

International Workshop on
Dynamic Stability Challenges of the Future Power Grids

Imperfect Competition in Markets for Short-Circuit Current Services

Presenter

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Spain

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Faults in electric power systems

Unintentional **short circuits**:

- Wear-and-tear (transformers, cable insulation)
- Lightning
- Tree contact
- Wildlife...

General strategy: **de-energize fault** by opening circuit

Current is measured in real time, and **circuit breakers trip** when **current exceeds** a pre-defined **threshold**



Short-Circuit Current decline and consequences

- **Inverter-based Resources (IBR)** contribute much less Short-Circuit Current (SCC) than Synchronous Generators (SGs)

IBR (**1–3 p.u.** SCC)

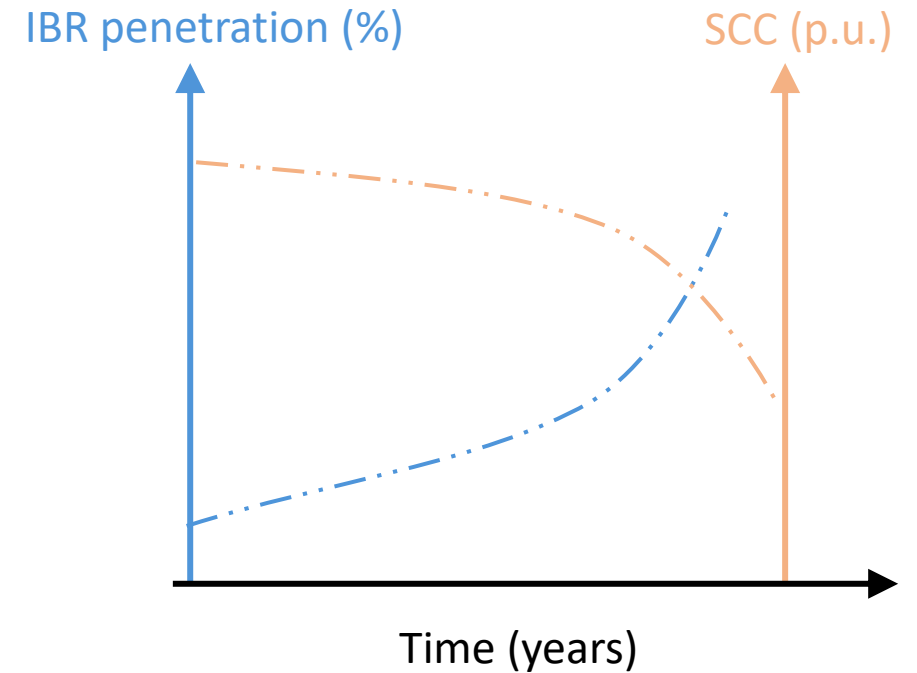


Electronic converters
(**burning of transistors**)

SGs (**5–8 p.u.** SCC)



Electromechanical physics



Short-Circuit Current decline and consequences

- **Inverter-based Resources (IBR)** contribute much less Short-Circuit Current (SCC) than Synchronous Generators (SGs)

IBR (1–3 p.u. SCC)



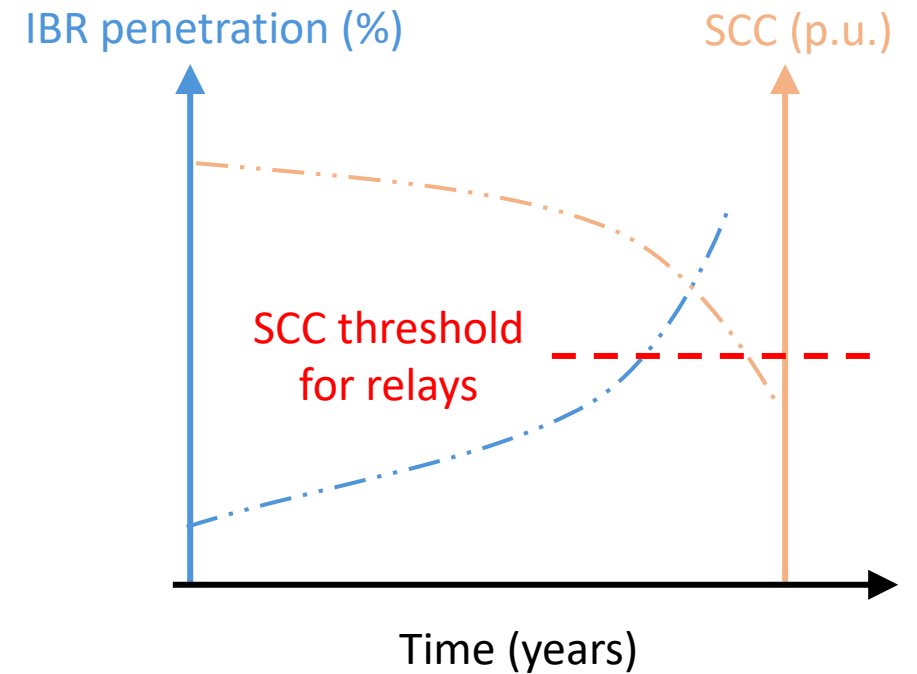
Electronic converters
(**burning of transistors**)

SGs (5–8 p.u. SCC)



Electromechanical physics

If fault current is reduced, the **relay may not be triggered**, so the fault **would not** be cleared



How to tackle the decline in SCC?

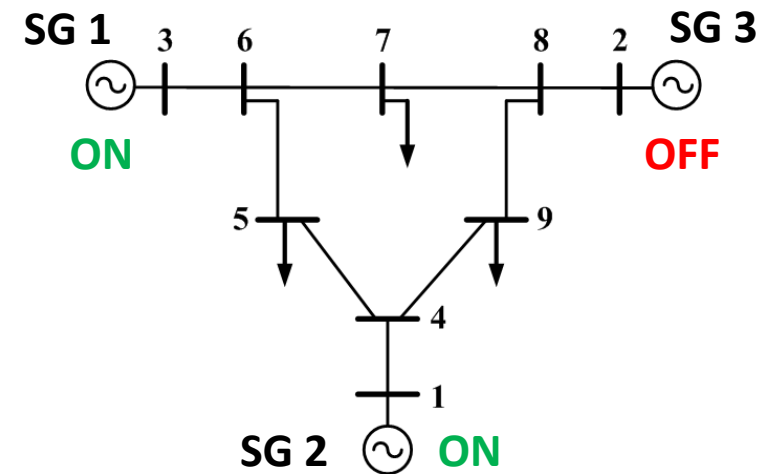
Option 1: invest in grid-supporting assets

Installing **synchronous condensers**



Option 2: security-constrained generation dispatch

Guarantee **sufficient generation online** for SCC



How to tackle the decline in SCC?

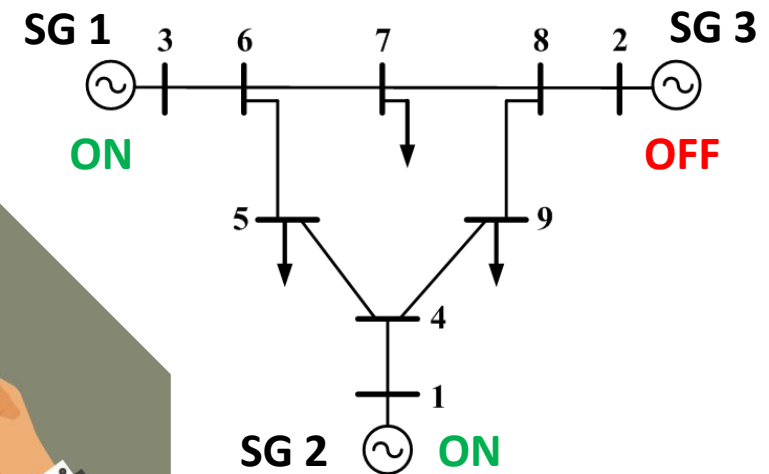
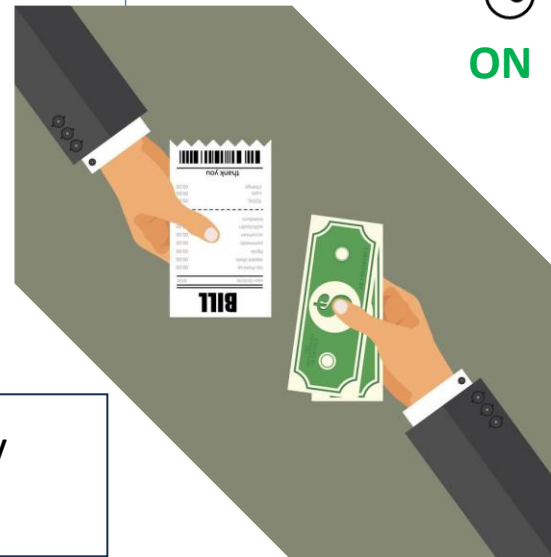
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Both options imply
economic cost!

How to tackle the decline in SCC?

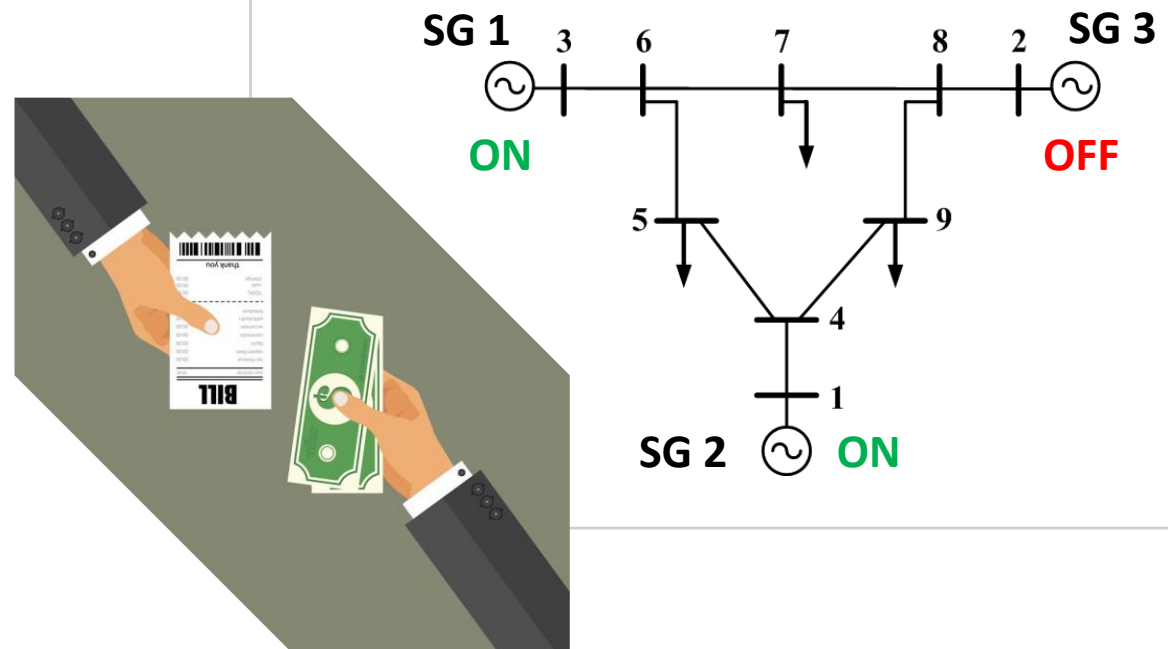
In this work, **we focus on option 2** (although sync condensers could also be considered in our framework)

The **questions** we want to shed some light on are:

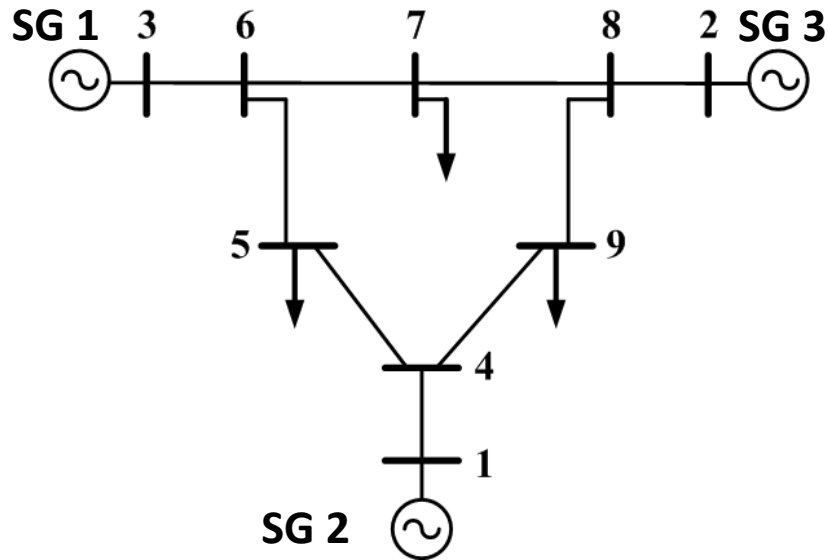
*Would it make sense **to create a market for SCC services?***

Would it be a **competitive market**, leading eventually to **lower costs for consumers?**

Guarantee **sufficient generation online** for SCC



Guaranteeing sufficient SCC: constraints in generation dispatch

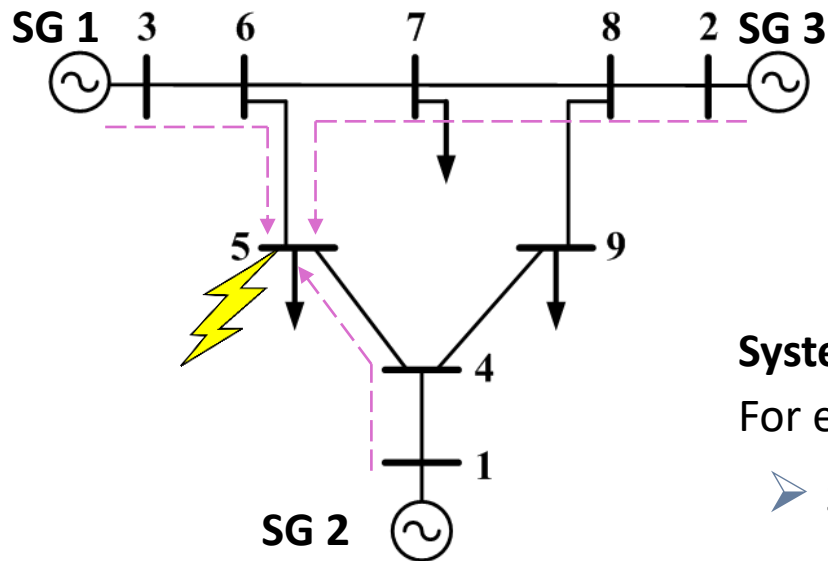


Guarantee at every bus that **SCC** is **above the threshold** ^[1]:

$$I_{b_{SC}} = \frac{\underbrace{\sum_{g \in \mathcal{G}} Z_{b\Psi(g)} I_g u_g}_{\text{SCC from SGs}} + \underbrace{\sum_{c \in \mathcal{C}} Z_{b\Phi(c)} I_c \alpha_c}_{\text{SCC from IBR}}}{\underbrace{Z_{bb}}_{\text{bus impedance}}} \geq \underbrace{I_{b_{lim}}}_{\text{threshold}}$$

¹Z. Chu and F. Teng, "Short circuit current constrained UC in high IBG-penetrated power systems," *IEEE Transactions on Power Systems*, 2021

Guaranteeing sufficient SCC: constraints in generation dispatch



Guarantee at every bus that **SCC is above the threshold** ^[1]:

$$I_{b_{SC}} = \frac{\text{SCC from SGs} + \text{SCC from IBR}}{Z_{bb}} \geq I_{b_{lim}}$$

The equation shows the short-circuit current at bus b as the sum of contributions from synchronous generators (SGs) and inverter-based resources (IBR), divided by the bus impedance Z_{bb} . The result must be greater than or equal to the limiting current $I_{b_{lim}}$. Annotations in the original image highlight the SG and IBR terms in orange and green respectively, and the denominator Z_{bb} in a grey box.

System impedance (Z) leads to different levels of SCC provision for each bus.

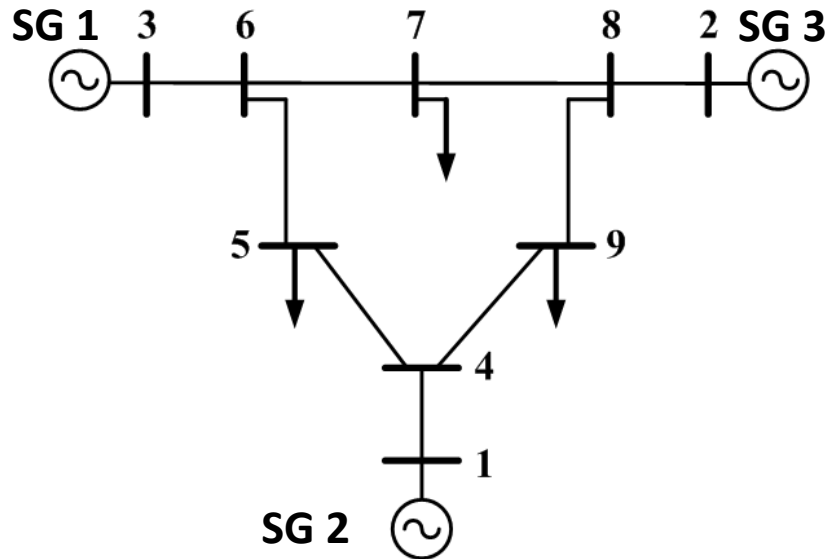
For example:

- SG 1 and SG 2 would contribute a larger share of SCC to bus 5, due to a closer **electrical distance**

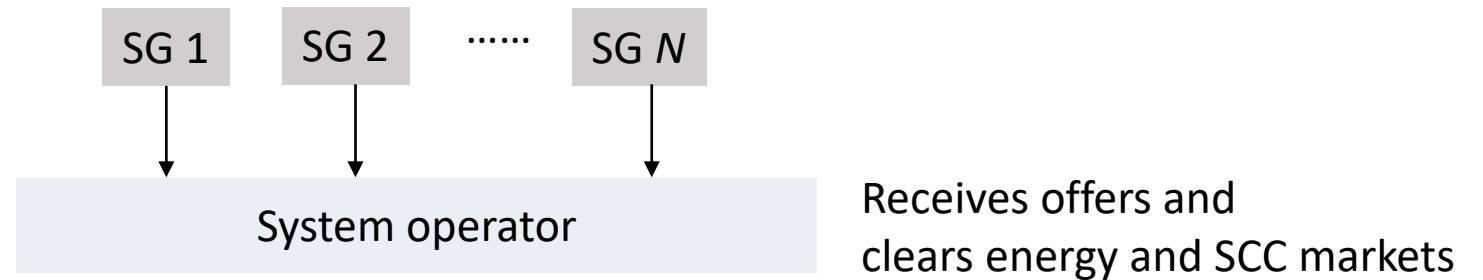
SCC provision is **very locational**

¹Z. Chu and F. Teng, "Short circuit current constrained UC in high IBG-penetrated power systems," *IEEE Transactions on Power Systems*, 2021

Potential problem: market power in SCC services?

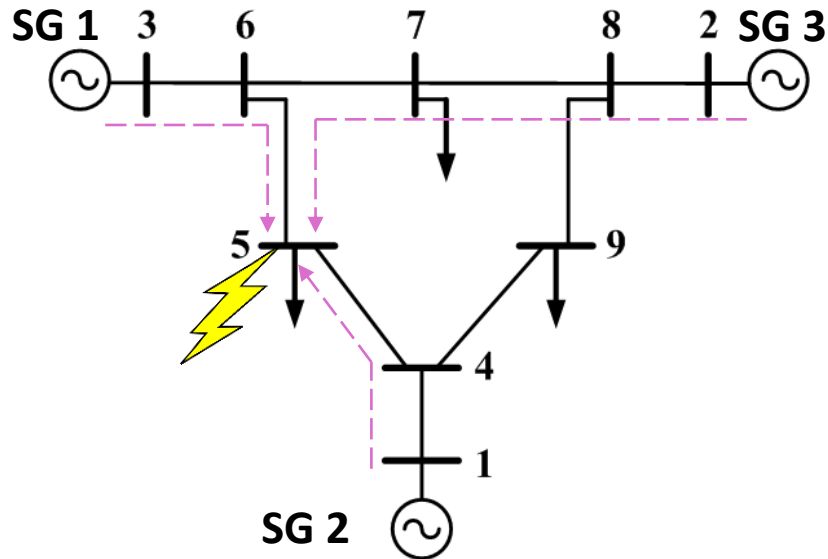


SCC may be procured as an **ancillary service** ^[2]

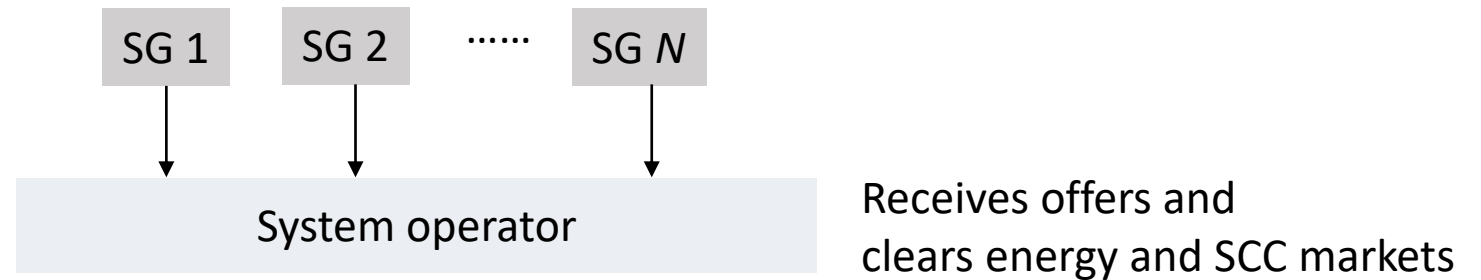


²Z. Chu, J. Wu and F. Teng, "Pricing of short circuit current in high IBR-penetrated system," *Electric Power Systems Research*, 2024

Potential problem: market power in SCC services?



SCC may be procured as an **ancillary service**

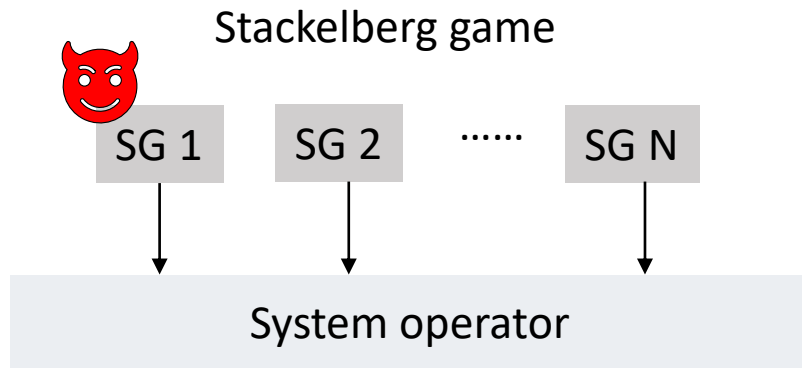


But SCC provision is **very locational**...

May an agent at an **advantageous location**
exert market power to **distort SCC prices**?

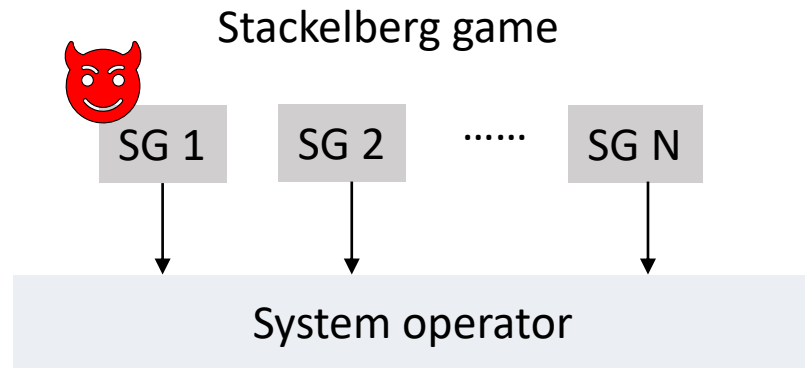


How to model imperfect competition in SCC services?



- Self-interested SG 1 → ***strategically*** bids for profits
- Other SGs → assumed to bid truthfully
- System operator → clears market

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Upper level
(SG 1)

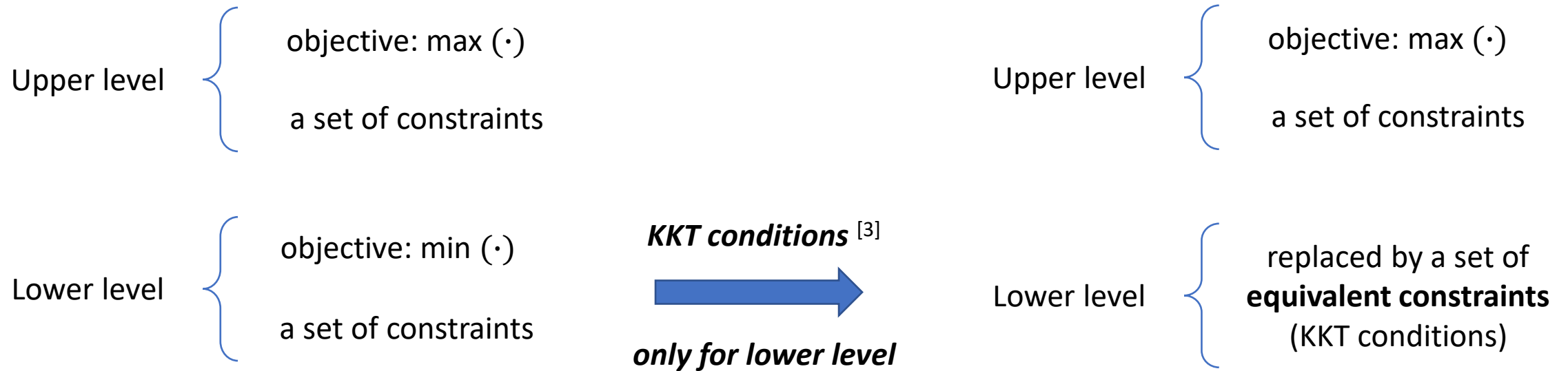
Objective: **max** profit
Actions: **dishonest** energy and SCC bids

Lower level
(System operator)

Objective: **min** system operating cost
Actions: receive bids from upper level, dispatch generators and define market prices

Solving a bilevel optimization problem

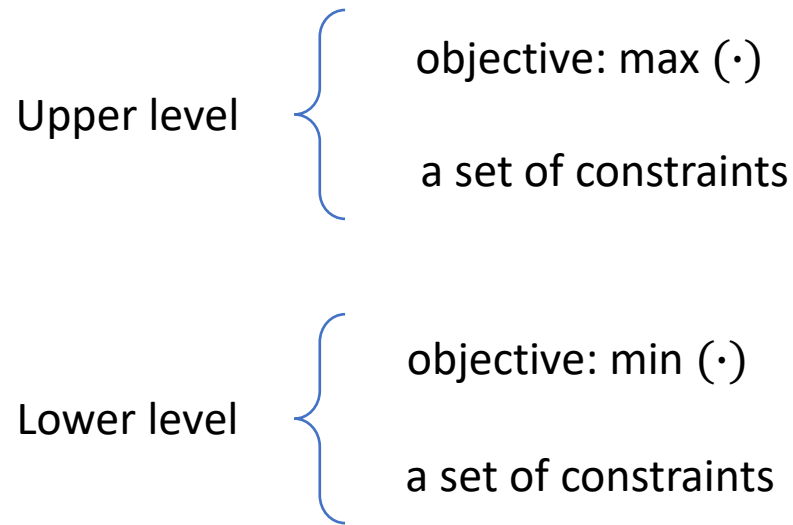
Traditional way to solve a *convex* bilevel problem:



³A. Conejo and C. Ruiz, "Complementarity, not optimization, is the language of markets," *IEEE Open Access Journal of Power and Energy*, 2020

Solving a bilevel optimization problem

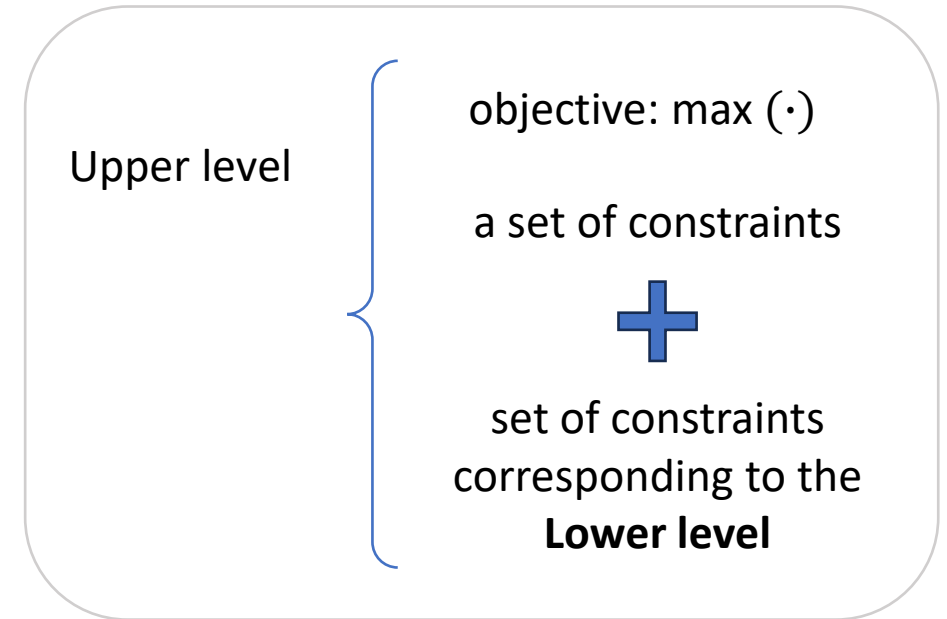
Traditional way to solve a **convex** bilevel problem:



KKT conditions ^[3]



only for lower level



Equivalent **single-level** optimization

³A. Conejo and C. Ruiz, "Complementarity, not optimization, is the language of markets," *IEEE Open Access Journal of Power and Energy*, 2020

Challenge: bilevel optimization + binary variables

Unfortunately, **our bilevel model cannot be easily solved**

- SCC from SGs is inherently related to **unit commitment** (binary variables) → discrete **non-convexities**

$$I_{b_{SC}} = \frac{\sum_{g \in \mathcal{G}} Z_{b\Psi(g)} \overset{\{0, 1\} \text{ (gen state OFF or ON)}}{I_g u_g} + \sum_{c \in \mathcal{C}} Z_{b\Phi(c)} I_c \alpha_c}{Z_{bb}} \geq I_{b_{lim}}$$

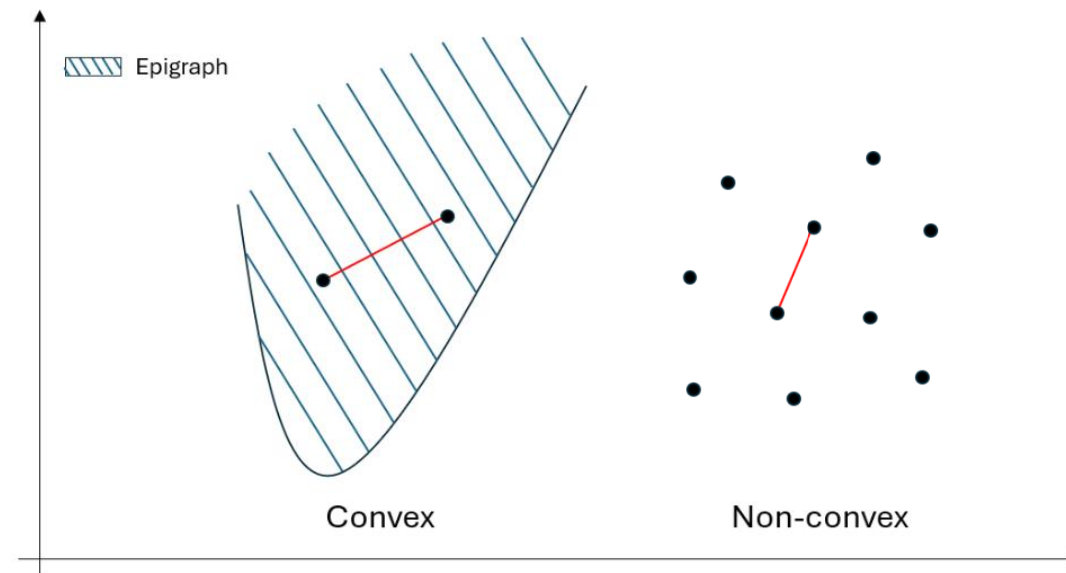
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{0, 1} (gen state OFF or ON)



If you want to read more:

[L. Badesa](#), "Duality in optimization, KKT and shadow prices – With applications to electricity markets," 2025

Challenge: bilevel optimization + binary variables

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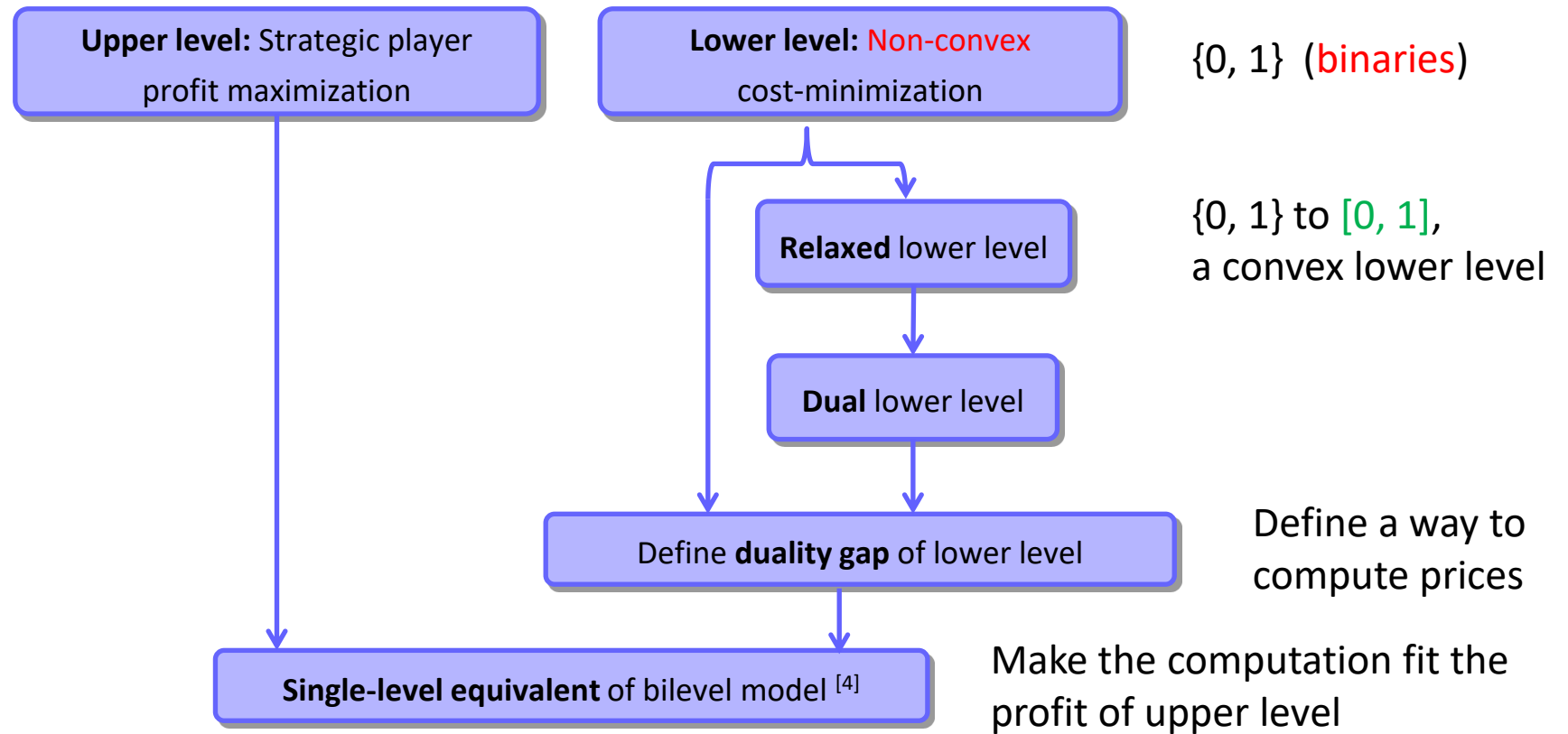
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The traditional solution method **requires** the **lower level** to be **convex**

- Otherwise, the **KKT conditions** are not an equivalent representation (they are necessary but **not sufficient** conditions **for optimality**)

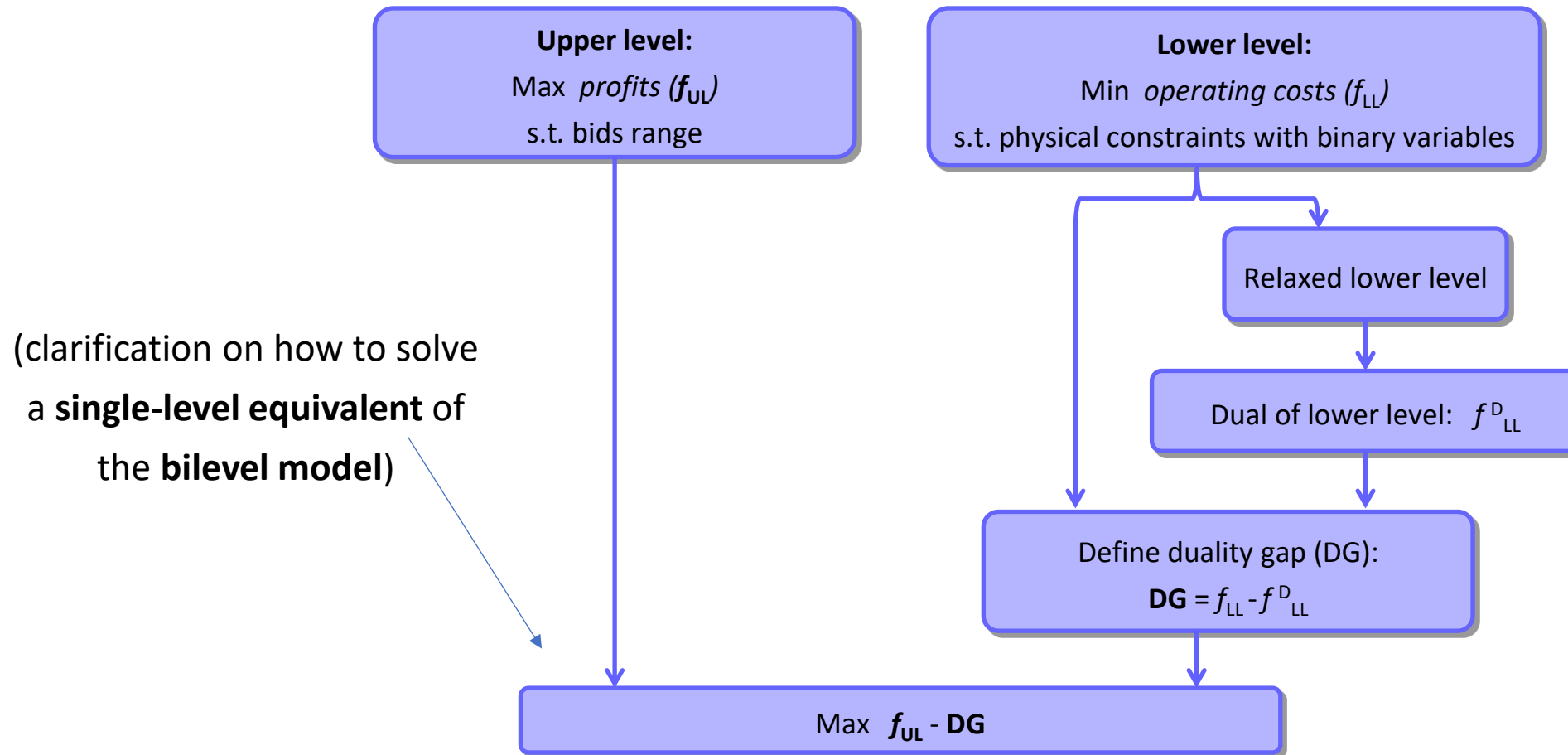
How to address non-convexity?

Solution:
primal-dual formulation
for lower level



⁴Y. Ye *et al.*, "Incorporating Non-Convex Operating Characteristics into Bi-Level Optimization Electricity Market Models," *IEEE Trans. on Power Syst.*, 2020

How to address non-convexity?

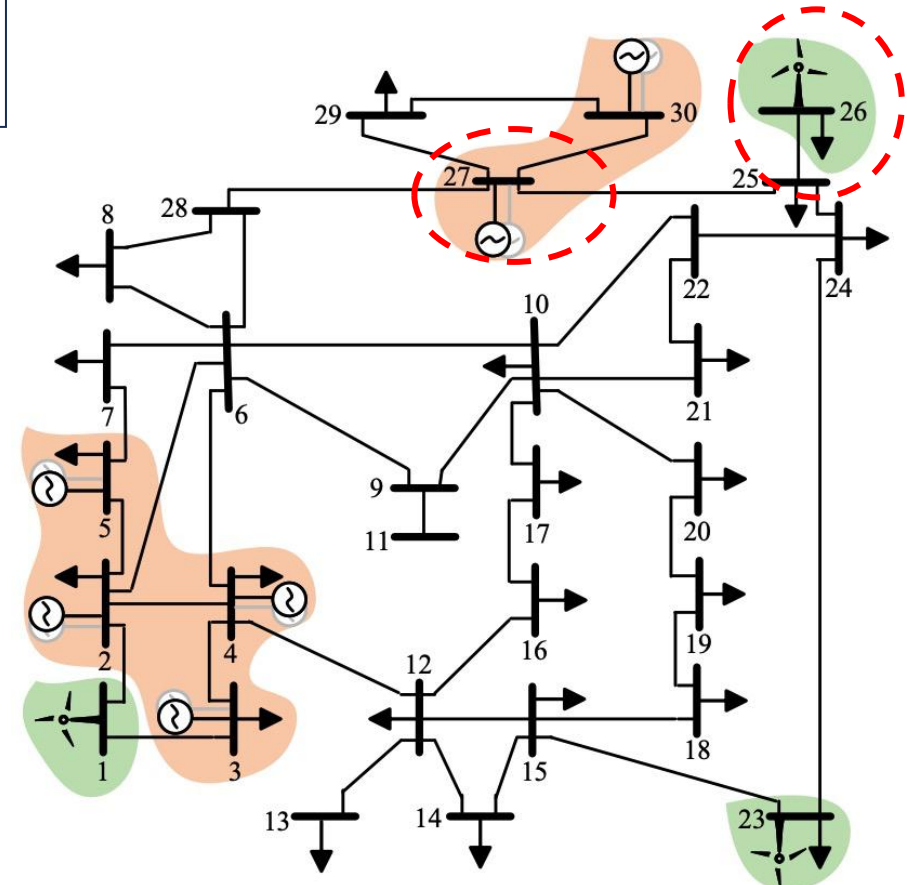


Research results — roots of market power

Locality of SCC + Discrete supply mechanism + Hard security requirement

The SCC at the system's **weak bus 26**, is **highly dependent** on **SGs at bus 27**

- Contribution from **SGs at bus 27**: **3.34 p.u.**
- Contribution from **all other SGs**: 2.77 p.u. at maximum



Modified IEEE 30-bus system

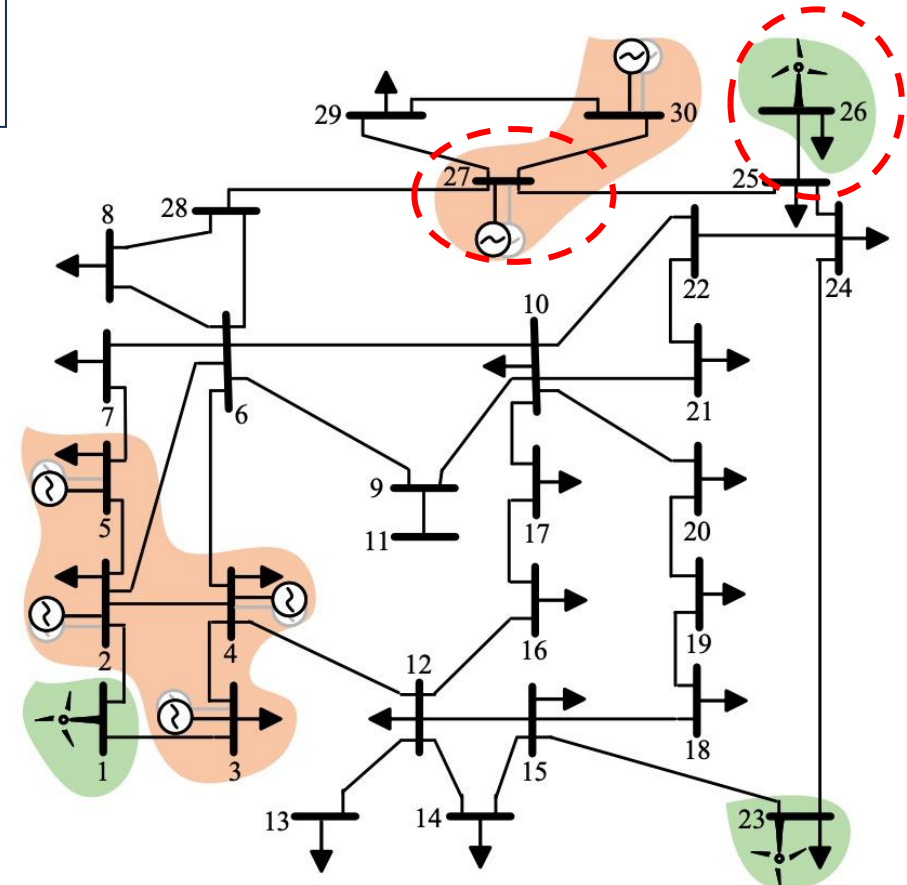
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- The ability to support SCC is determined by **electrical distance**
- Only *nearby* SGs can provide *sufficient* SCC
- While distant SGs have no substitutable value, creating a **natural local supply barrier**



Modified IEEE 30-bus system

Research results — roots of market power

Locality of SCC + **Discrete supply mechanism** + **Hard security requirement**

$$I_{b_{SC}} = \frac{\sum_{g \in \mathcal{G}} Z_{b\Psi(g)} \mathbf{I}_g u_g + \sum_{c \in \mathcal{C}} Z_{b\Phi(c)} \mathbf{I}_c \alpha_c}{Z_{bb}} \geq I_{b_{lim}}$$

- The **SCC provision** of SGs **is discrete**: it's an **all-or-nothing service**
(an online generator provides a given volume of SCC; offline provides none)
- A bus must meet a minimum **SCC threshold**, otherwise grid security is threatened

Research results — consequences of market power

	Bidding truthfully	Bidding strategically
SCC revenue of SGs at bus 27	44.4 k€	147.9 k€ (+ 3.3x)
Consumers cost	65.0 k€	175.6 k€ (+ 2.7x)

Key takeaways

Would it make sense **to create a market for SCC services?**



Maybe, but **with care**

Certain generators could more than

 **triple their revenues** 

from this service if **market power** issues are not properly mitigated

- SCC ancillary service is **highly location-dependent**: generators near vulnerable buses possess inherent market power due to *irreplaceable SCC*

Key takeaways

Would it make sense *to create a market for SCC services?*



Maybe, but **with care**

(**market power** issues)

So *what can we do about it?*

Further work needed to properly answer this question

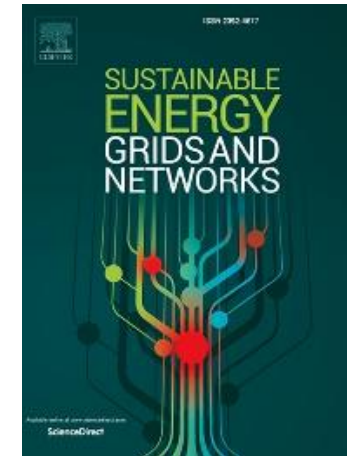
- Installing **synchronous compensators owned by the TSO** in the most critical buses could help make the remaining SCC market more competitive
- **Price cap**: directly limit SCC service prices

Future work

- Study interactions between **multiple strategic players** (EPEC, Equilibrium Problem with Equilibrium Constraints)
- Consider **unbalanced faults** (current work only considers three-phase faults)
- Analyze markets for **other stability services**, such as voltage stability

Paper reference

P. Wang and L. Badesa, "Imperfect Competition in Markets for Short-Circuit Current Services,"
Sustainable Energy, Grids and Networks, vol. 47, 2026



Peng
Wang

(**first author**,
PhD student
at UPM)

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