

Imperfect Competition in Markets for Short-Circuit Current Services

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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)

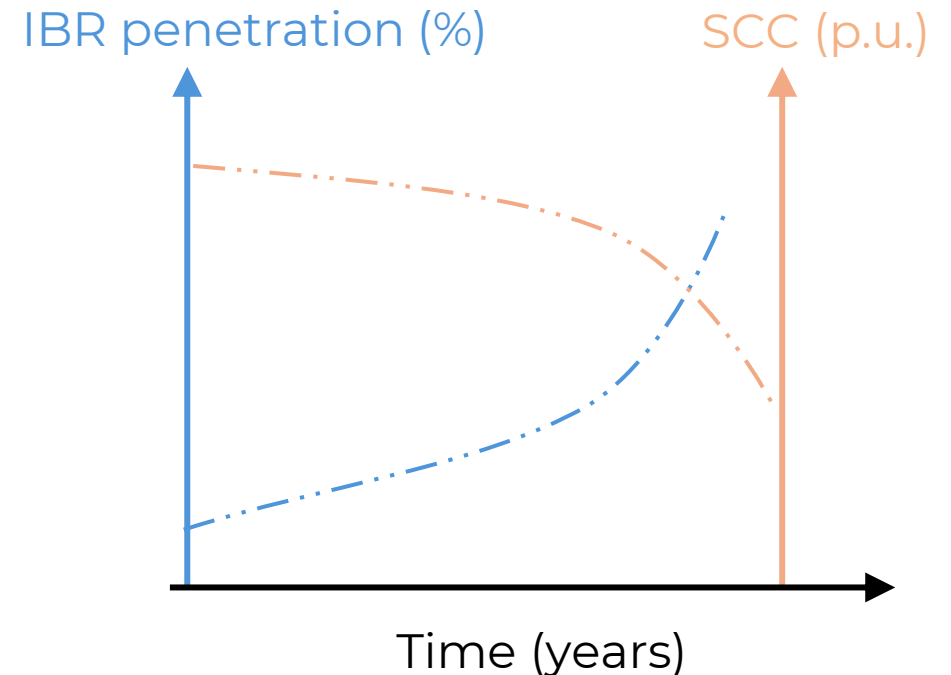


Electronic converters
(**burning of transistors**)

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)

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

IBR (**1–3 p.u.** SCC)

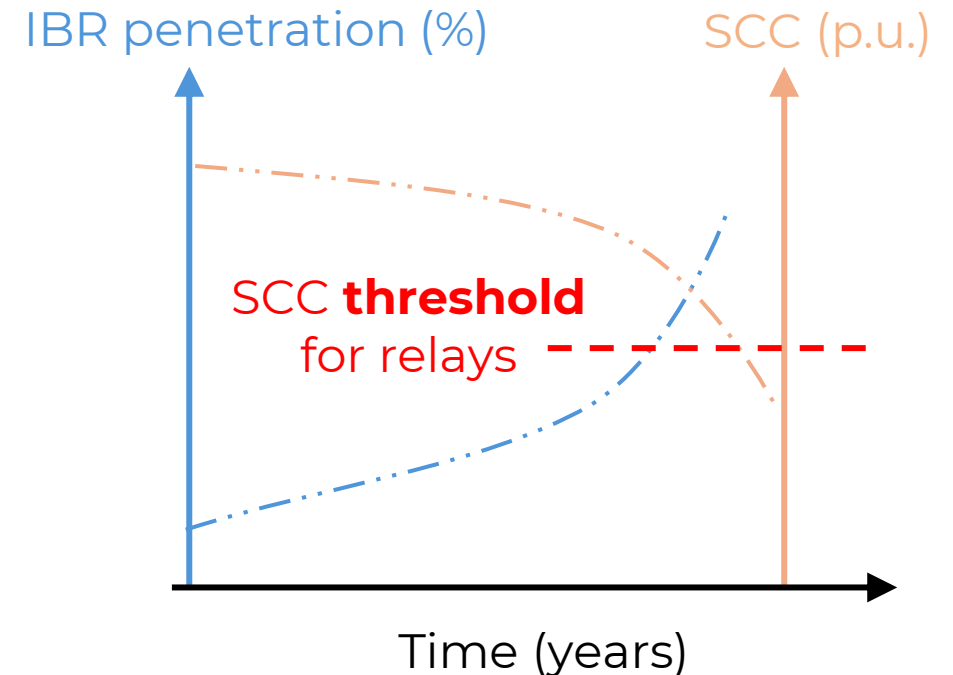


Electronic converters
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Electromechanical
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How to tackle the decline in SCC?

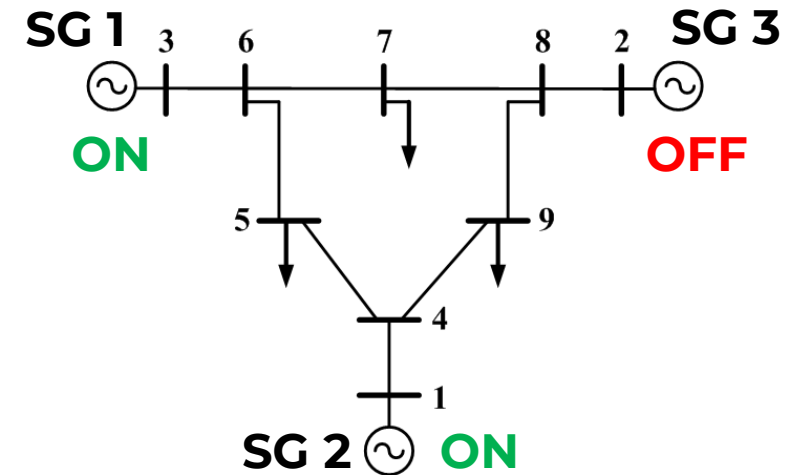
Option 1: invest in **grid-supporting assets**

Installing **synchronous condensers**



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

Guarantee **sufficient generation online** for SCC



How to tackle the decline in SCC?

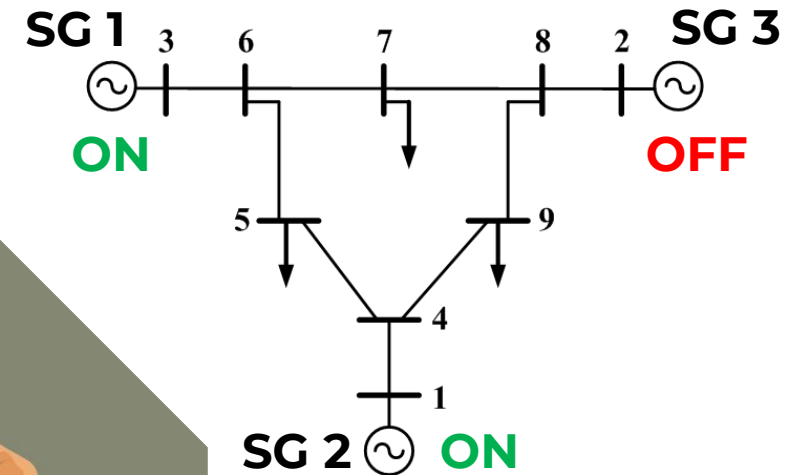
Option 1: invest in **grid-supporting assets**

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Both options imply
economic cost!

How to tackle the decline in SCC?

In this work, **we focus on option 2**

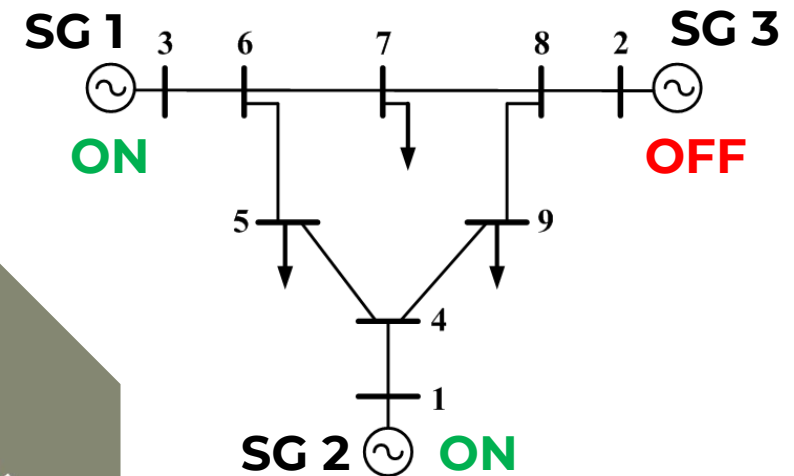
(although sync condensers could also be considered in our framework)

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

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

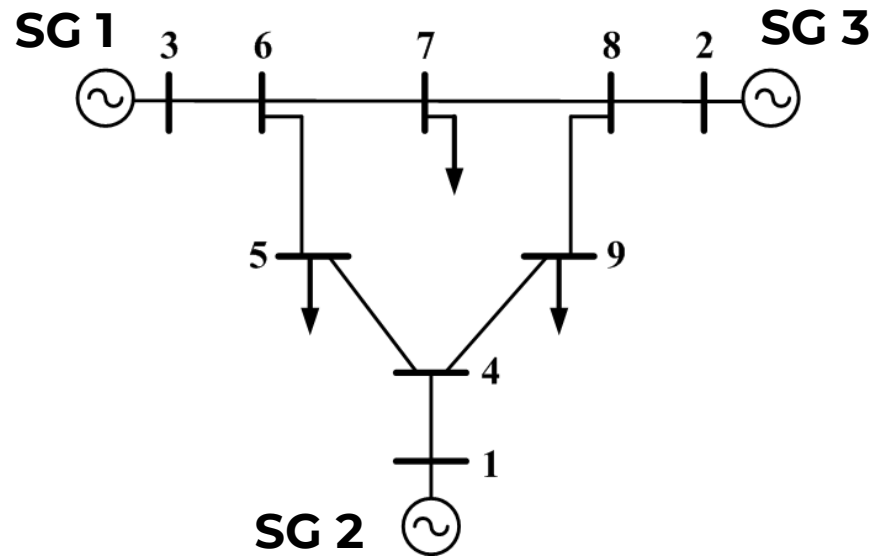
Would it be a **competitive market**, leading eventually to **lower costs for consumers?**

Guarantee **sufficient generation online** for SCC



Guaranteeing sufficient SCC: constraints in generation dispatch

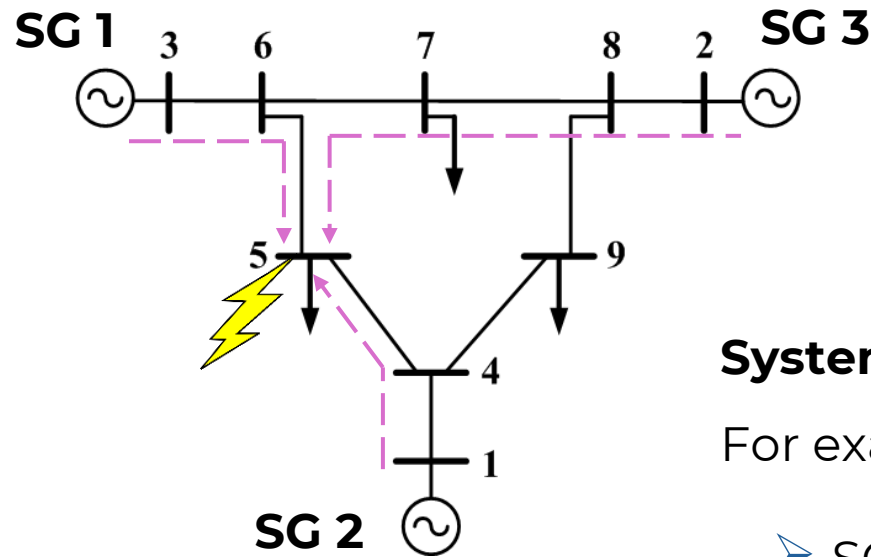
Guarantee at every bus that **SCC** is **above the threshold** ^[1]:



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

Guaranteeing sufficient SCC: constraints in generation dispatch

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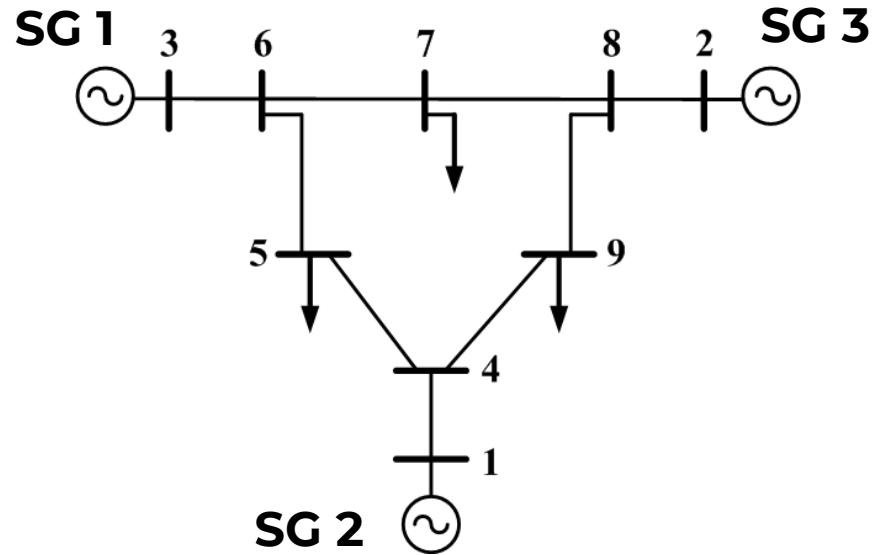
System impedance (Z) leads to different SCC levels for each bus

For example:

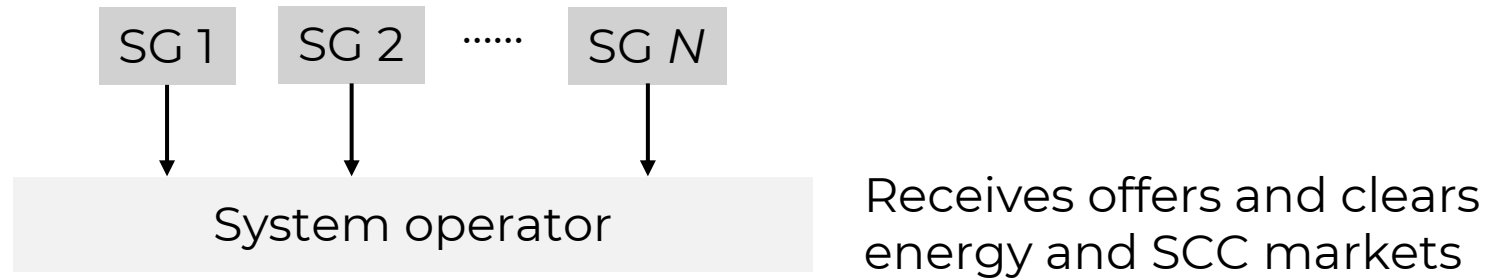
- SG 1 and SG 2 would contribute a larger share of SCC to bus 5, due to a closer **electrical distance**

SCC provision is **very locational**

Potential problem: market power in SCC services?



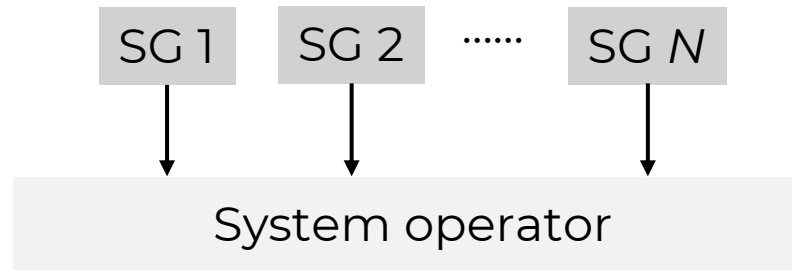
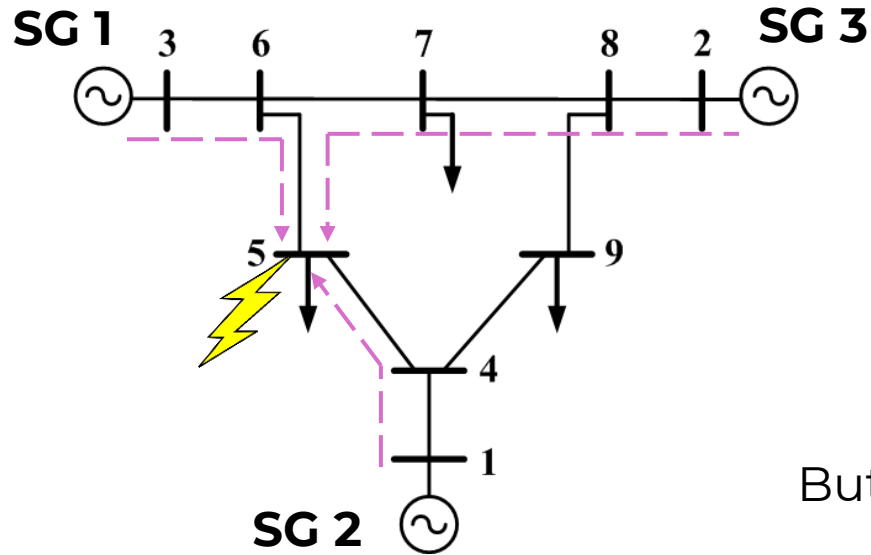
SCC may be procured as an **ancillary service** ^[2]



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

Potential problem: market power in SCC services?

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



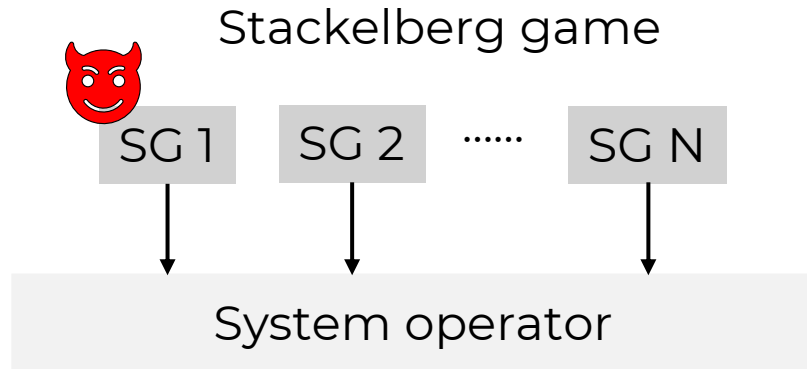
Receives offers and clears energy and SCC markets

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

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

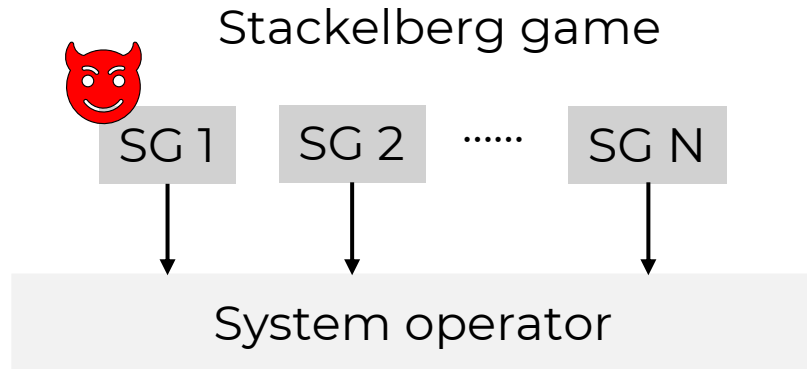


How to model imperfect competition in SCC services?

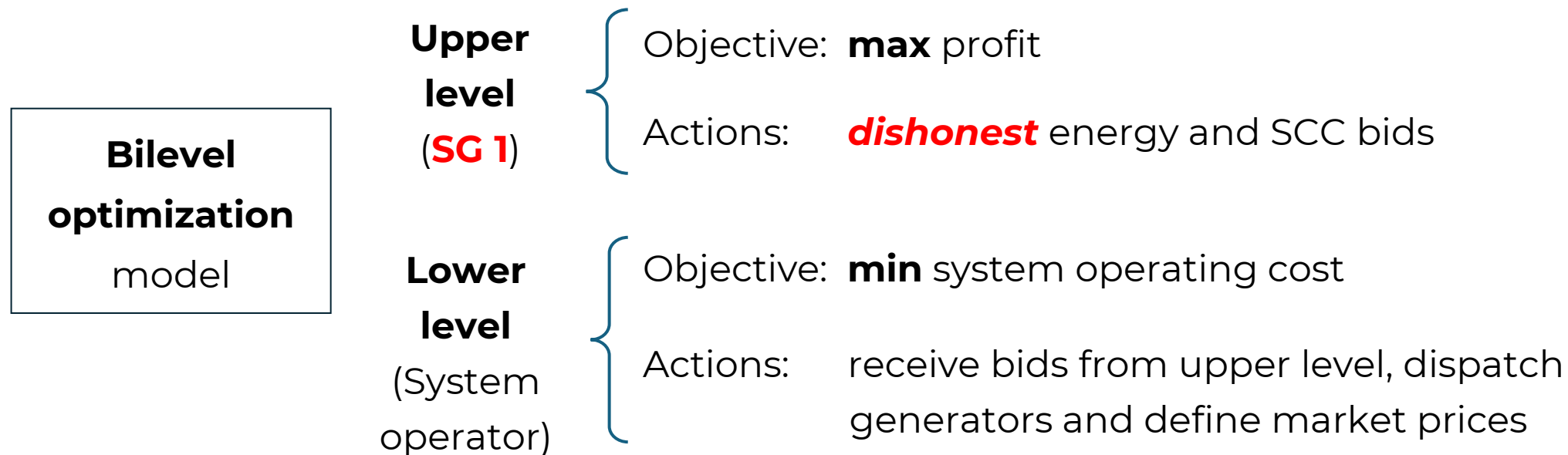


- Self-interested SG 1 → **strategically** bids for profits
- Other SGs → assumed to bid truthfully
- System operator → clears market

How to model imperfect competition in SCC services?

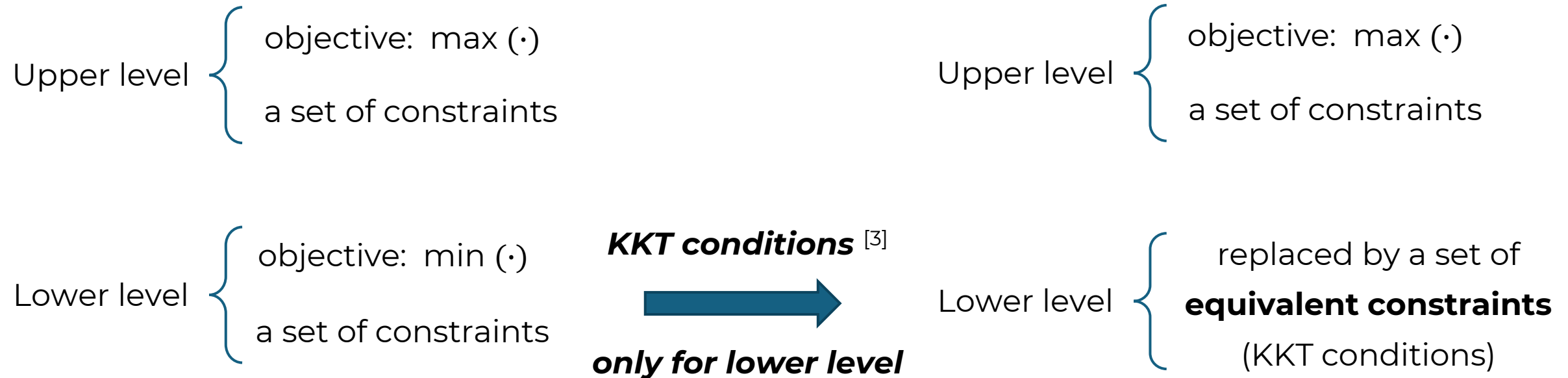


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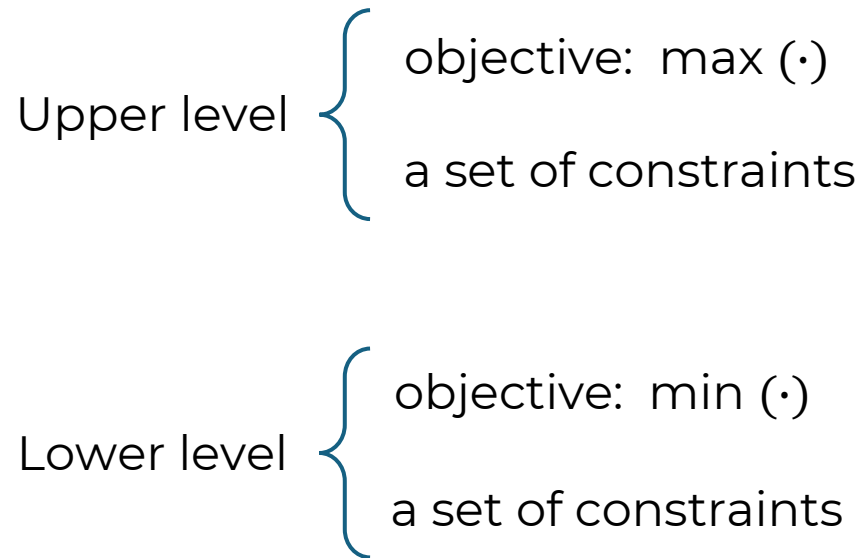
Solving a bilevel optimization problem

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



Solving a bilevel optimization problem

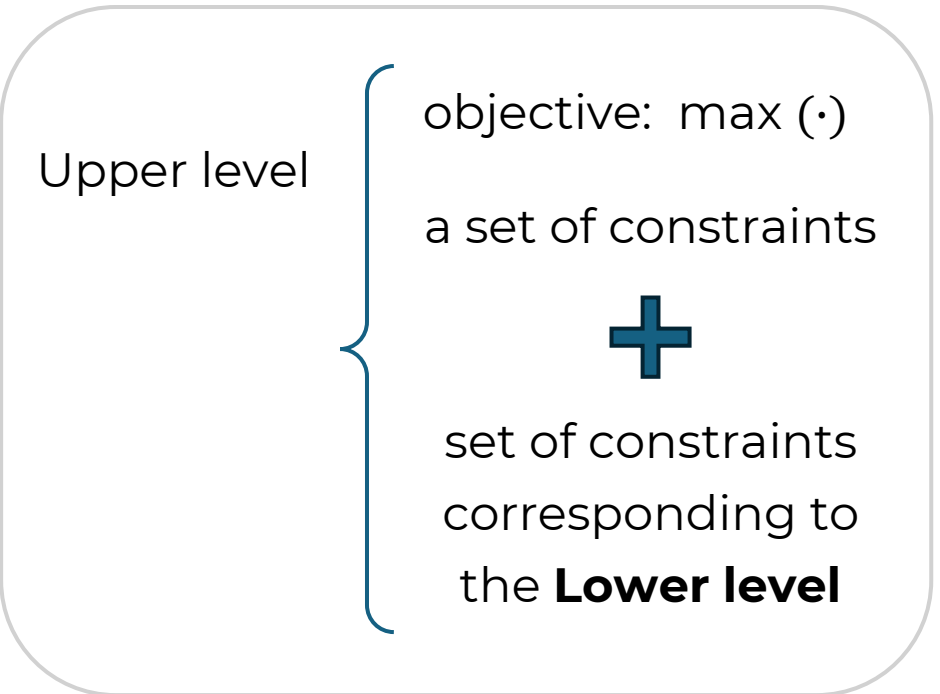
Traditional way to solve a **convex** bilevel problem:



KKT conditions ^[3]

only for lower level

Equivalent **single-level** optimization



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)

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

Challenge: bilevel optimization + binary variables

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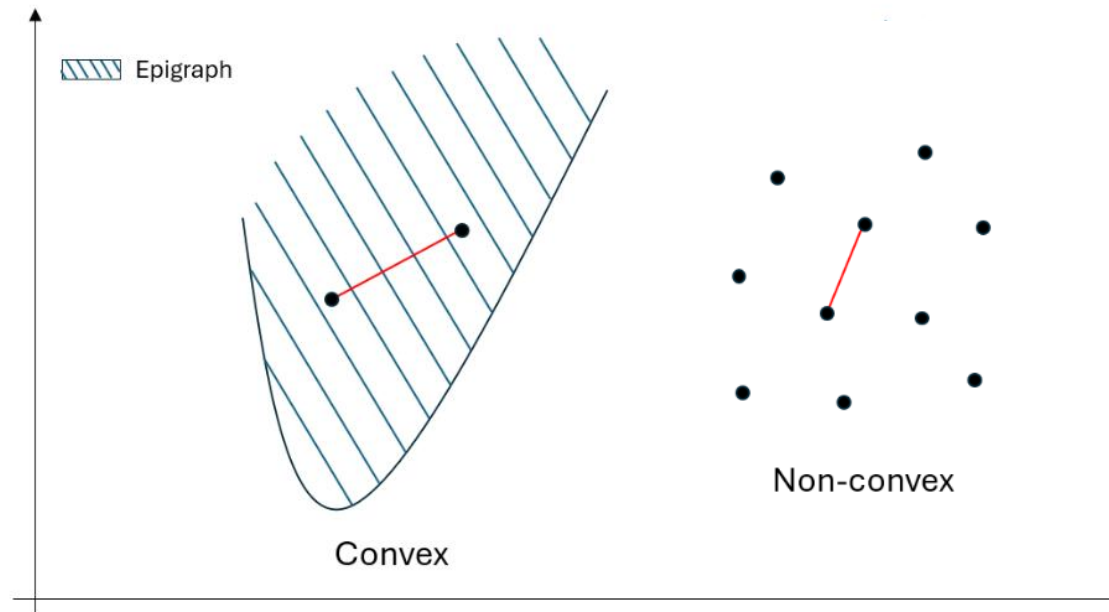
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If you want to read more:

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



Challenge: bilevel optimization + binary variables

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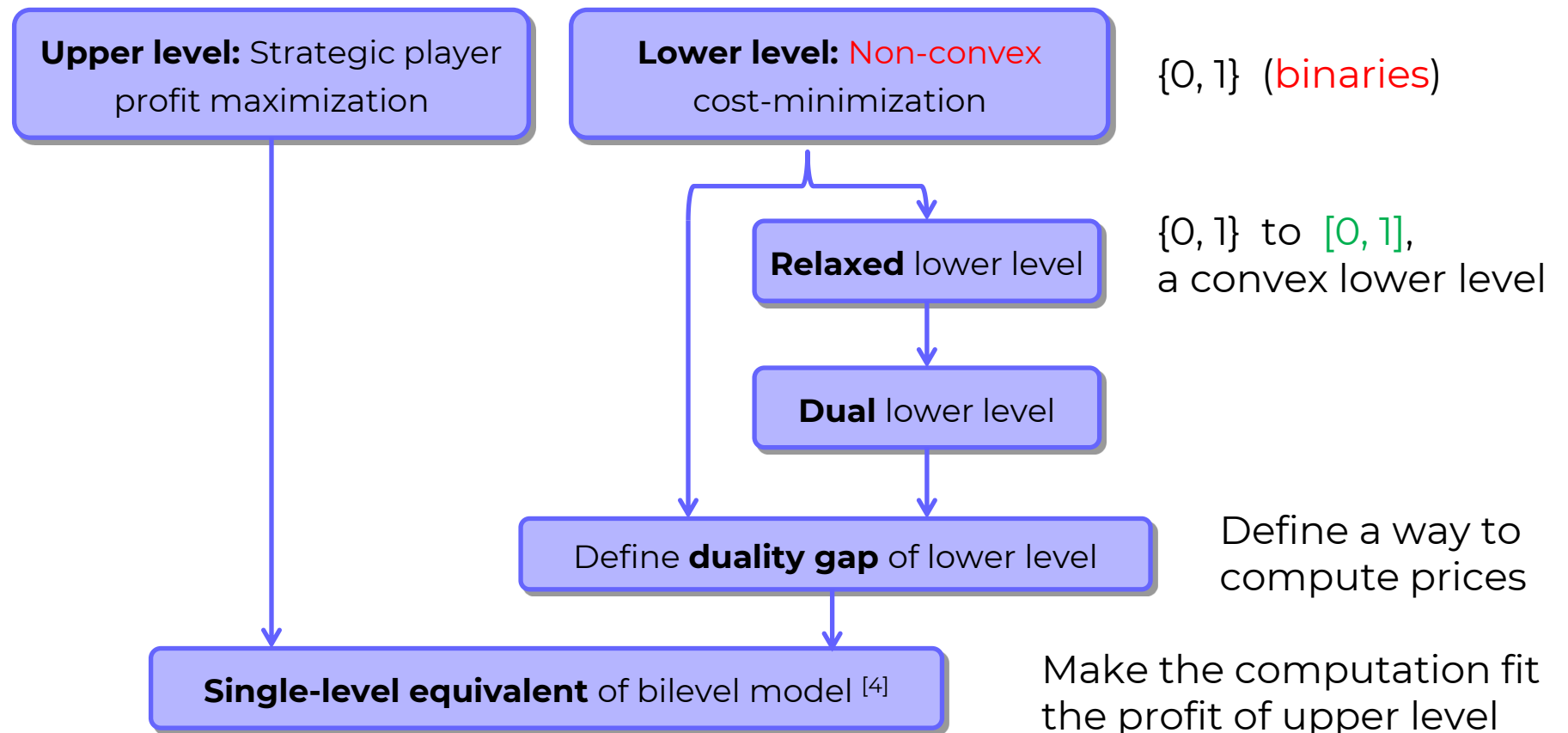
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The traditional solution method **requires** the **lower level** to be **convex**

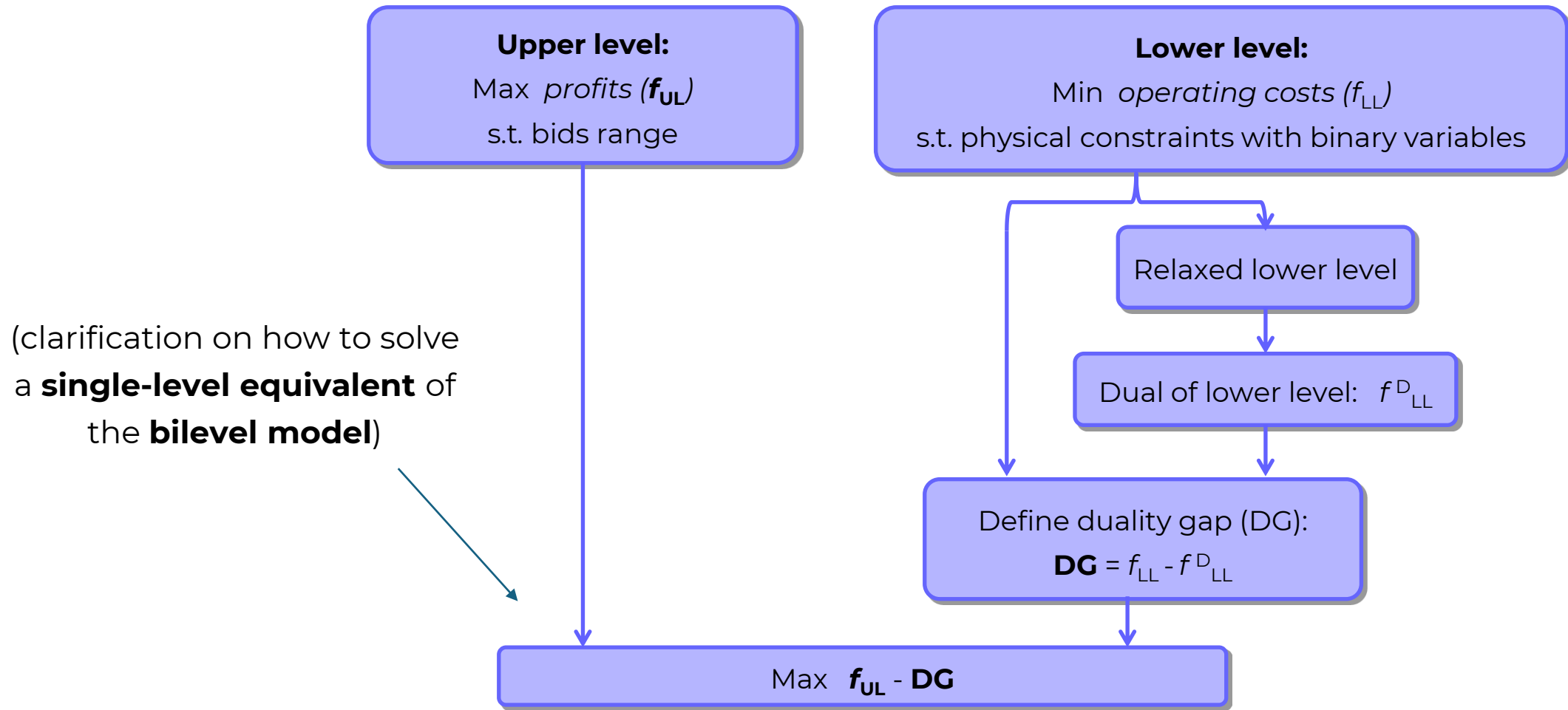
- Otherwise, the **KKT conditions** are not an equivalent representation (they are necessary but **not sufficient** conditions **for optimality**)

How to address non-convexity?

Solution:
primal-dual formulation
for lower level



How to address non-convexity?



Research results — roots of market power

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

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

- 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

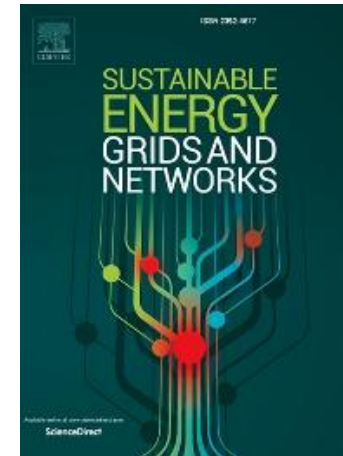
- Installing **synchronous compensators owned by the TSO** in the most critical buses could help make the remaining SCC market more competitive
- **Price cap:** directly limit SCC service prices

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,"
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