10 DynPOWER 2026

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Swiss National Science Foundation

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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Technical University of Madrid
Spain

Monday, 7 September 2026, Winterthur, Switzerland

Faults in electric power systems

Unintentional **short circuits**:

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

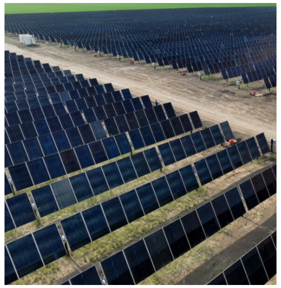
General strategy: **de-energize fault** by opening circuit

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)

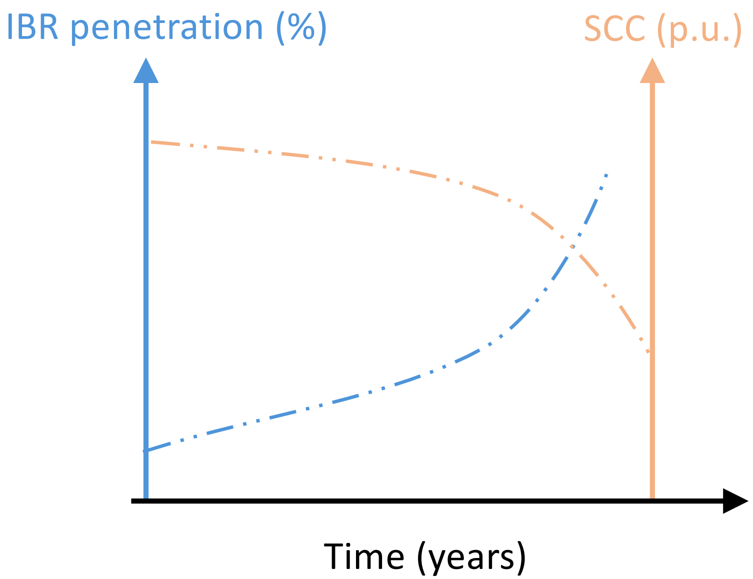
IBR (**1–3 p.u.** SCC)



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)

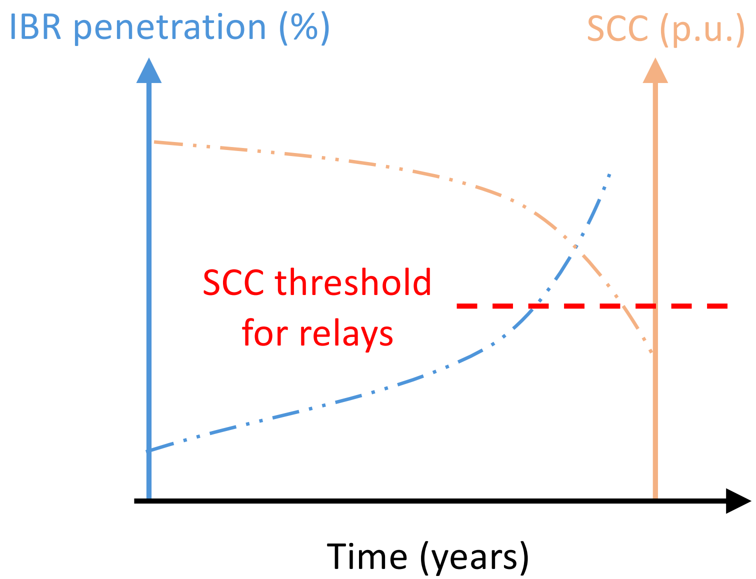
If fault current is reduced, the relay may **not be triggered**, so the fault ***would not*** be cleared

IBR (1–3 p.u. SCC)

Electronic converters (**burning of transistors**)

SGs (5–8 p.u. SCC)

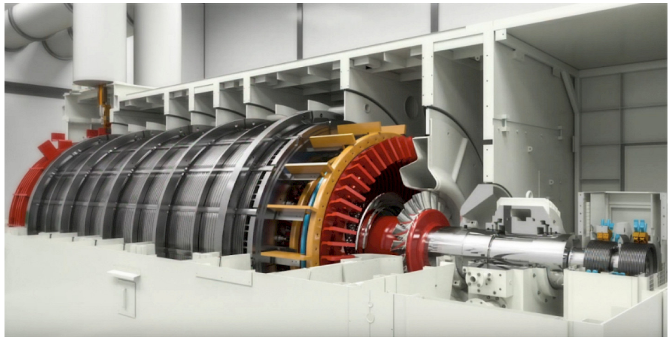
Electromechanical physics



How to tackle the decline in SCC?

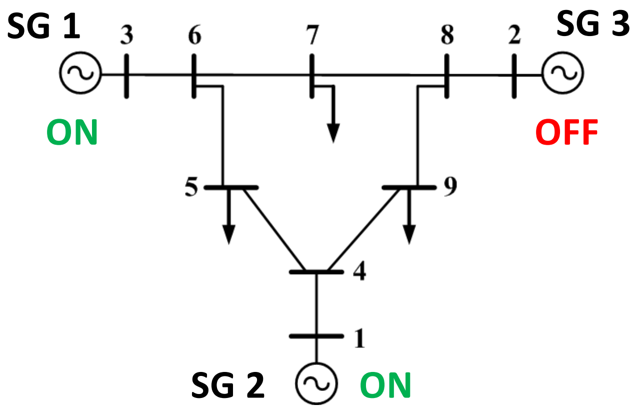
Option 1: invest in **grid-supporting assets**

Installing **synchronous condensers**



Option 2: security-constrained **generation dispatch**

Guarantee **sufficient generation online** for SCC



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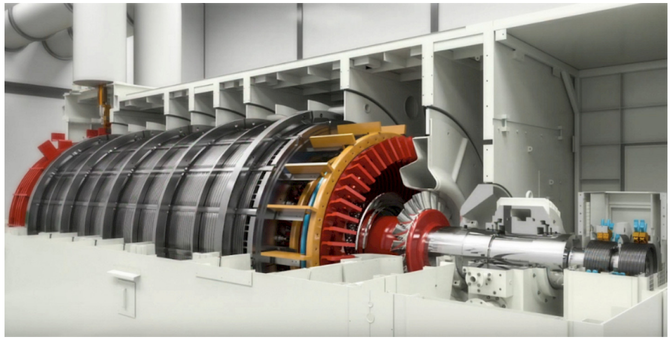

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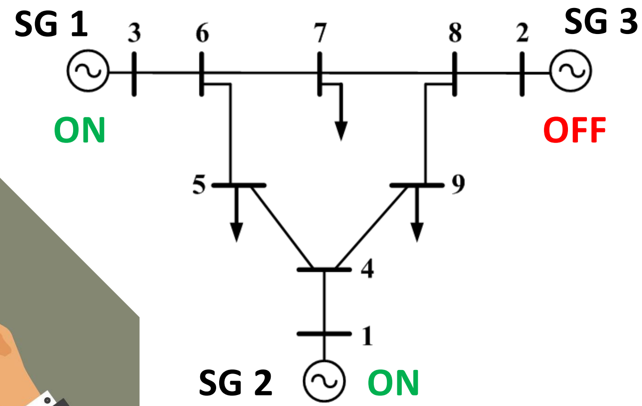
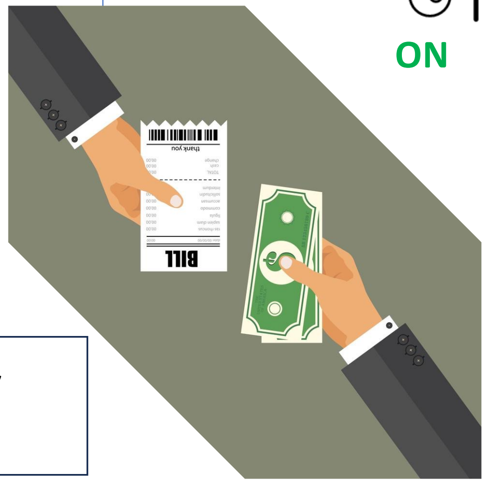




Both options imply
economic cost!

How to tackle the decline in SCC?

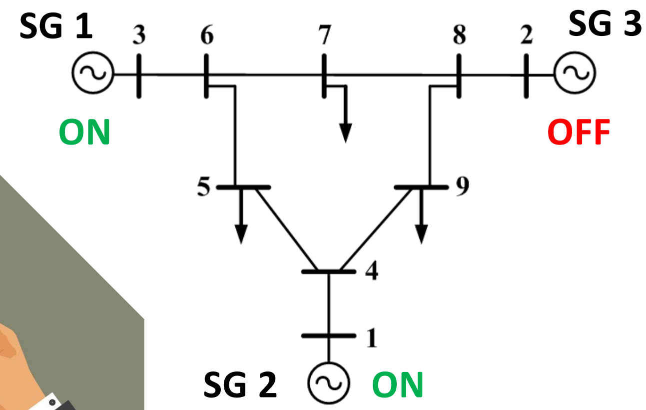
In this work, **we focus** on **option 2** (although sync condensers could also be considered in our framework)

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

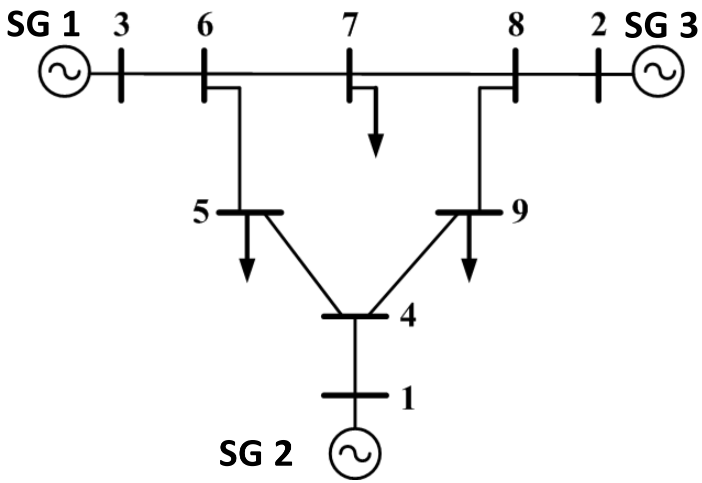
Would it make sense ***to create a market*** *for* ***SCC services****?*

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]:

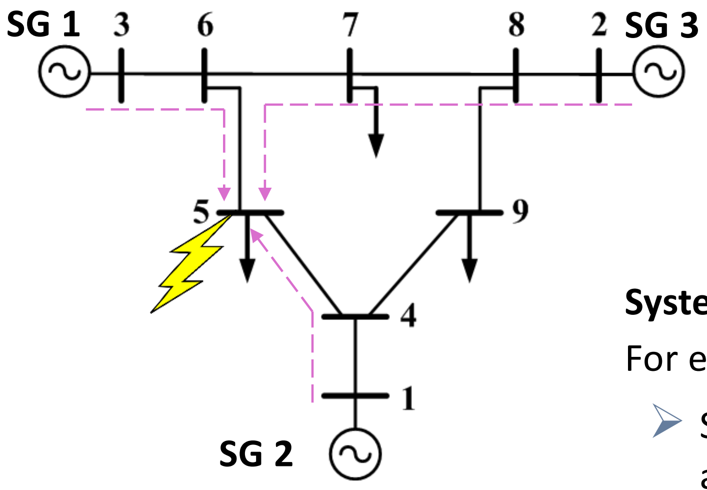
SCC from SGs

SCC from IBR

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

[1] Z. 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



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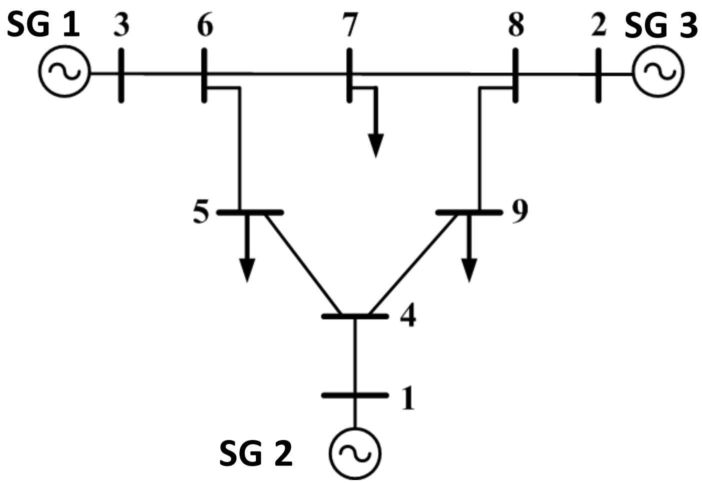
System impedance (Z) leads to different levels of SCC provision for each bus. For example:

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

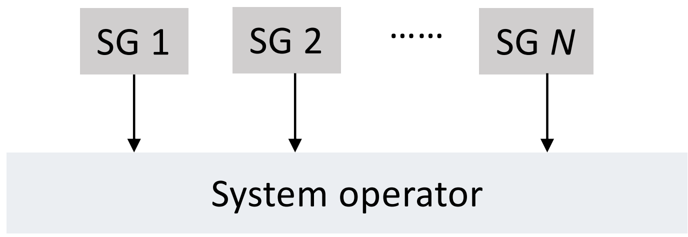
SCC provision is **very locational**

[1]Z. 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]



Receives offers and
clears energy and SCC markets

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

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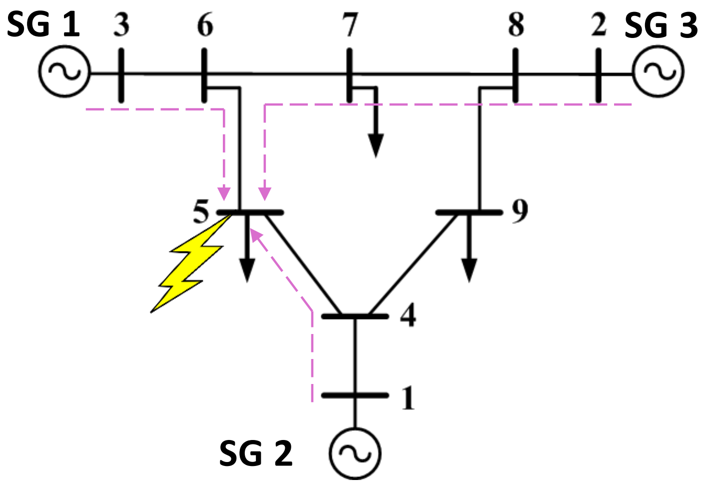
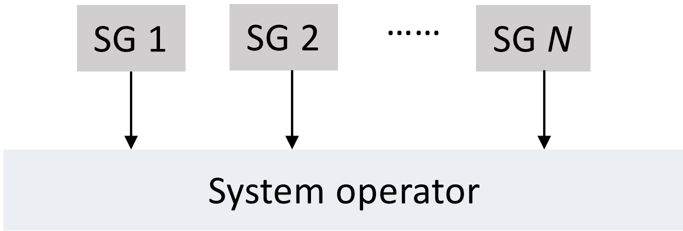


SCC may be procured as an **ancillary service**

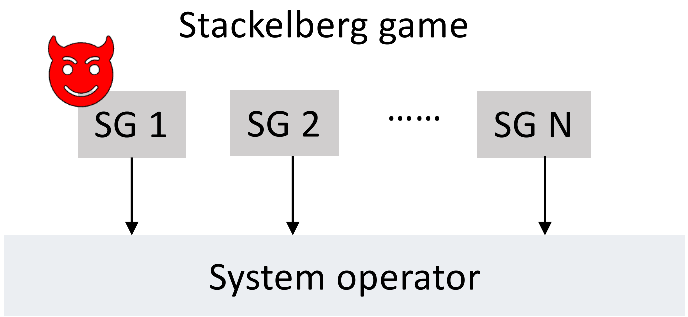


Receives offers and
clears energy and SCC markets

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

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

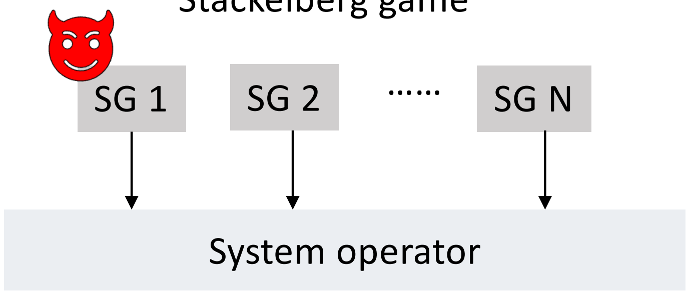
How to model imperfect competition in SCC services?



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

How to model imperfect competition in SCC services?

Stackelberg game



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Bilevel optimization model

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:

Upper level: objective: max $(\cdot)$; a set of constraints

Lower level: objective: min $(\cdot)$; a set of constraints

KKT conditions [3] → ***only for lower level***

Upper level: objective: max $(\cdot)$; a set of constraints

Lower level: replaced by a set of **equivalent constraints** (KKT conditions)

[3] A. 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:

Upper level
- objective: max (·)
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Lower level
- objective: min (·)
- a set of constraints

KKT conditions [3]

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Upper level
- objective: max (·)
- a set of constraints

+

set of constraints corresponding to the **Lower level**

Equivalent **single-level** optimization

[3] A. 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**

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

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

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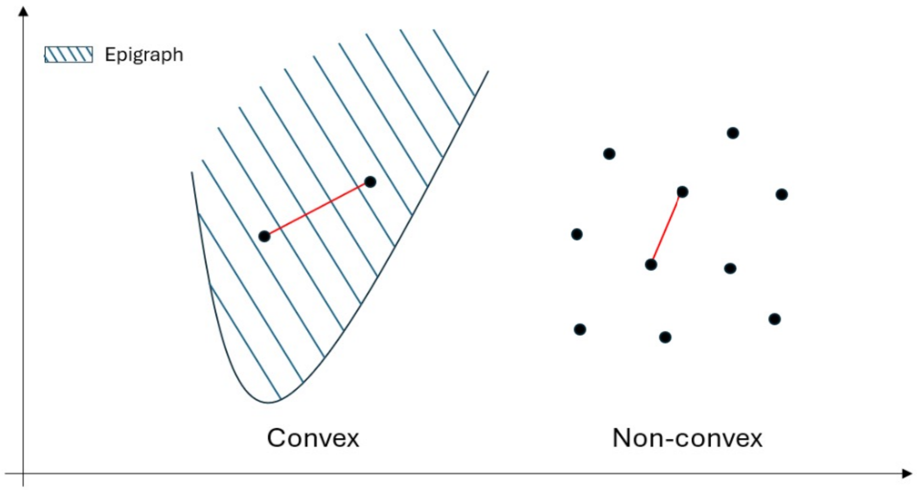

If you want to read more:

L. Badesa, "Duality in optimization, KKT and shadow prices – With applications to electricity markets," 2025

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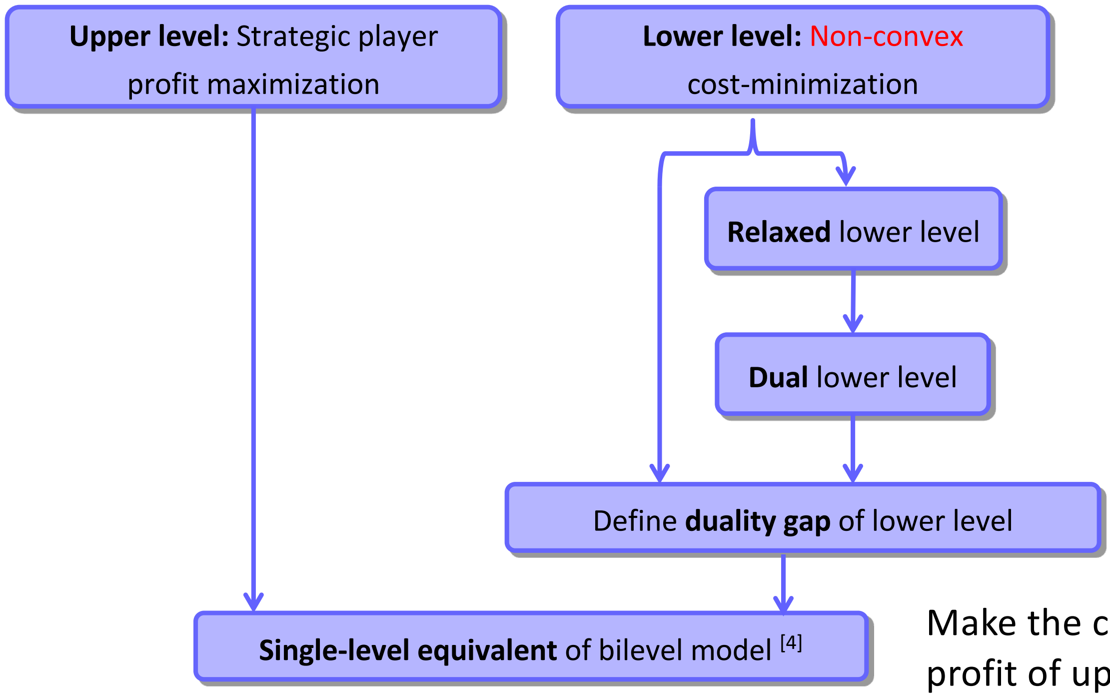
The traditional solution method **requires** the **lower level** to be **convex**

- 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



{0, 1} (binaries)

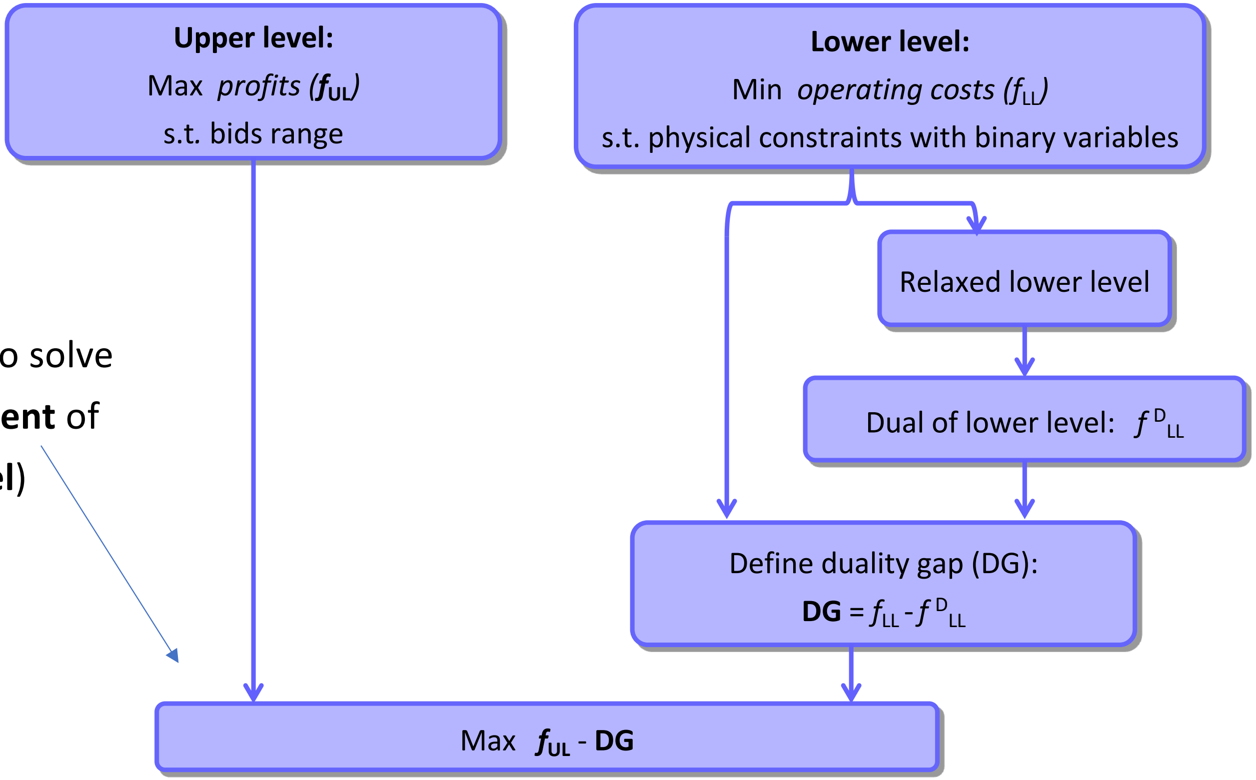
{0, 1} to [0, 1],
a convex lower level

Define a way to
compute prices

Make the computation fit the
profit of upper level

[4] Y. 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?



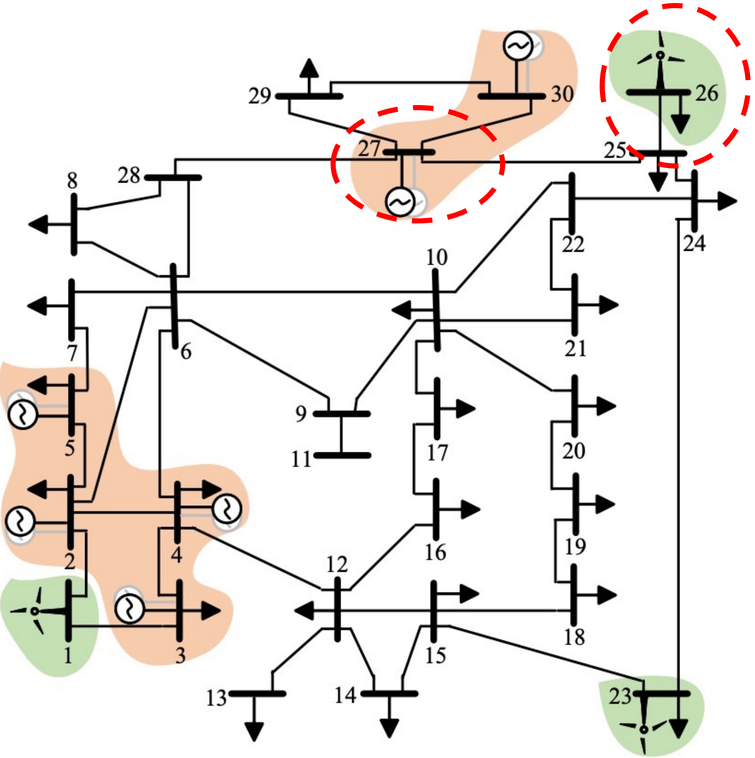
(clarification on how to solve a **single-level equivalent** of the **bilevel model**)

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

Research results — roots of market power

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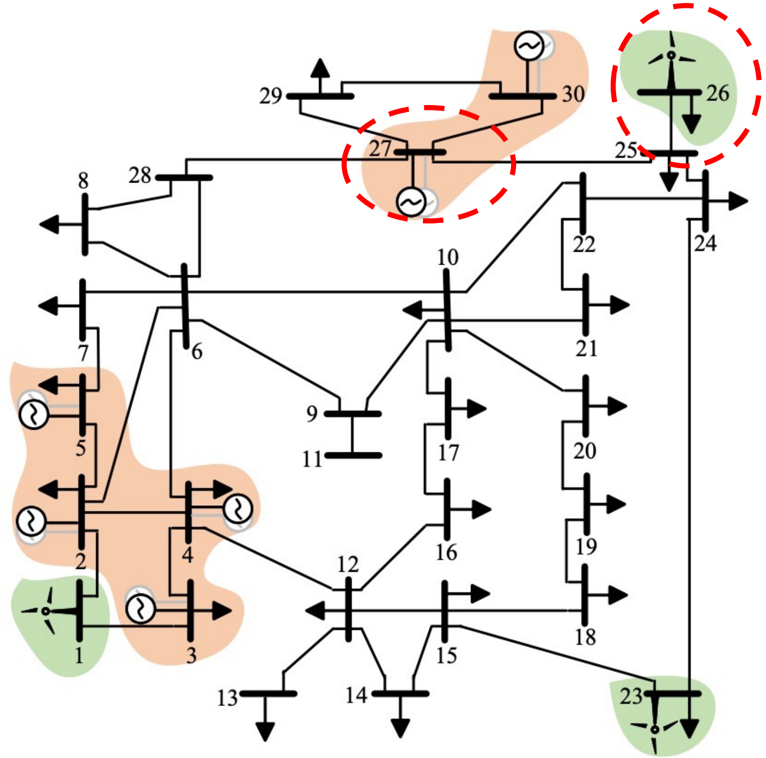
- The ability to support SCC is determined by **electrical distance**
- Only *nearby* SGs can provide *sufficient SCC*
- While distant SGs have no substitutable value, creating a **natural local supply barrier**



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- 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 **SG**s 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

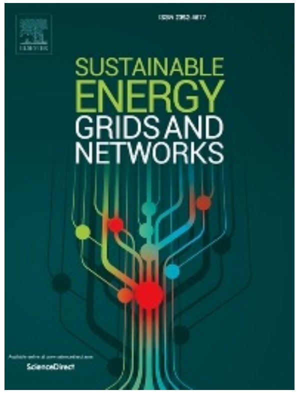
- Installing **synchronous compensators owned by the TSO** in the most critical buses could help make the remaining SCC market more competitive
- **Price cap**: directly limit SCC service prices

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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Funding acknowledgement

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