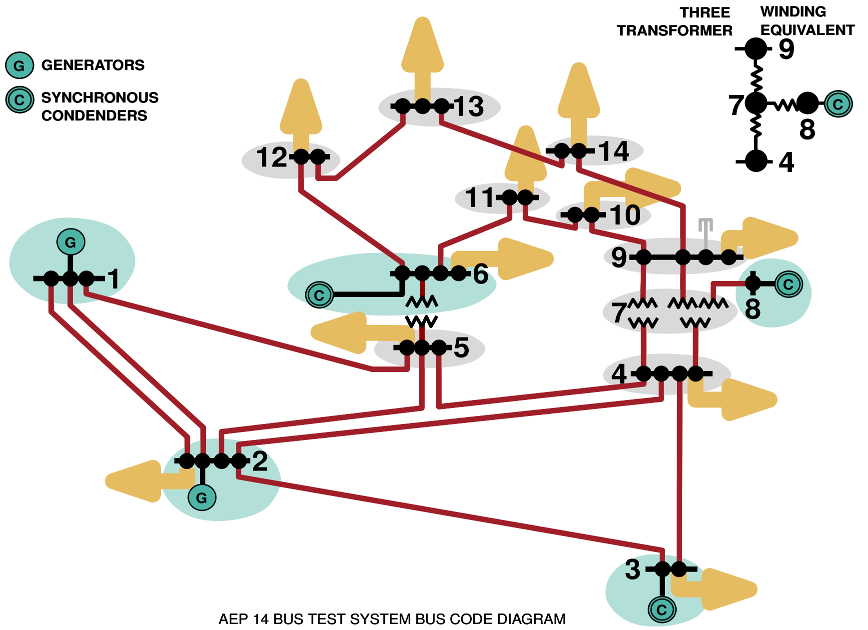
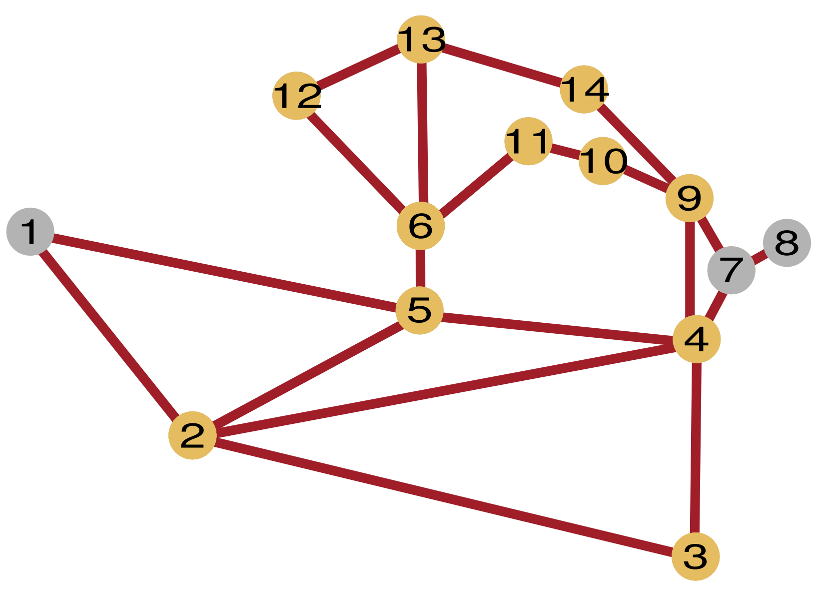
- Generators $\rightarrow$ set $V_G \subseteq V$ of generator buses
- Load $\rightarrow$ set $V_L \subseteq V$ of load buses





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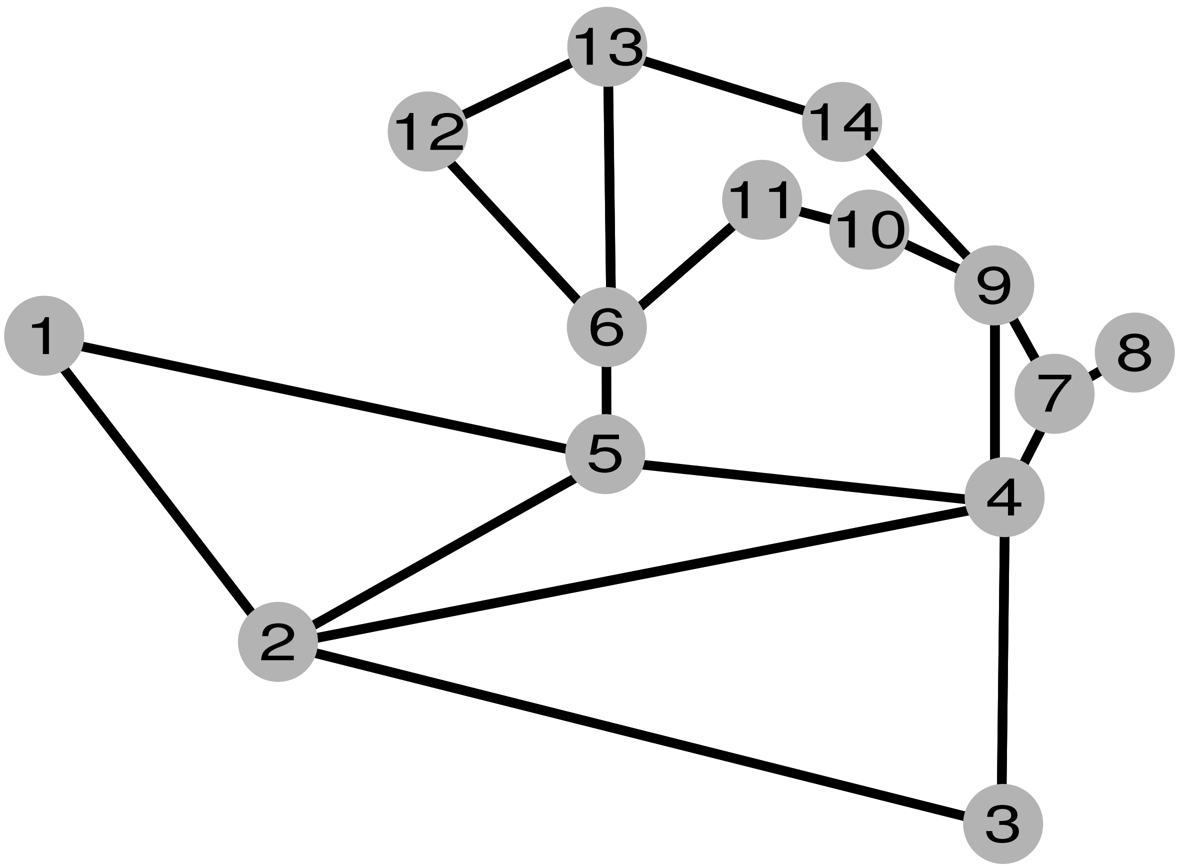
Hybrid Flow Model



Kirchhoff's circuit laws:

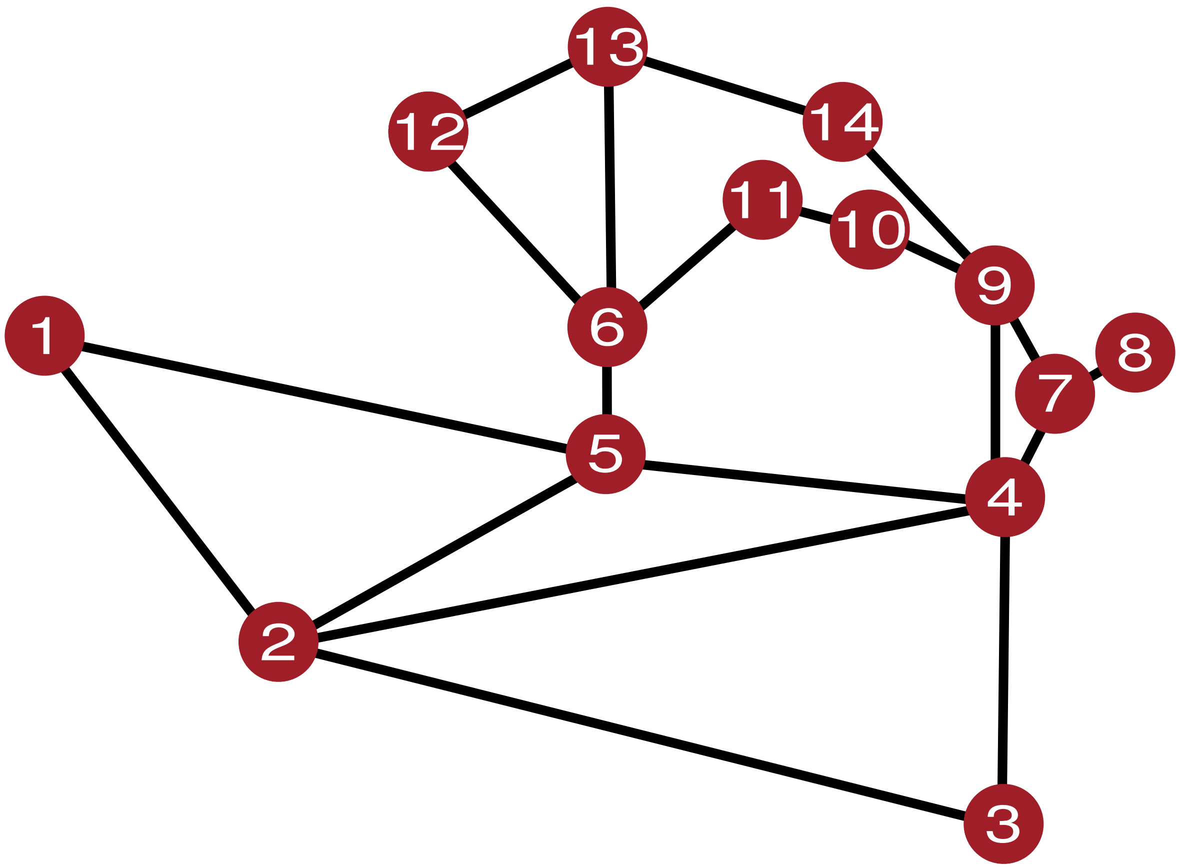
Kirchhoff's current law ✓

Kirchhoff's voltage law ✓

Physical Model

(as a DC approximation)

Hybrid Flow Model



● control unit

— controlled flow

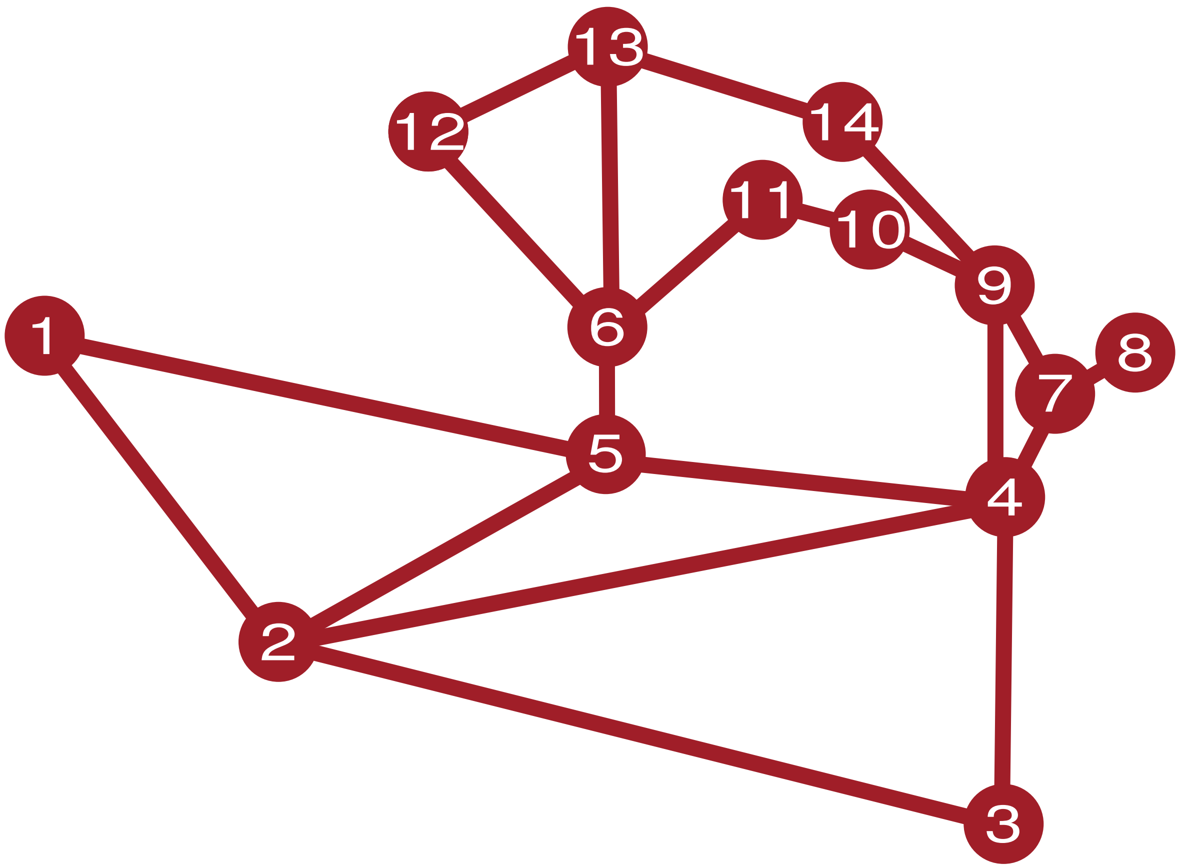
Kirchhoff's circuit laws:

Kirchhoff's current law ✓

Kirchhoff's voltage law

Flow Model

Hybrid Flow Model



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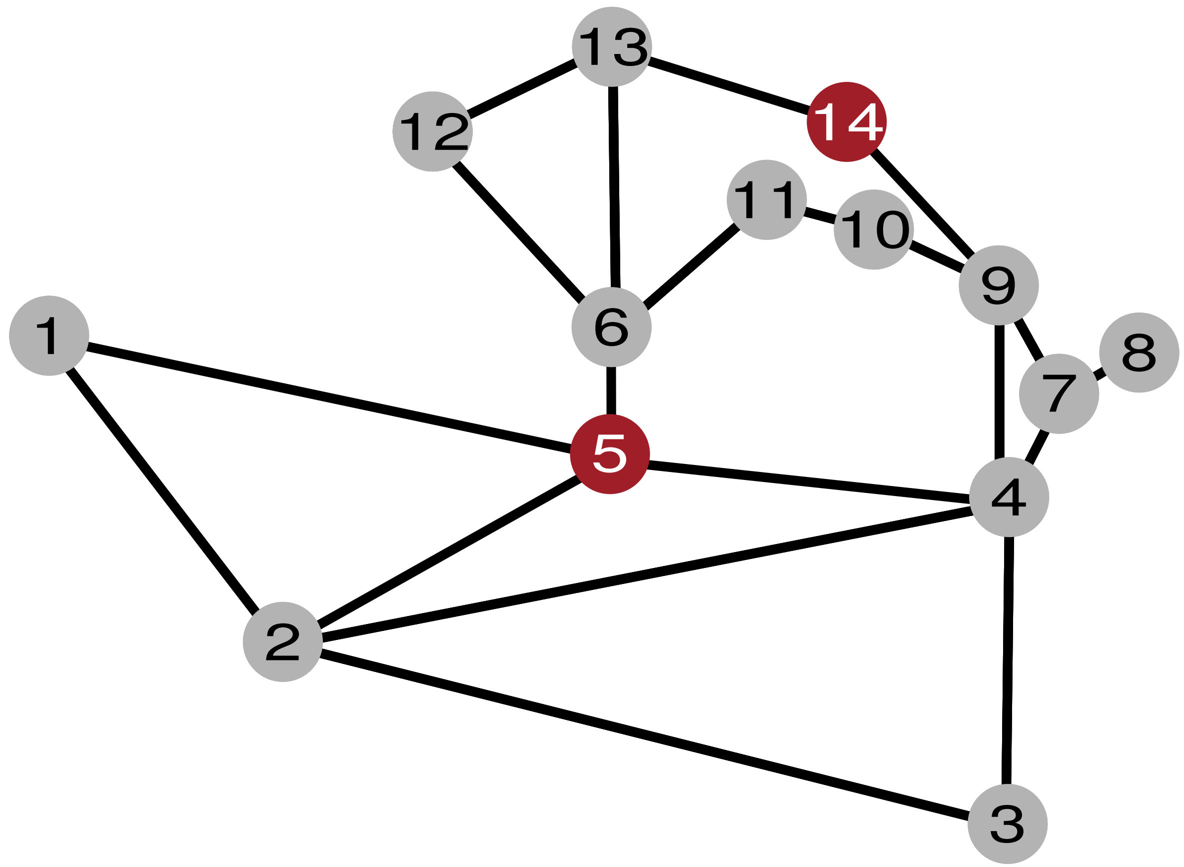
Flow Model

Hybrid Flow Model



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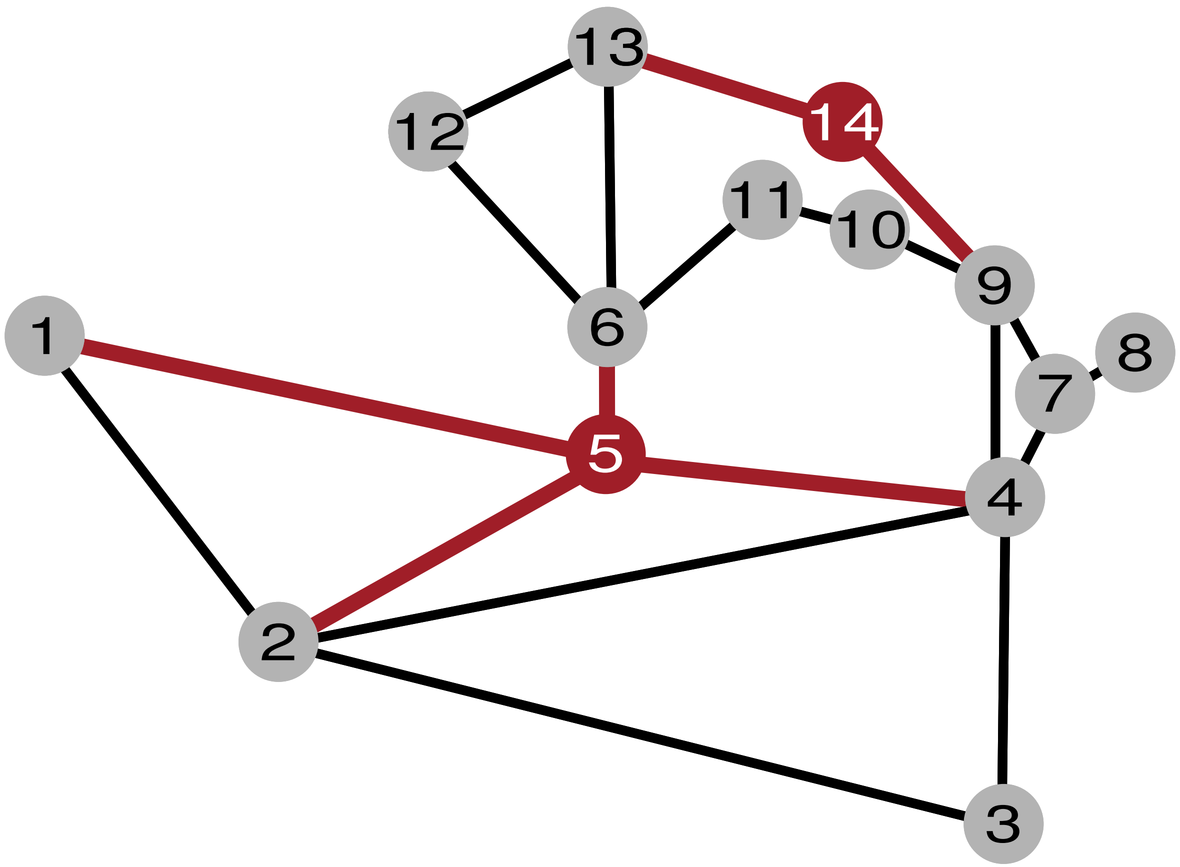
Hybrid Model = Flow Model + Physical Model

Hybrid Flow Model



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Hybrid Model = Flow Model + Physical Model

Hybrid Flow Model

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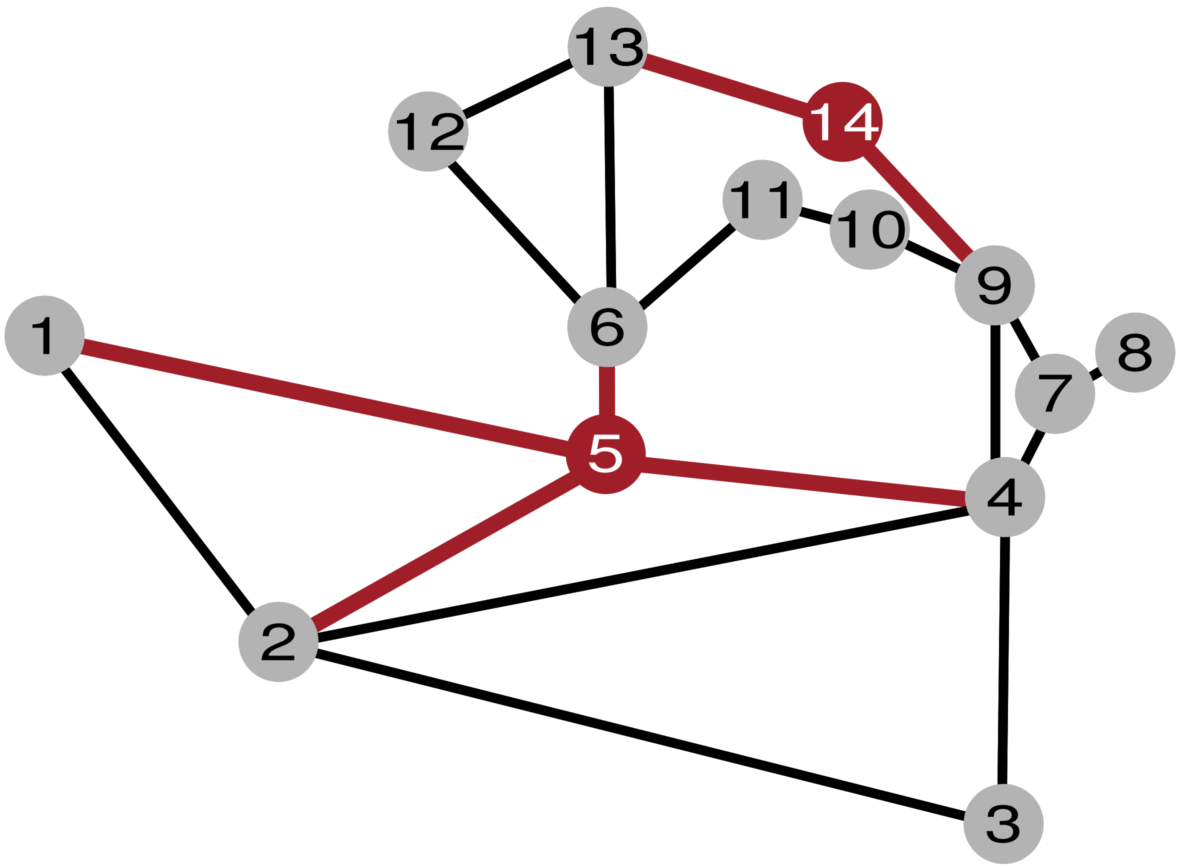


control unit

controlled flow

Kirchhoff's circuit laws:

Kirchhoff's current law ✓

Kirchhoff's current law ✓

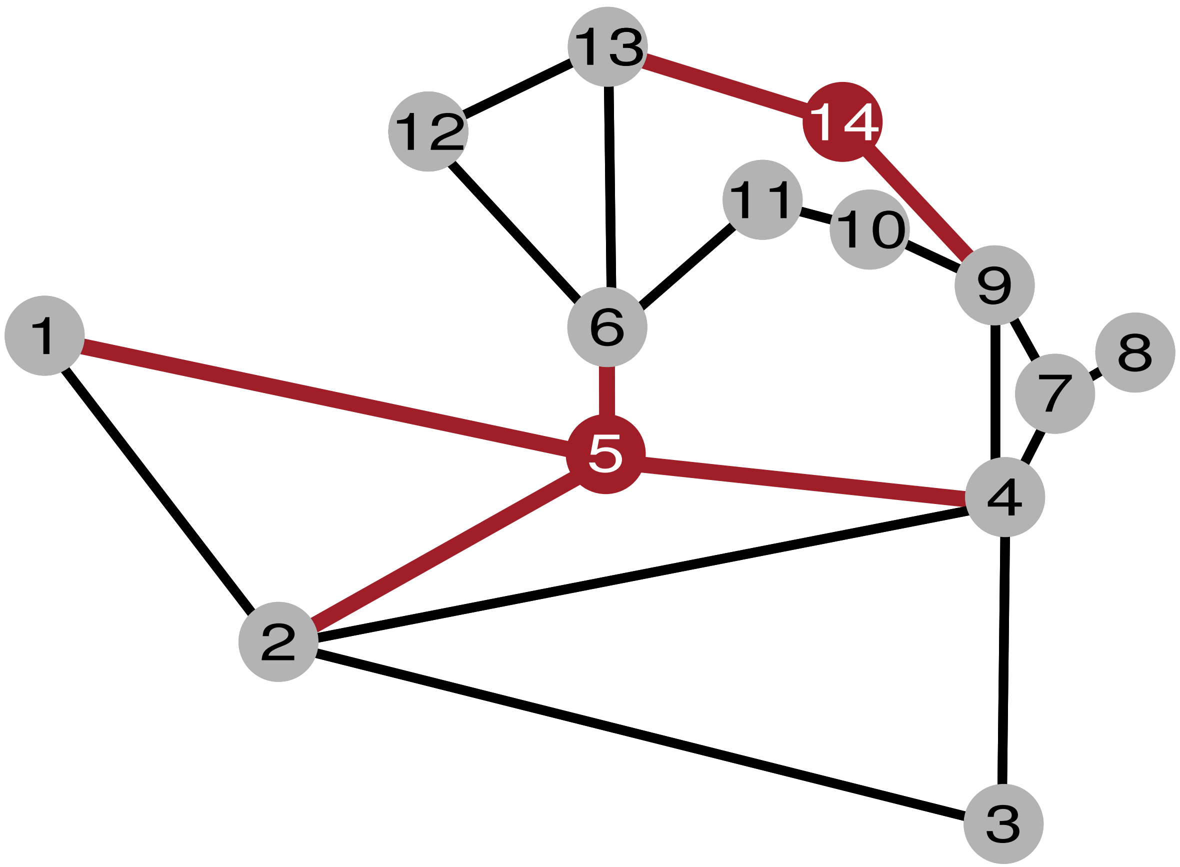
Kirchhoff's voltage law ✓

Hybrid Model = Flow Model + Physical Model

$\Downarrow$

Lower Bound

Hybrid Flow Model



● control unit

— controlled flow

Kirchhoff's circuit laws:

Kirchhoff's current law ✓

Kirchhoff's current law ✓

Kirchhoff's voltage law ✓

Hybrid Model = Flow Model + Physical Model

$\Downarrow$ Lower Bound $\Downarrow$ Upper Bound

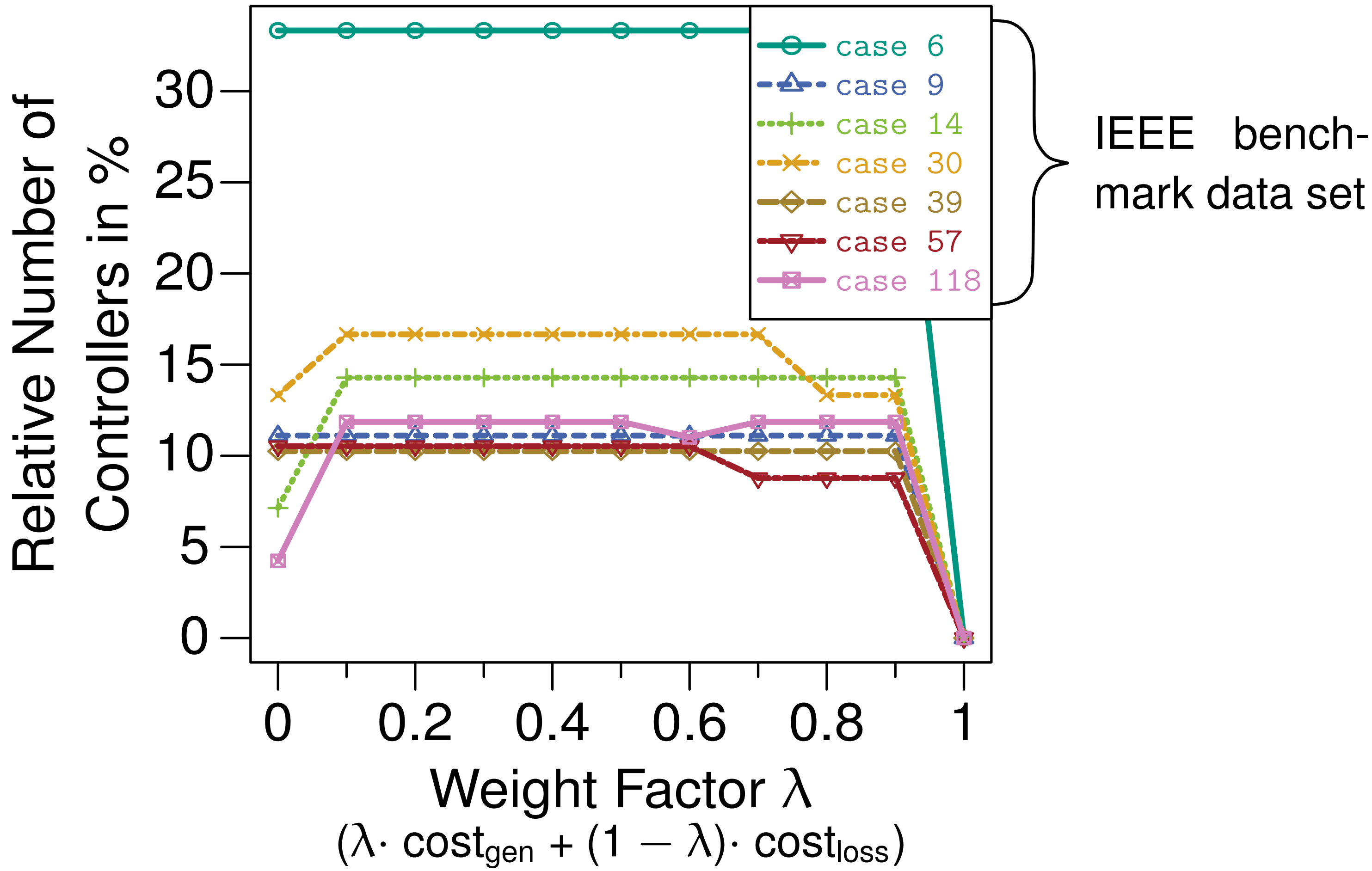
Research Questions

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

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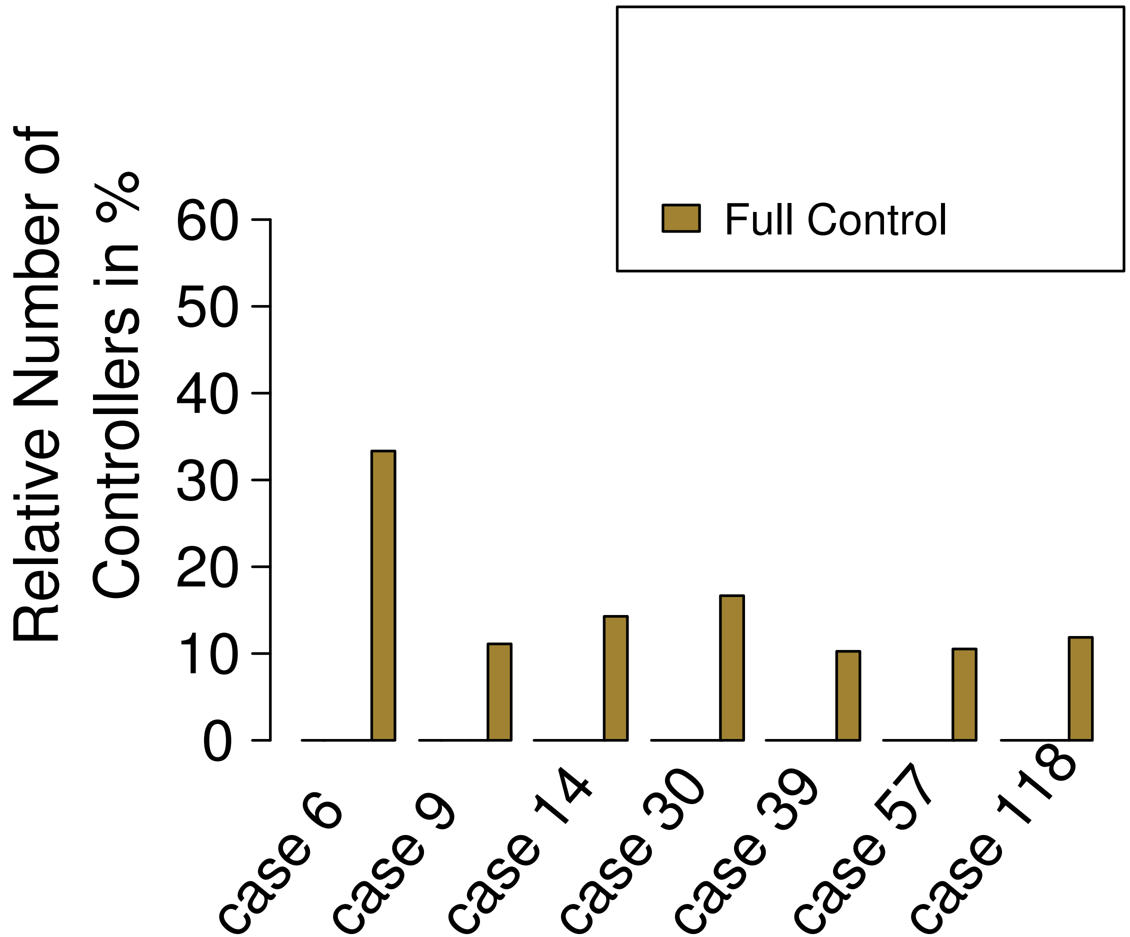
Number of Control Buses

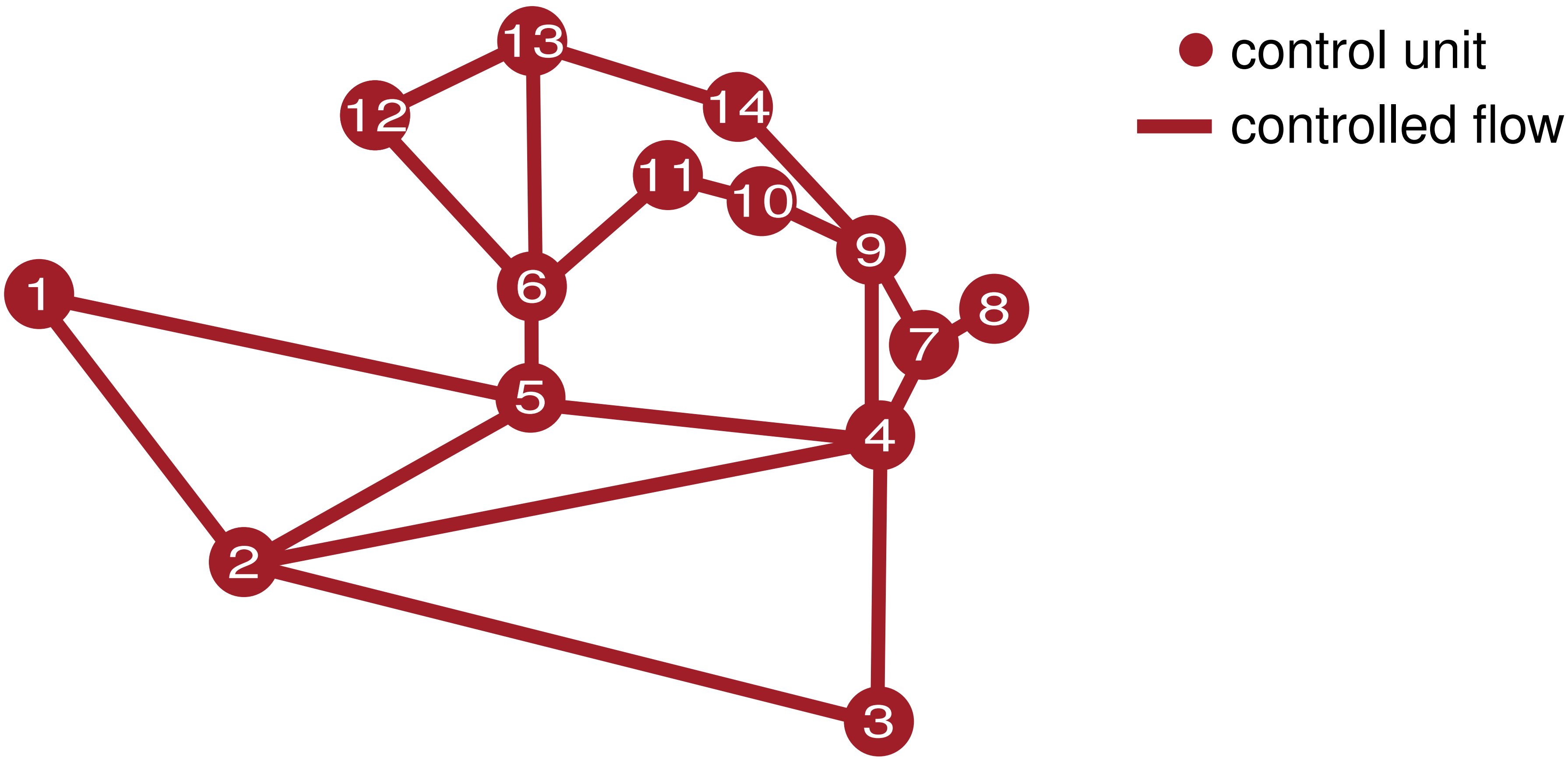


- For each benchmark case: $\max_{\lambda} \min \#Controller$

Matching the Flow Model (Q1)

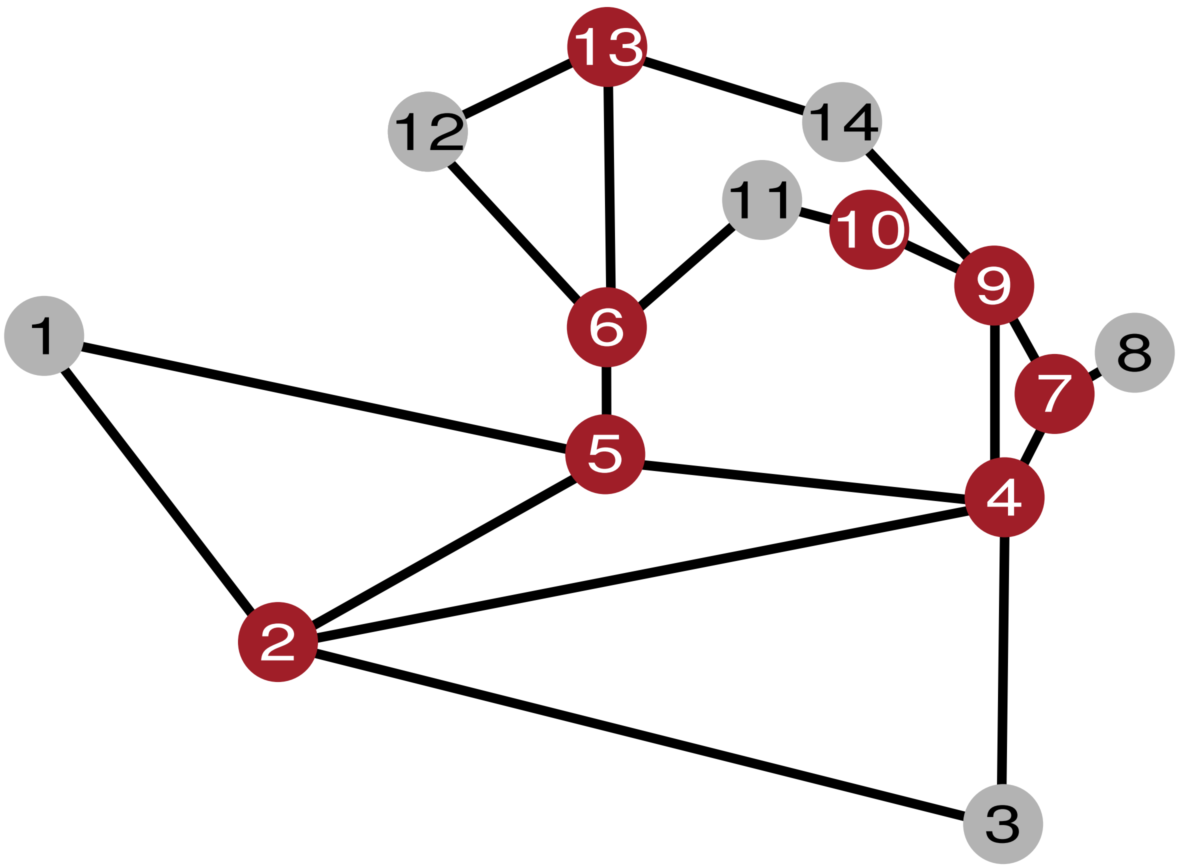
- How many flow control buses are necessary to obtain globally optimal power flows and which buses need to be controlled?

Globally Optimal Power Flows

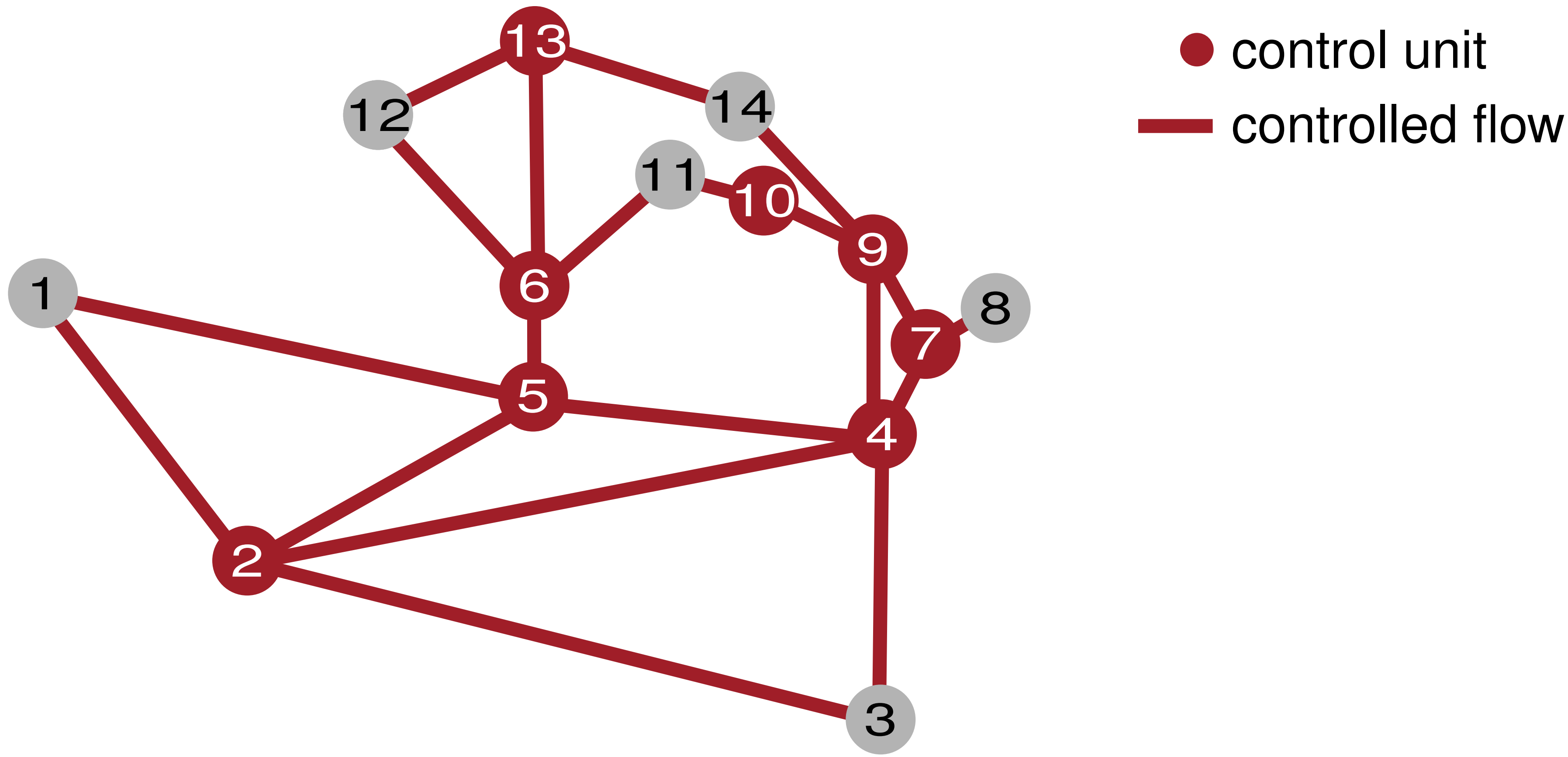


Can we become as good as the Flow Model with fewer control busses?

Vertex Cover



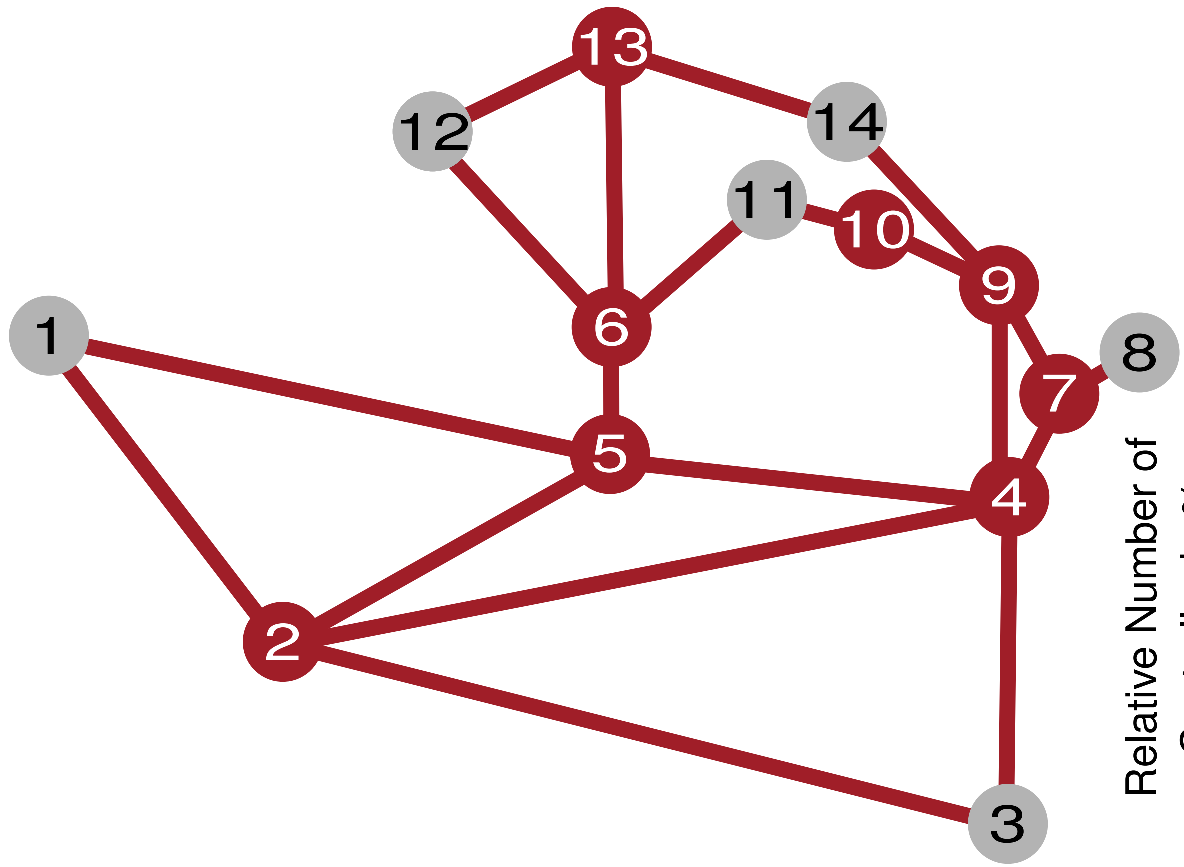
Vertex Cover

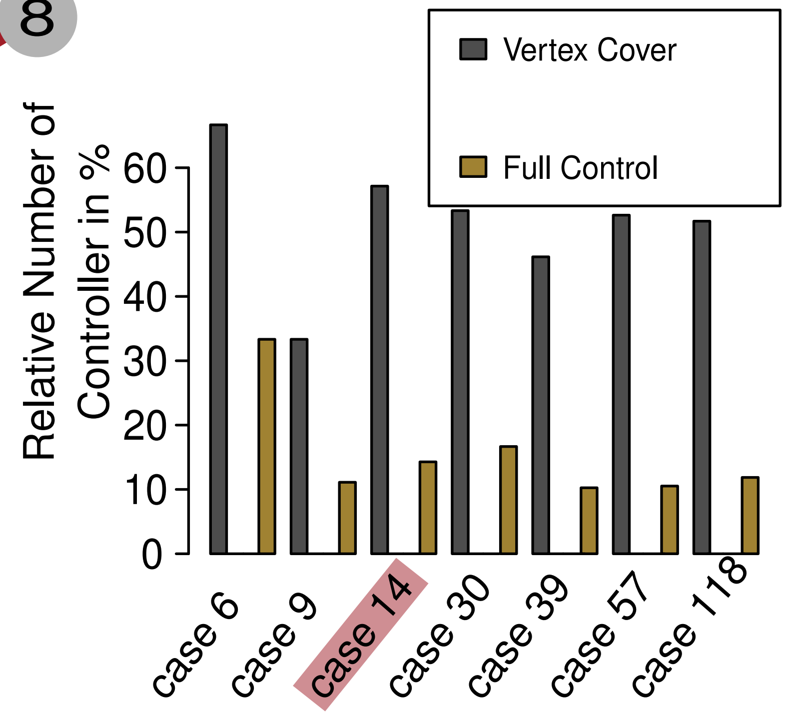


- Control flow on all edges
- As good as Flow Model

⇒ Still too many flow control buses

Vertex Cover





Fewer than 8 flow control buses sufficient?

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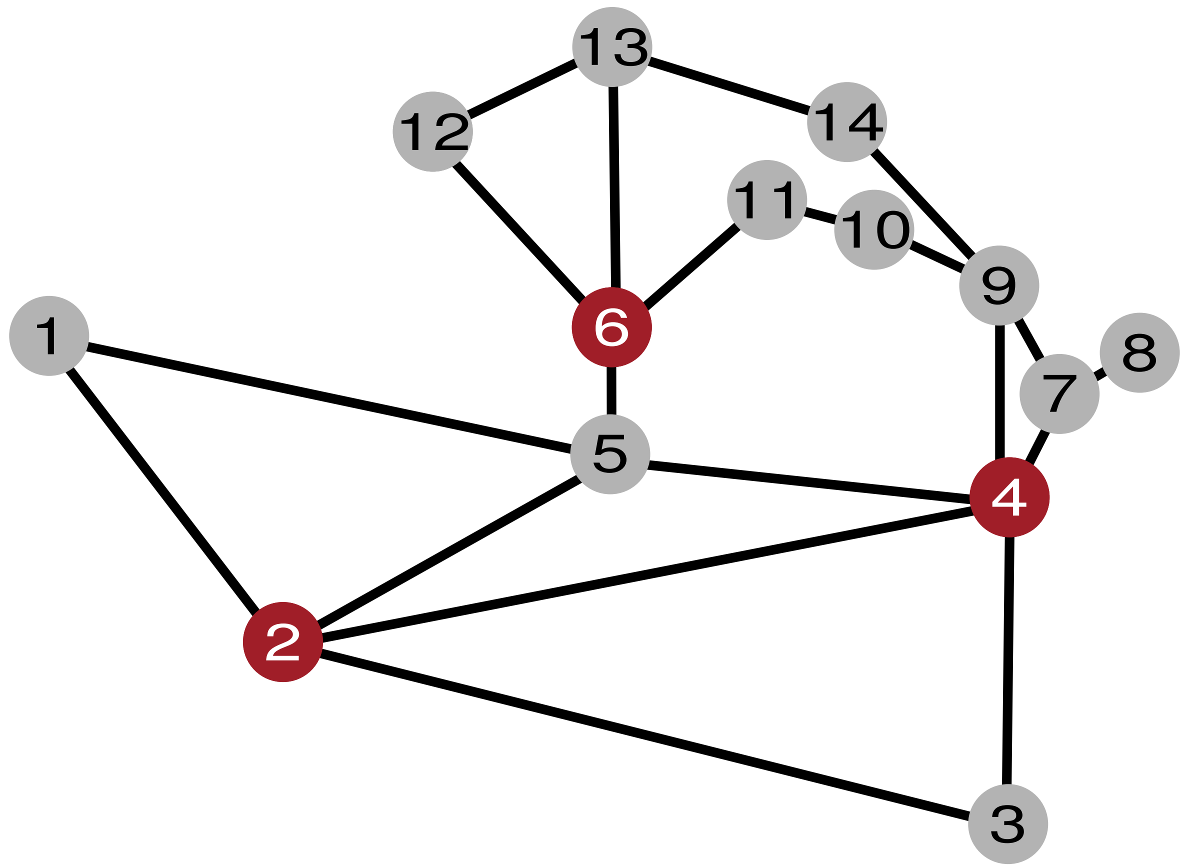
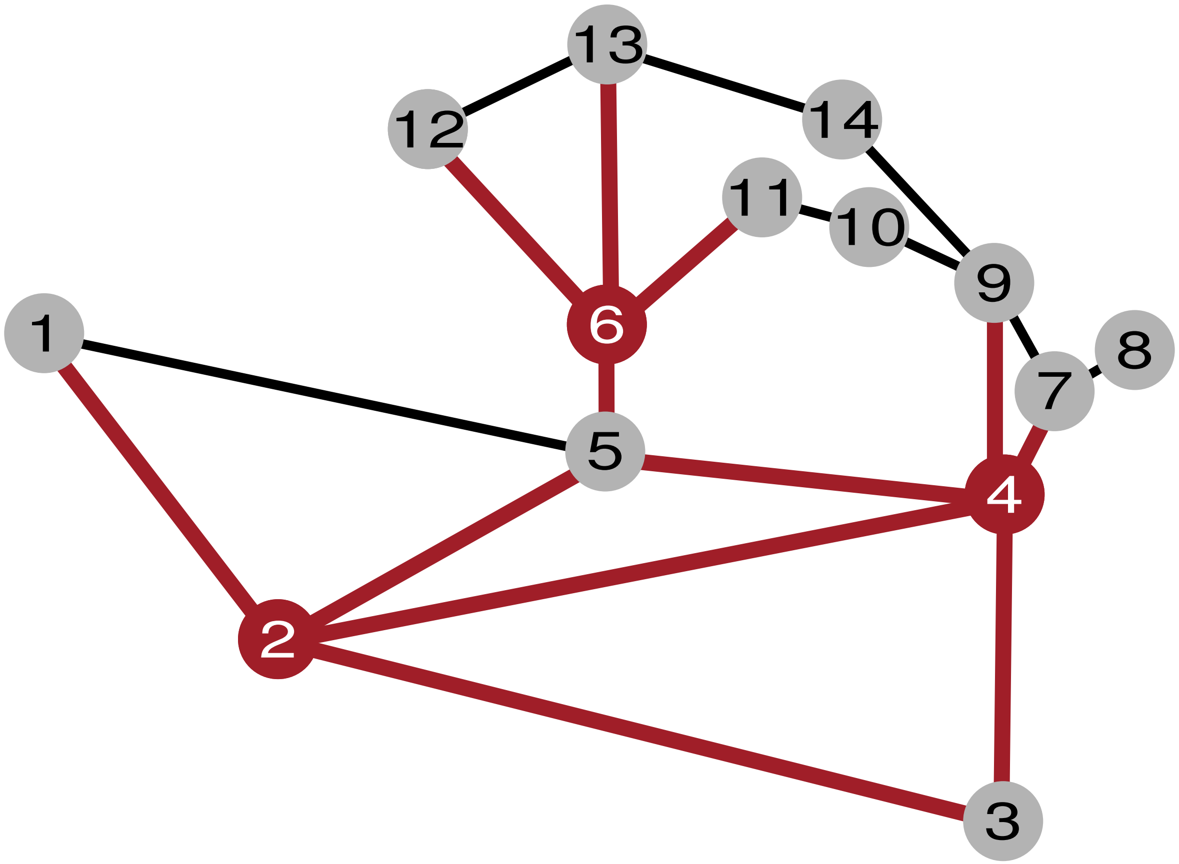
Feedback Forest Set



feedback forest set

Feedback Forest Set

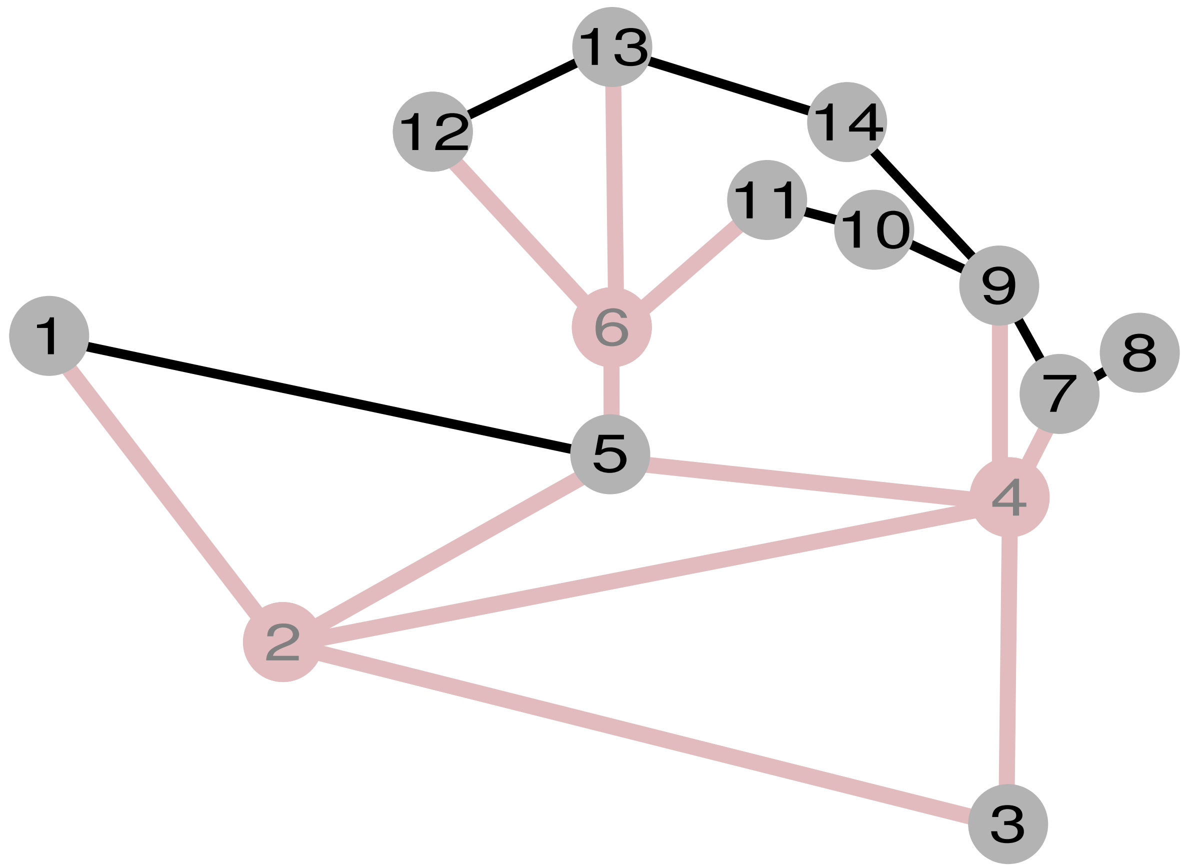


feedback forest set

$\Downarrow$

A set of trees (*forest*) remains!

Feedback Forest Set



feedback forest set

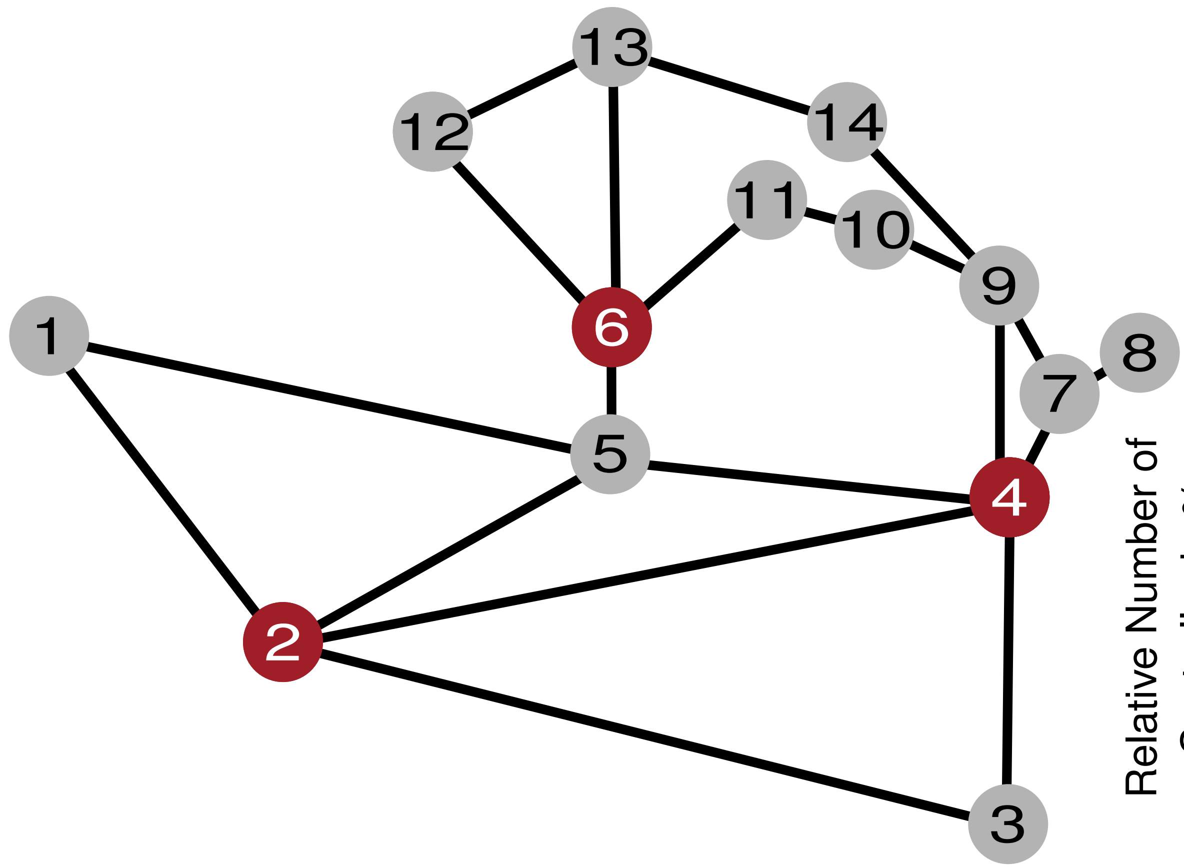
$\Downarrow$

A set of trees (*forest*) remains!

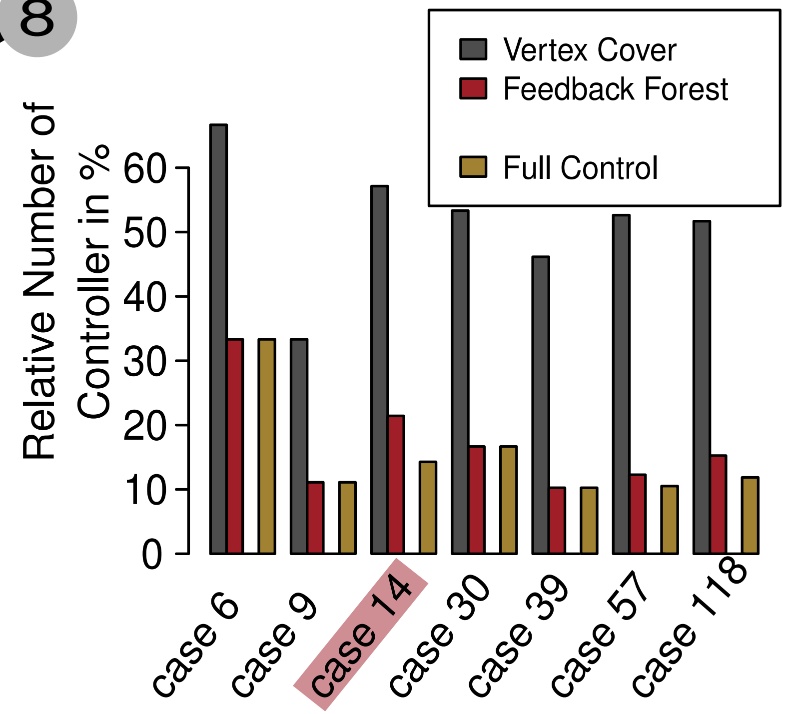
Theorem 1

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

Feedback Cactus Set



● feedback forest set



Fewer than 3 flow control buses sufficient?

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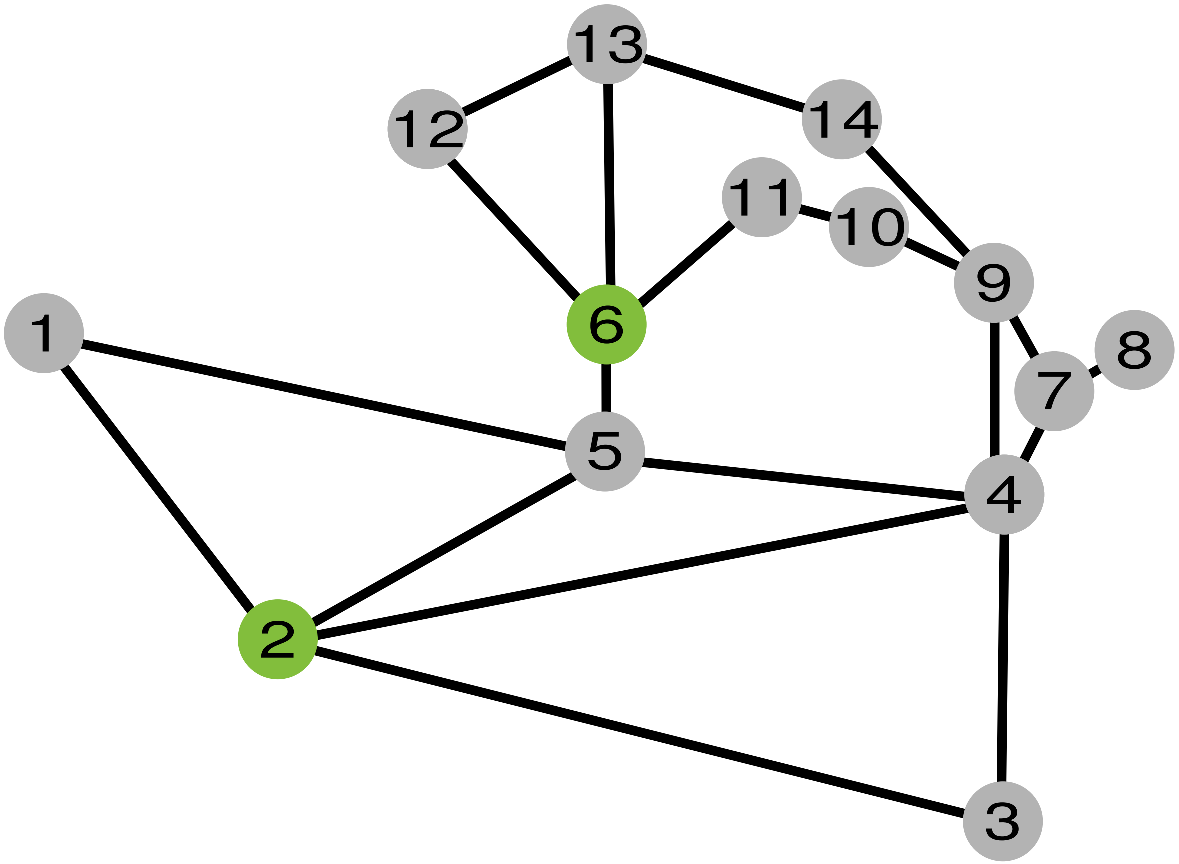
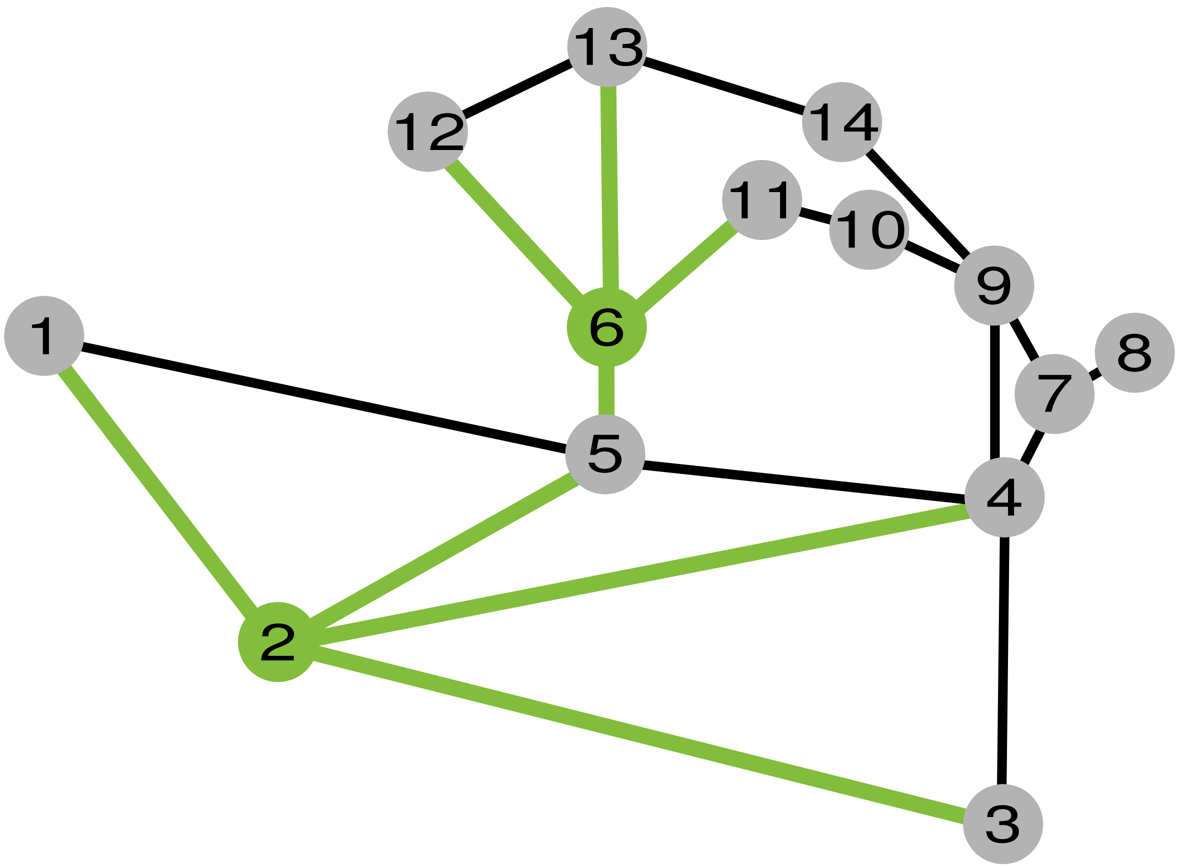
Feedback Cactus Set



feedback cactus set

Feedback Cactus Set

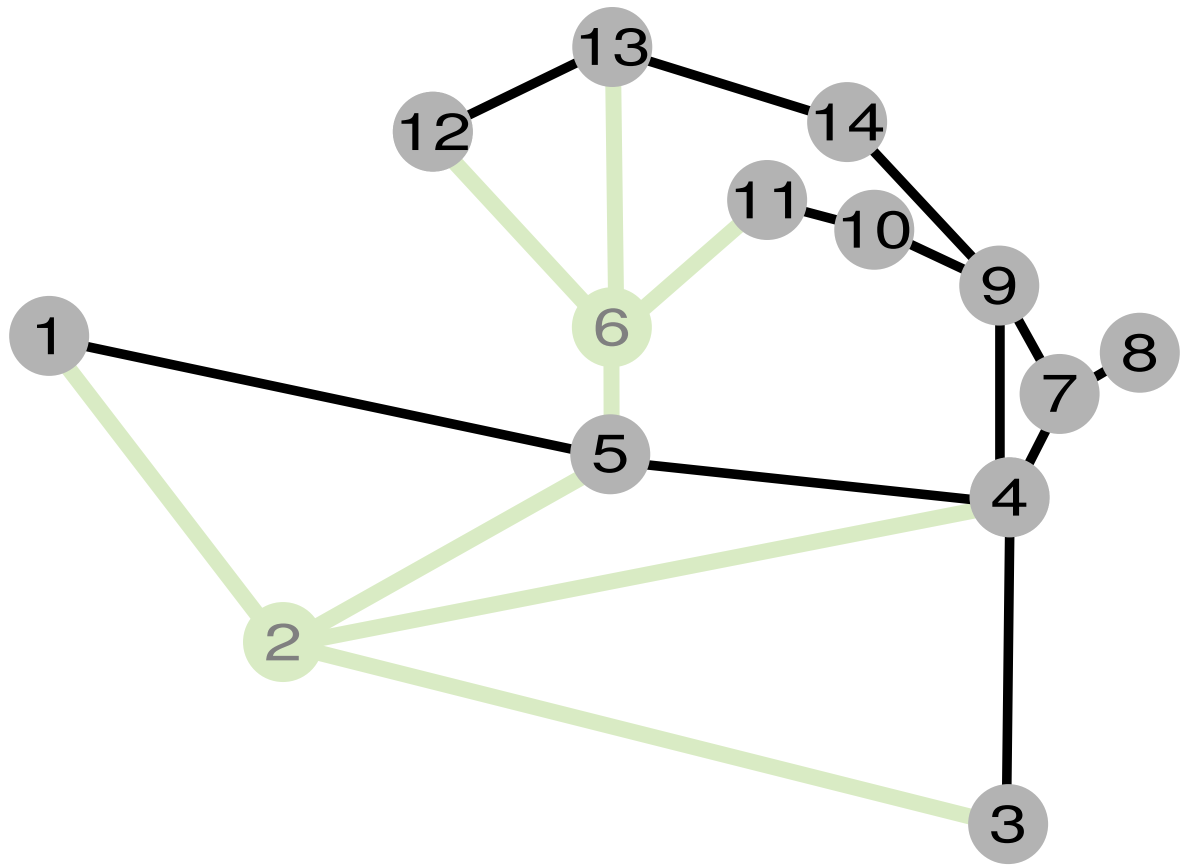


feedback cactus set

$\Downarrow$

A set of *cacti* remains!

Feedback Cactus Set



feedback cactus set

$\Downarrow$

A set of *cacti* remains!

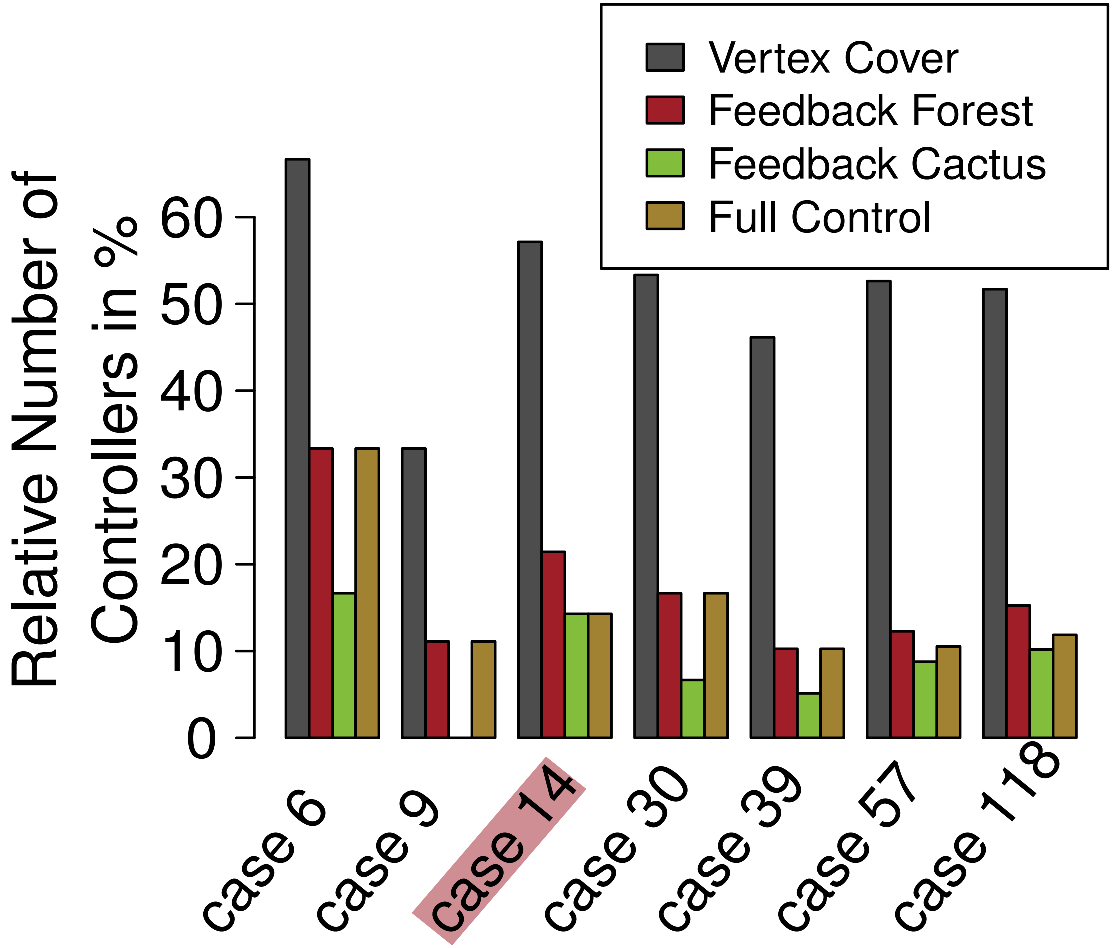
Theorem 2

Physical subgrid cactus, line limits on cactus suitably bounded.

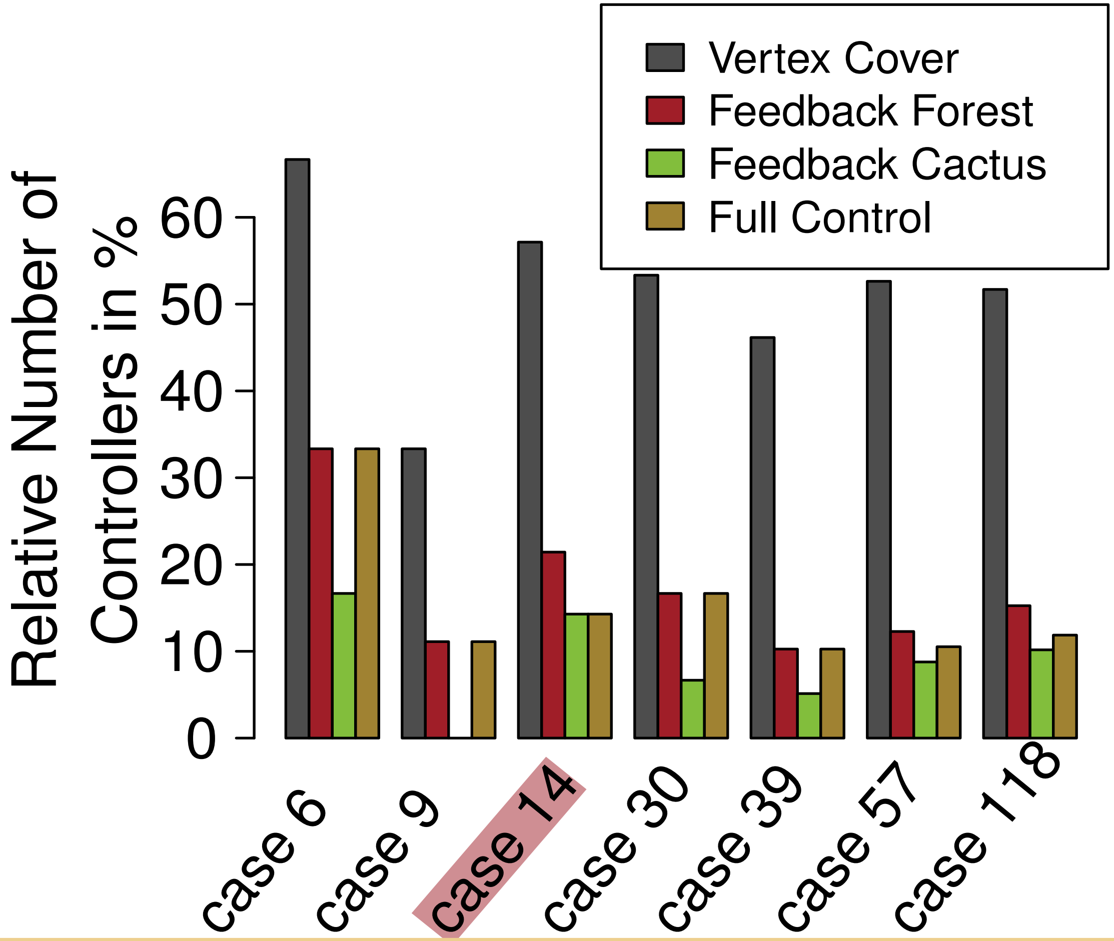
$$\Rightarrow$$

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

Number of Control 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.

Effect of Few Flow Control Buses (Q2)

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

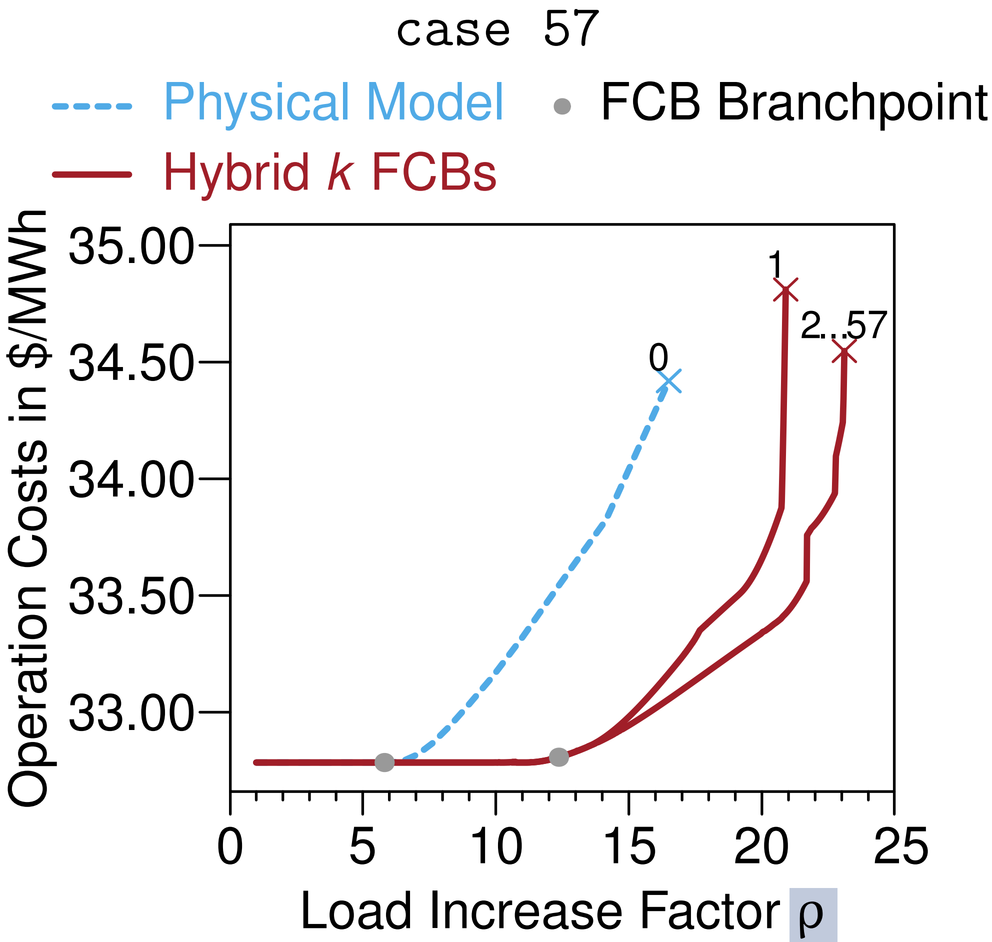
Effect of Few Flow Control Buses

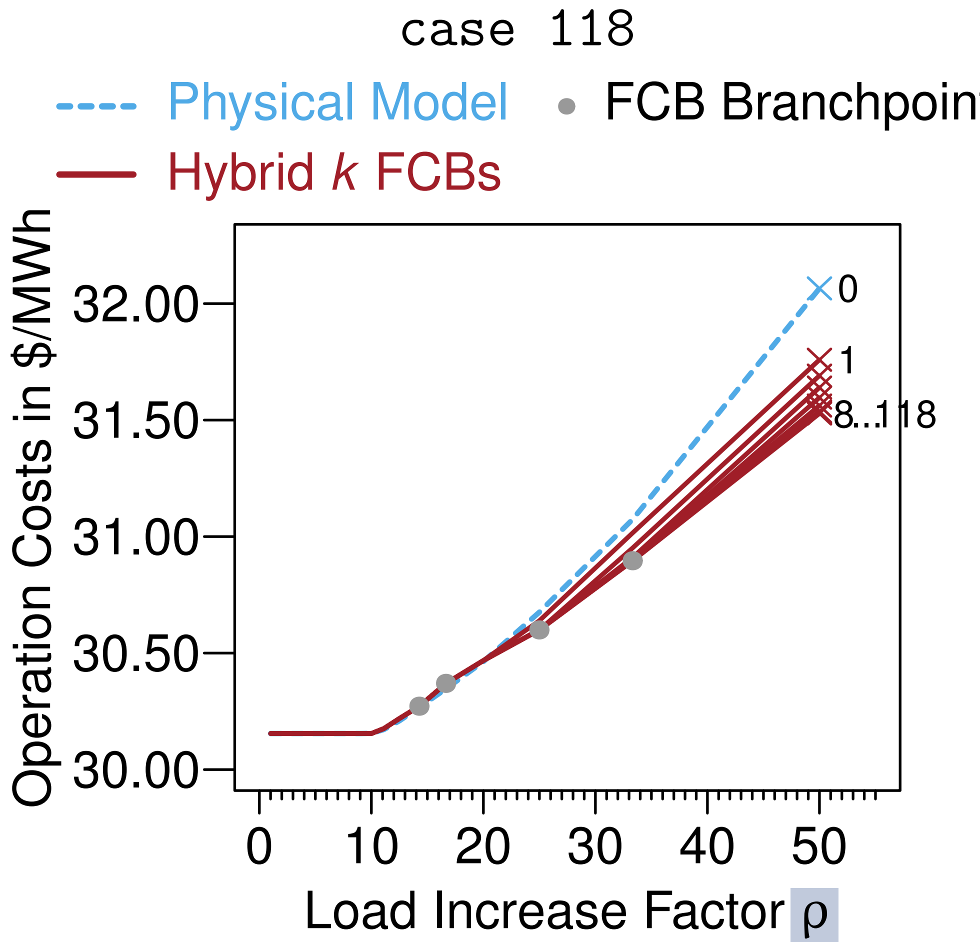
- Simulate load increase by a load increase factor ρ
- Simulations with different numbers of flow controllers

Test Data:

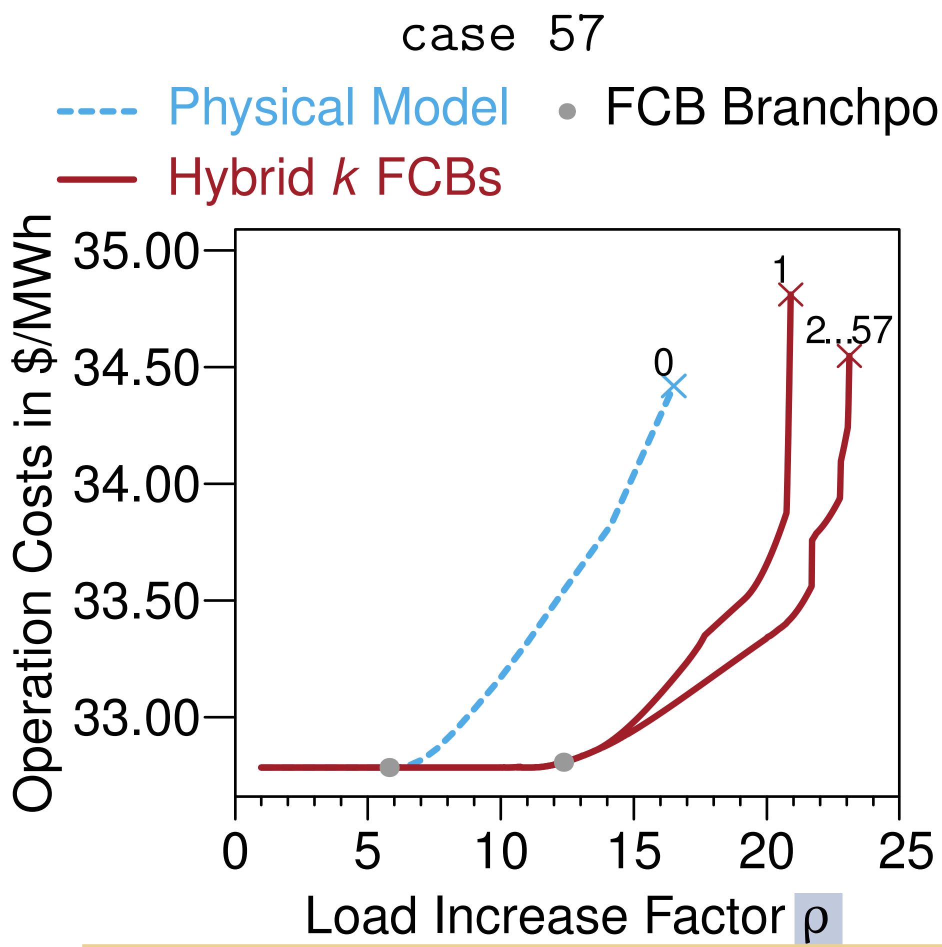
- IEEE instances have basically “unlimited” edge capacities
- Reduce capacities to total demand (no effect on cost and feasibility)
- Gradually increase all loads by factor ρ, or, alternatively, reduce all capacities by $1/\rho$
- Compute generation cost and required number of controllers for optimality

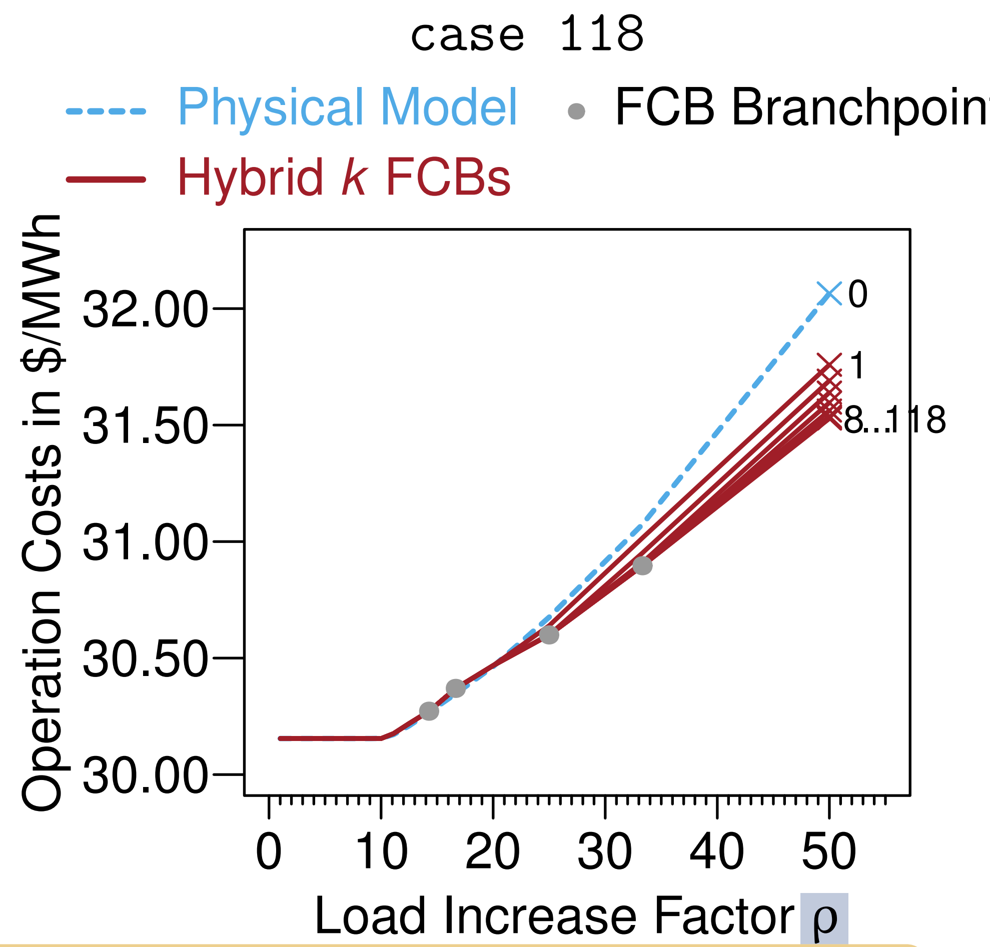
Hybrid Model Operation under Increasing Loads





Hybrid Model Operation under Increasing Loads





Findings

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

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Summary & Future Work

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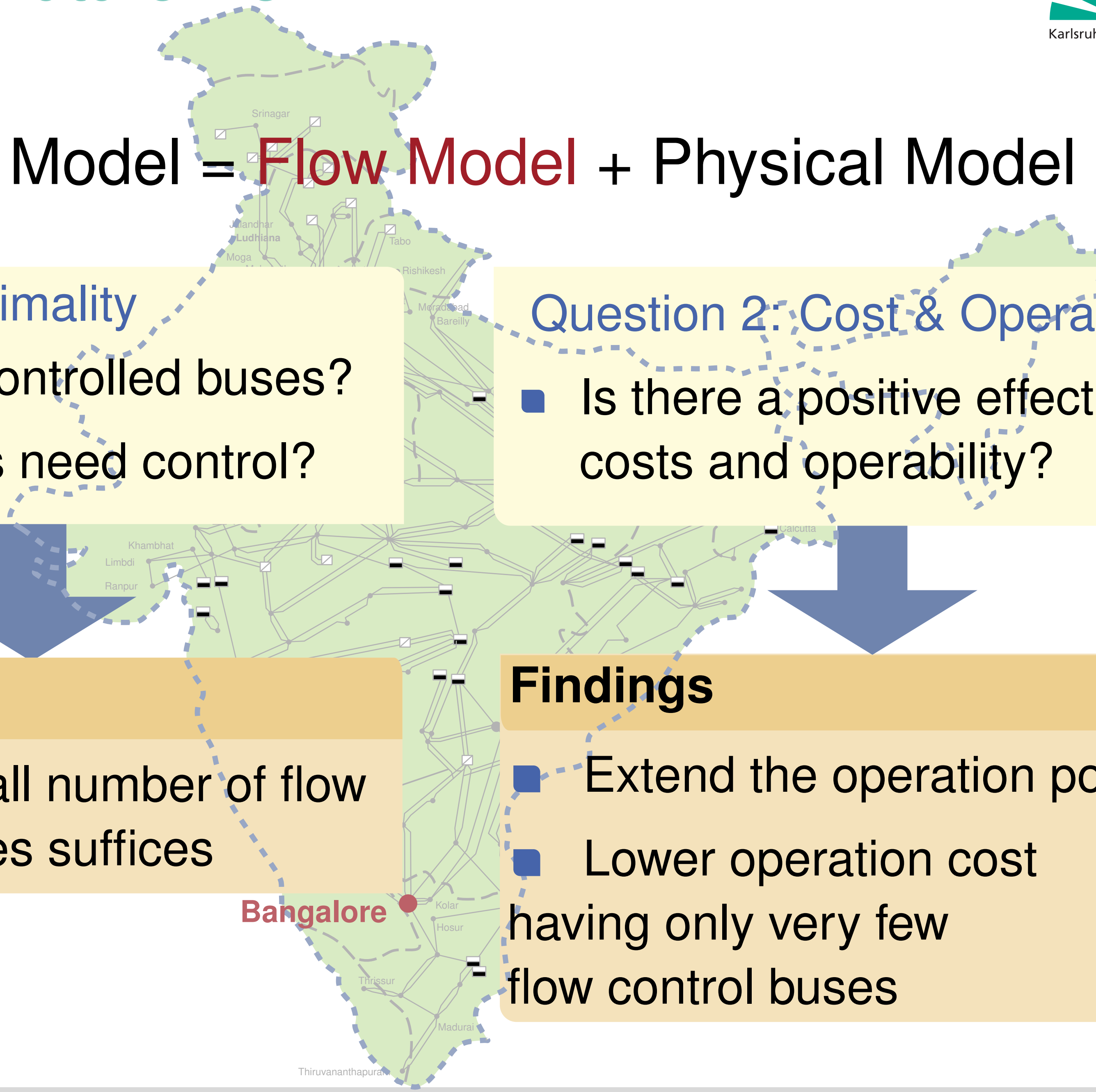

Hybrid Model = Flow Model + Physical Model

Question 1: Optimality

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

Findings

- Often a small number of flow control buses suffices

Question 2: Cost & Operability

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

Findings

- Extend the operation point
- Lower operation cost

having only very few flow control buses

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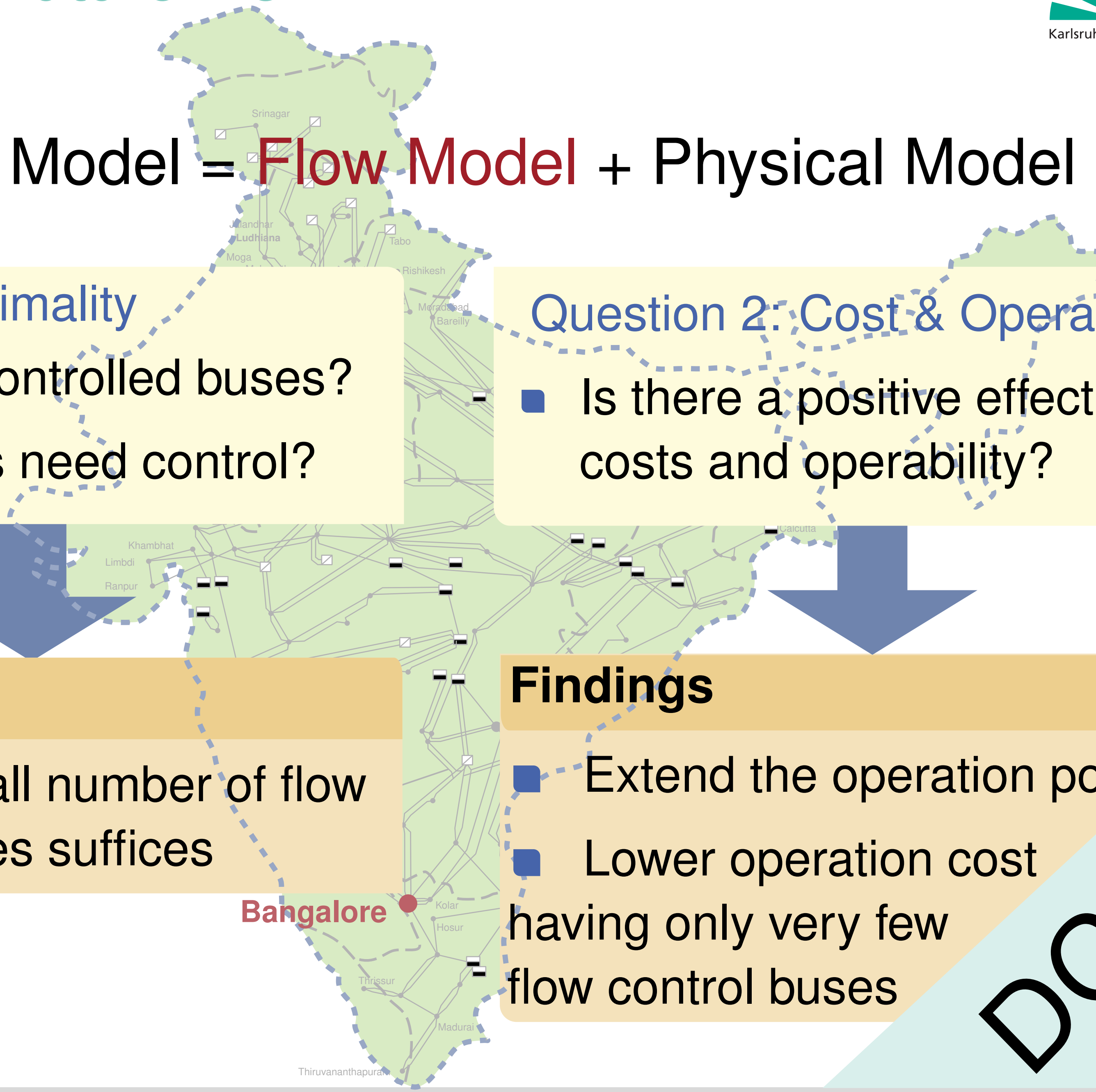

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having only very few flow control buses

DC/AC

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Backup 1

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