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Markets for Short-Circuit Current Services

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SCC challenge

Definition of SCC

Short-Circuit Current (SCC) is the electrical current that flows during a short-circuit fault (e.g., line-to-ground fault) in a power system.

Why It Matters

- **Protective Relay Operation**
  SCC is essential for relays to **"see" and detect faults**, triggering circuit breakers to isolate issues. **Low SCC** cause faults to go undetected, potentially cascading **blackouts**.

- **System Stability**
  Adequate SCC maintains voltage stability during faults and prevents Inverter-Based Resources (IBR) from losing synchronization with the grid.

SCC challenge

The Modern Challenge

- Wind and solar IBR are **replacing** traditional Synchronous Generators (SGs) in modern power systems.
- IBR contribute about **1/5** of the SCC of an equivalent SG.
- The overall system SCC level is consequently **declining**, causing the protection relays to fail.

Synchronous machines

Magnetic energy

5–8 p.u. SCC

Grid-following IBR

Electronic converters

1–3 p.u. SCC, even lower

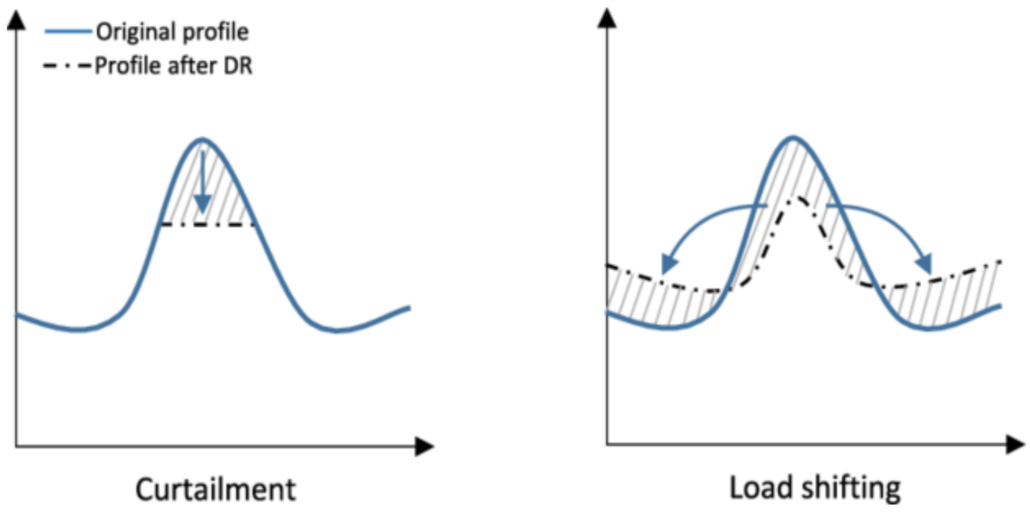
For a power system incorporating SGs and IBR, the SCC at bus *b* due to their current injections can be expressed as:

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

SCC is being decreasing

DR makes SCC worse

Demand Response (DR) is economically beneficial to grids

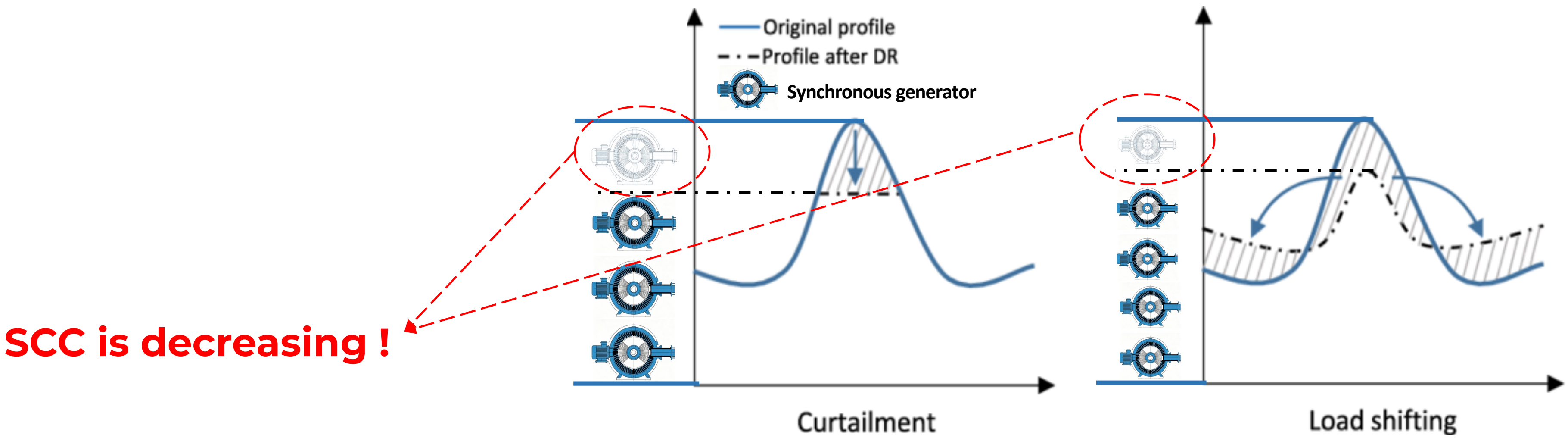


DR makes SCC worse

The **"Double-Edged Sword"** of DR

Demand Response (DR) is economically beneficial to grids, but may reduce system load, leading to fewer SGs being online.

This exacerbates the SCC deficiency.



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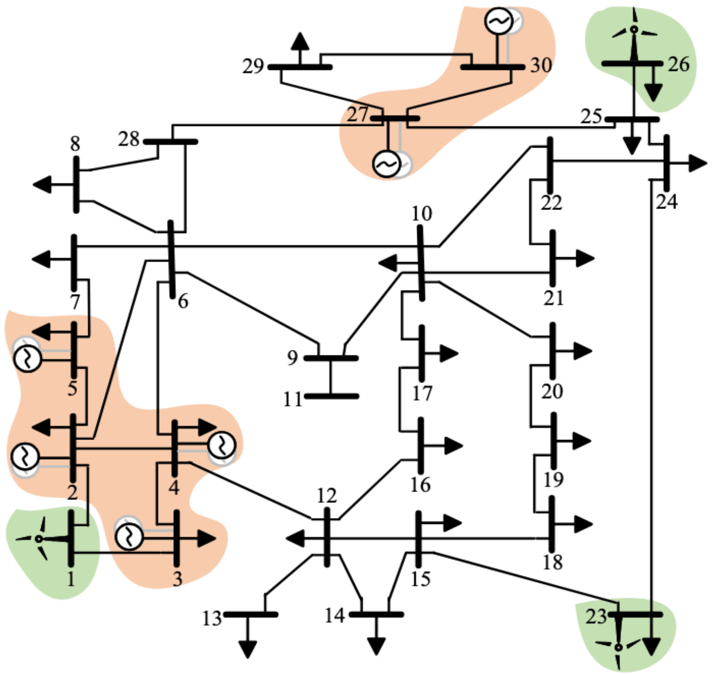


Fig. Modified IEEE 30-bus system

SCC constraints

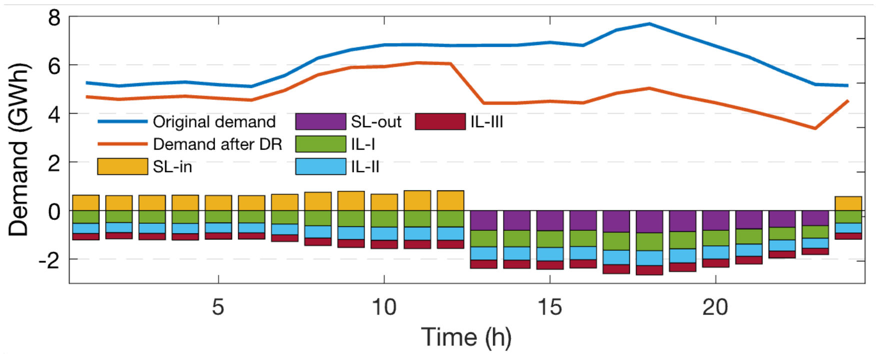
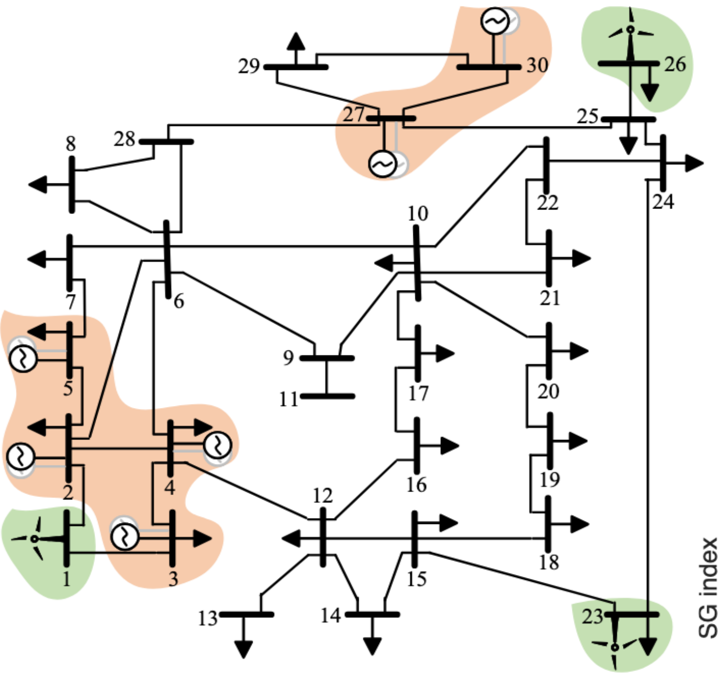


Fig. System demand in the case of no SCC constraints.

- Interruptible load is **curtailed** for compensation to lower electricity costs.
- Shiftable load **moves** from peak hours to off-peak to reduce bills.

DR makes SCC worse



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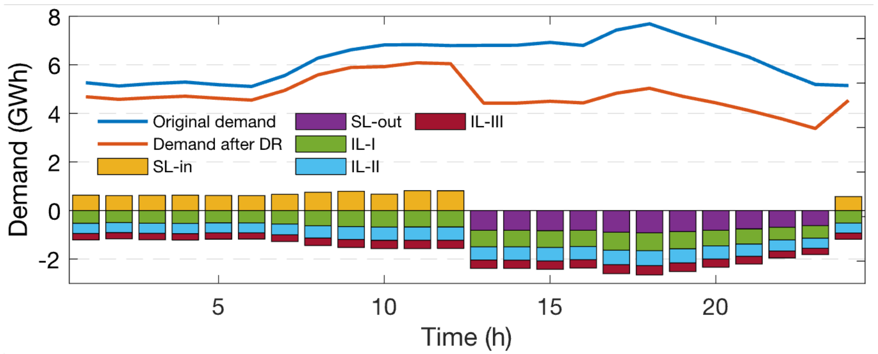

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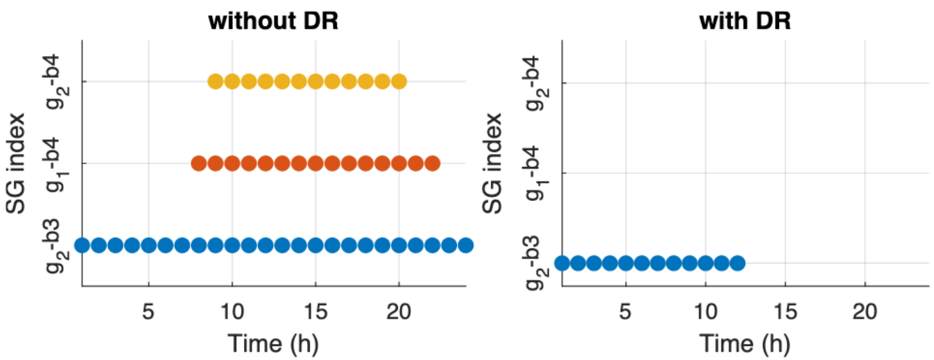
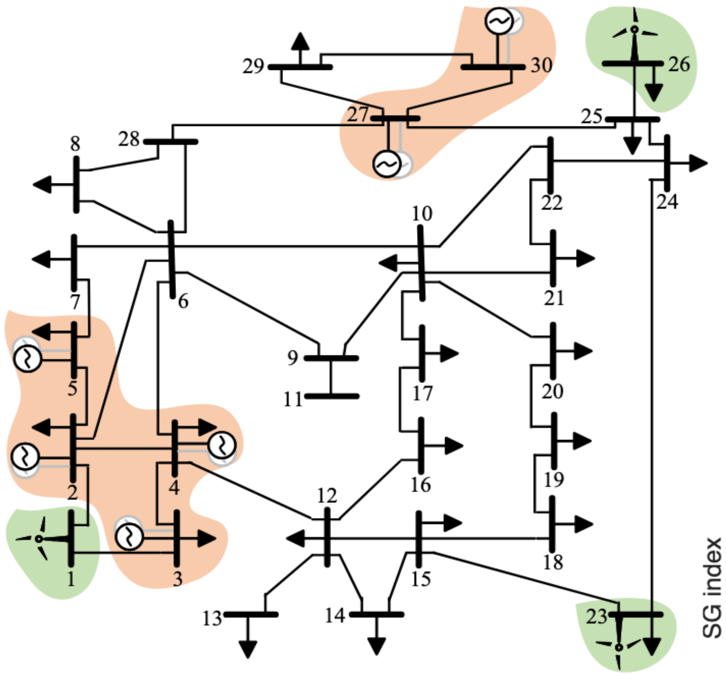


Fig. Generators whose commitment state is affected by DR.

The reduced load **lowers generator dispatch**: one (●) operates at reduced output, while two (●●) are shut down throughout the day.

DR makes SCC worse



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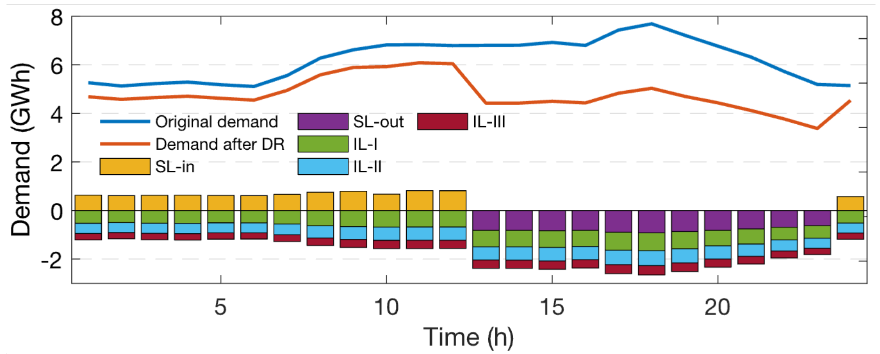

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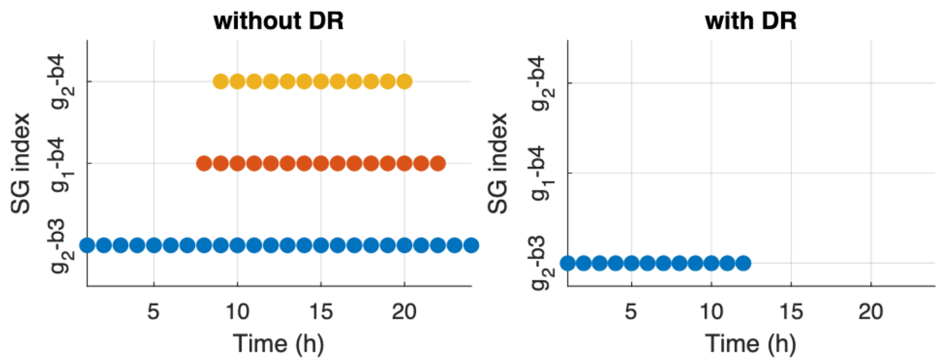

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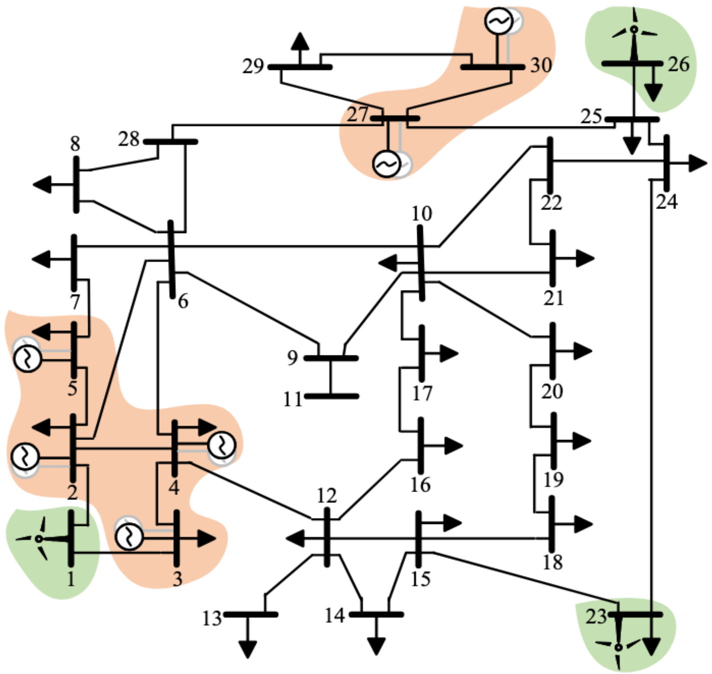
How about SCC of the system ? >>

DR makes SCC worse



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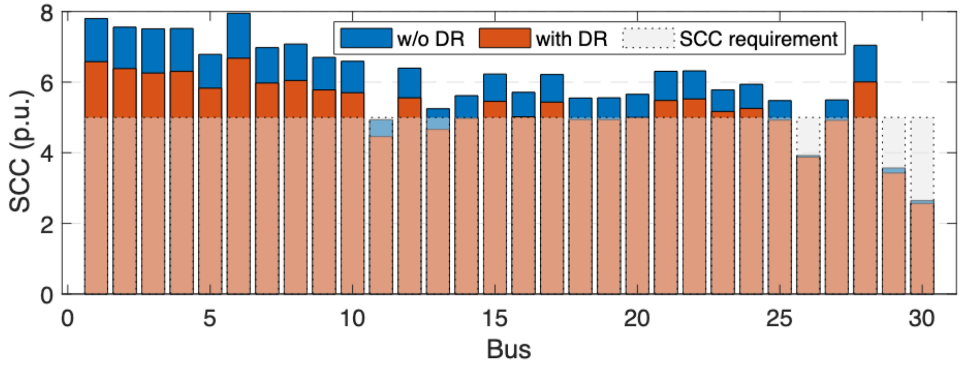


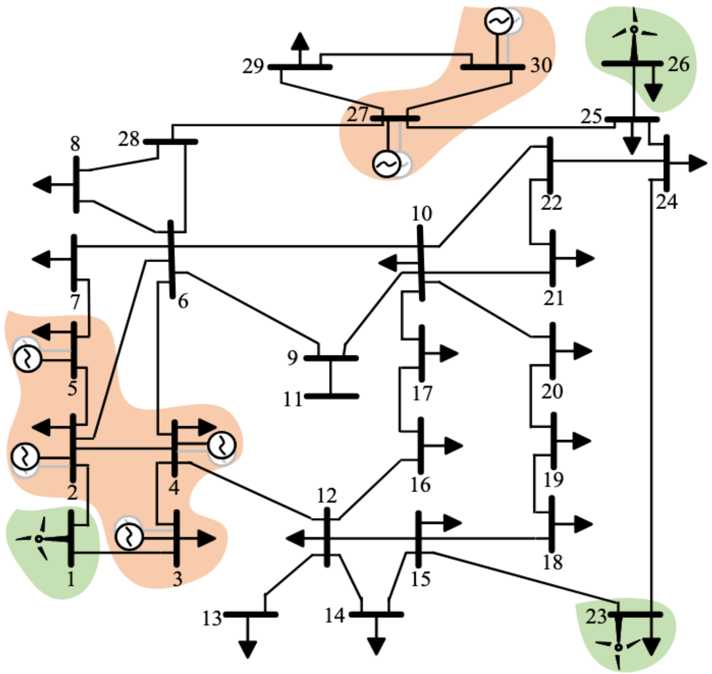
Fig. Unconstrained minimum SCC level at each bus.

Table. Buses with Inadequate SCC Level

DR implementation	Bus index
without DR	11, 26, 29, 30
with DR	11, **13**, **14**, **18**, **19**, **20**, **25**, 26, **27**, 29, 30

SCC security level for buses: 5 p.u.

DR makes SCC worse



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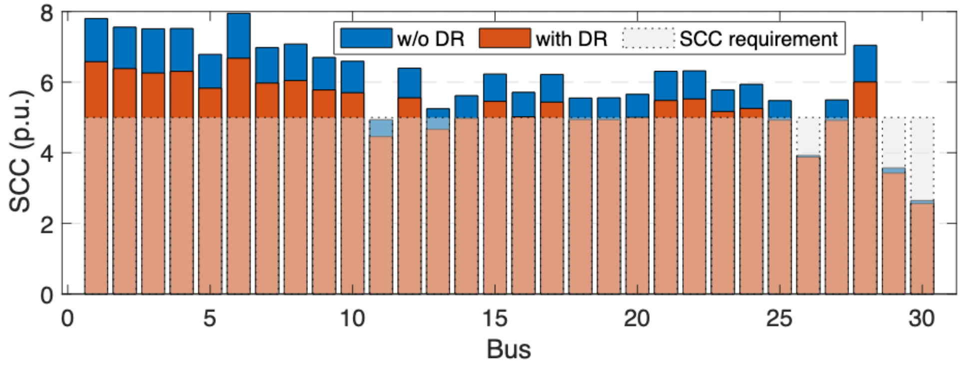

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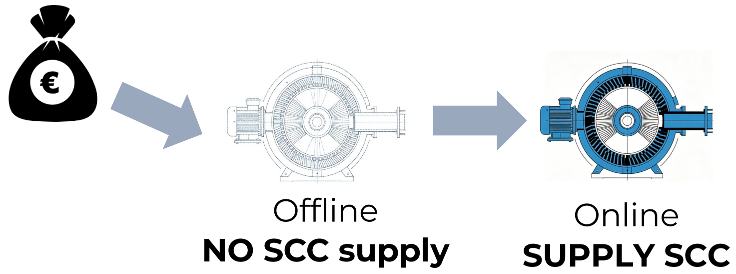
DR leads to insufficient SCC in more buses.

Explicit SCC constraints are required ! >>

How to price SCC services

Pricing SCC is relevant, as it places necessary **financial incentives** to generators for SCC supply when needed.



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Pricing SCC is basically computing dual variable of SCC constraint.

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

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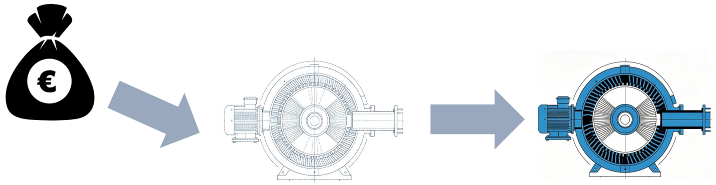

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Inherent **discrete** (binary) variables **prevent price formation**.

Because the **prices** derived from duality theory must need the problem to be **continuous and convex**.

Duality in optimization, KKT and shadow prices – With applications to electricity markets (https://doi.org/10.5281/zenodo.16504513)

How to address non-convexity ? >>

How to price SCC services

Primal-Dual Formulation:
A formulation that tries to **minimize the duality gap**, considering non-negative profit for each unit:

Primal of SCC-Constrained UC
(Non-convexity from binary variables)
1

1: Decide **quantity** of products, i.e., energy and SCC

How to price SCC services

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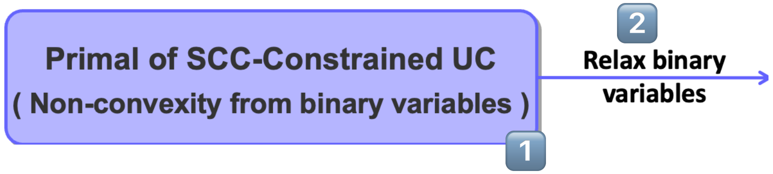

1: Decide **quantity** of products, i.e., energy and SCC
2: Make the whole problem convex and continuous

How to price SCC services

Primal-Dual Formulation:
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Primal of SCC-Constrained UC
(Non-convexity from binary variables) 1

2 Relax binary variables →

Dual of Relaxed SCC-Constrained UC 3

1: Decide **quantity** of products, i.e., energy and SCC

2: Make the whole problem convex and continuous

3: Decide **prices** of products, i.e., energy and SCC

How to price SCC services

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Non-Negative Profit Constraint 4

Energy revenue + SCC revenue – operating cost >= 0

1: Decide **quantity** of products, i.e., energy and SCC
2: Make the whole problem convex and continuous
3: Decide **prices** of products, i.e., energy and SCC
4: Make sure the prices are **revenue-adequate**

How to price SCC services

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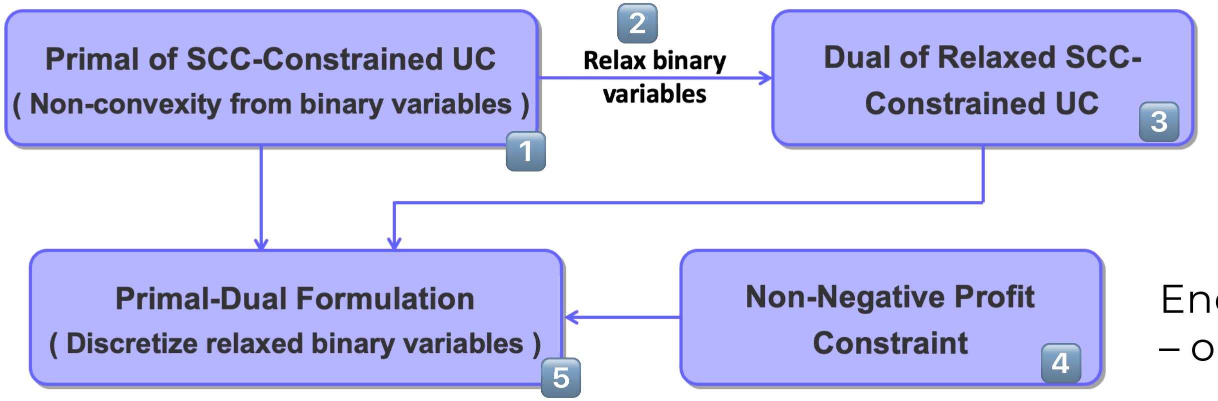

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- 5: Coordinate the primal and dual problems to **co-optimize quantity and price**

How to price SCC services

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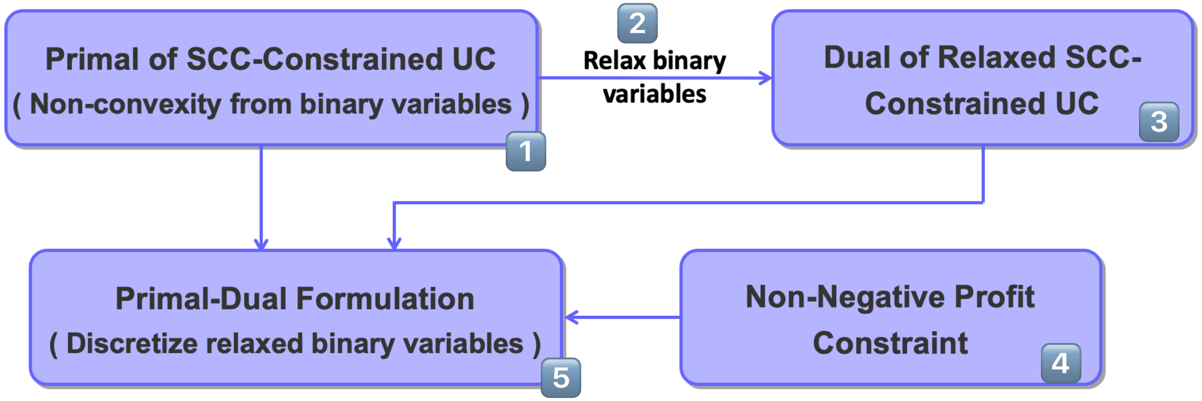

$$\min_{V} \ \mathrm{Obj}_{primal} - \mathrm{Obj}_{dual}$$

where:

$$V = \left\{ V_{primal}, V_{dual} \right\}$$

subject to:

Primal constraints

Dual constraints

Non-negative profit constraint

- 1: Decide **quantity** of products, i.e., energy and SCC
- 2: Make the whole problem convex and continuous
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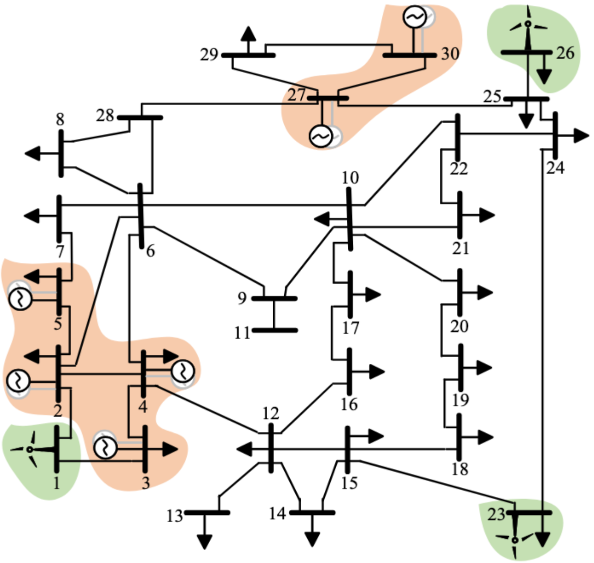

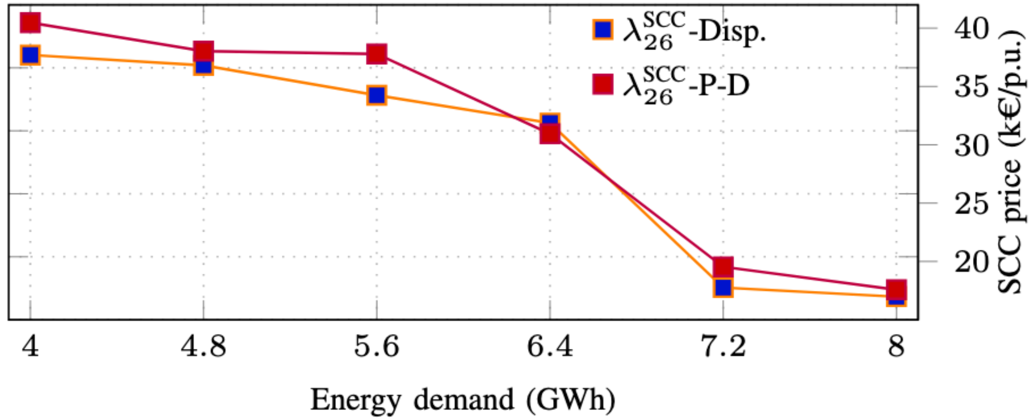

Dispatchable pricing is a method which simply relaxes binary variables to compute prices

The SCC price derived from P-D is higher than the dispatchable

How to price SCC services

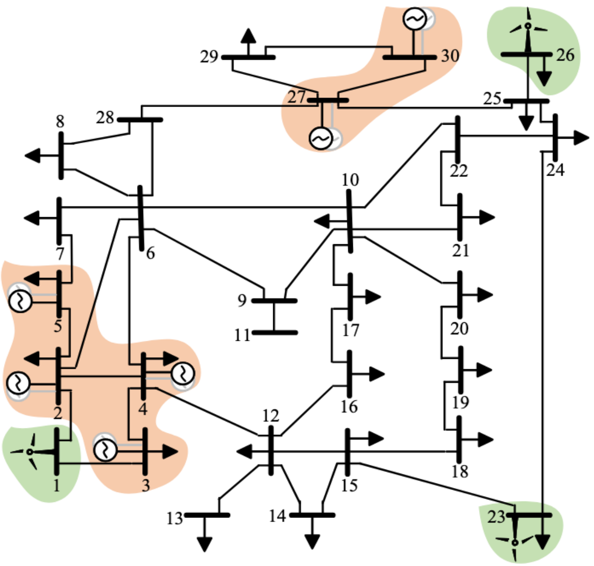

Table. Revenues and profits of SGs under *dispatchable pricing method* (k€)

Bus of SG	Energy profit	SCC revenue	Profit
Bus 2	-1.74	1.73	-0.01
Bus 4	-2.40	2.23	-0.17
Bus 30	-4.43	4.37	-0.06

Table. Revenues and profits of SGs under *primal-dual formulation*

Bus of SG	Energy profit	SCC revenue	Profit
Bus 2	-1.72	1.85	0.13
Bus 4	-2.39	2.39	0
Bus 30	-4.43	4.69	0.26

Primal-dual formulation decides prices that fully recover SGs' operating costs

Key Takeaways

1. Sufficient SCC is essential for protective relays to detect short-circuit faults, yet high IBR penetration reduces system-wide SCC.
2. DR may shut down excess synchronous units and further lower SCC.
3. Primal-dual formulation can appropriately price SCC as an ancillary service to incentivize SCC provision.

Ref

- *Chu, Zhongda, and Fei Teng. "Short circuit current constrained UC in high IBG-penetrated power systems." IEEE Transactions on Power Systems 36.4 (2021): 3776-3785.*
- *Wang, Peng, Zhengmao Li, and Luis Badesa. "Analyzing the Impact of Demand Response on Short-Circuit Current via a Unit Commitment Model." PESGM 2026, arXiv preprint arXiv:2510.05293 (2025).*
- *Wang, Peng, and Luis Badesa. "Pricing Short-Circuit Current via a Primal-Dual Formulation for Preserving Integrality Constraints." arXiv preprint arXiv:2510.05293 (2025).*

Acknowledgements

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- *MICIU/AEI/10.13039/501100011033 and ERDF/EU under grant PID2023-150401OA-C22,*
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