Pricing Short-Circuit Current as a Service: Method Comparison and Analysis

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Outline

- Two papers
- Short-circuit current constraints
- Three existing pricing methods
- A new pricing method
- Prices under different pricing methods

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Two papers

Two papers

Chu, Zhongda, Jingyi Wu, and Fei Teng. "Pricing of short circuit current in high IBR-penetrated system." *Electric Power Systems Research* 235 (2024): 110690.

- How to express Short-Circuit Current (SCC)
- Dispatchable pricing
- Restricted pricing
- Marginal unit pricing

Address limitations in handling non-convexities

Wang, Peng, and Luis Badesa. "Pricing Short-Circuit Current via a Primal-Dual Formulation for Preserving Integrality Constraints." *arXiv preprint arXiv:2510.05293* (2025).

- A primal-dual formulation for pricing SCC

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Short-circuit current constraints

Short-circuit current constraints

SCC:

- Maximum **Short-Circuit Current** capability at the fault bus (three phase fault assumed).
- Determined by the **equivalent impedance** and **SCC contribution capability** of resources.

In IBR-dominated grids:

Synchronous machines ⬇

Magnetic energy & rotor inertia

5–8 p.u. SCC

Grid-following IBR ⬆

Electronic converters

1–3 p.u. SCC, even lower

Ongoing trend:

- Increased equivalent impedance
- Limited SCC contributions from IBR
- Lack of rotational inertia
- ……

SCC is being decreasing

Potential risks:

- <u>Protection failure</u>: Fault currents are too low to reliably trigger protection.
- <u>Severe voltage depression</u>: Low SCC causes deep voltage dips and slow recovery.
- <u>Higher risk of cascading events</u>: Delayed or uncleared faults can propagate system disturbances.

Low SCC undermines **protection reliability**, **voltage stability**, and **overall system security** in IBR-dominated power systems.

Short-circuit current constraints

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

Inverse operation between impedance matrix and admittance matrix

Data-driven method to approach the real SCC level

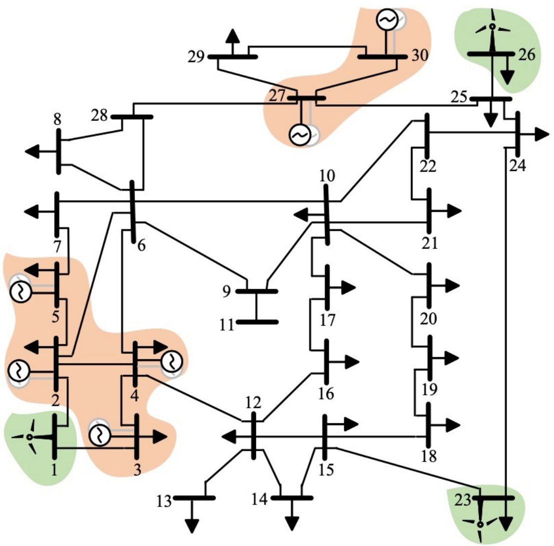
$$I_{b_{L}} = \sum_{g} k_{bg} u_g + \sum_{c} k_{bc} \alpha_c + \sum_{m} k_{bm} \eta_m$$

u_g: commitment variable

α_c: IBR's capacity factor

η_m: product of generators' operating states

For a cost minimization UC problem:



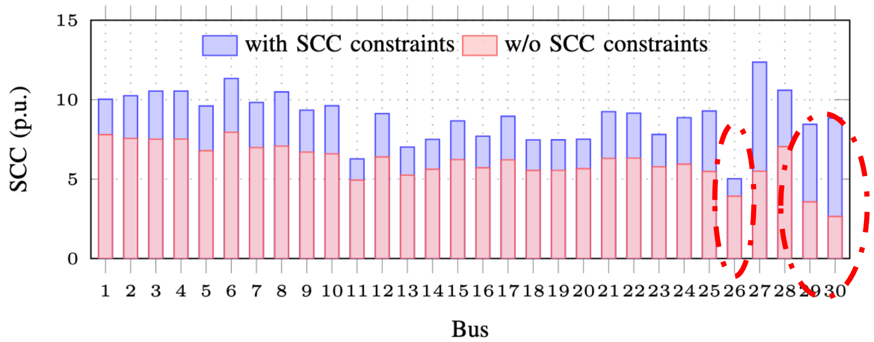


Fig. 8. Minimum SCC level at each bus with/without SCC constraints over the market horizon. The SCC threshold $\mathrm{I}_{b_{\mathrm{lim}}} = 5$ p.u..

Bus 26: only IBR

Bus 29: distant from the main grid and no local SCC support machine

Bus 30: too expensive to be dispatched

Buses with insufficient SCC are constrained to stay in a safe range

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Three existing pricing methods

Three existing pricing methods

Dispatchable pricing: This method is based on *relaxing the binary commitment decisions* of SGs for calculating the shadow prices.

$$u_g \in \{0,1\} \Rightarrow 0 \leq u_g \leq 1$$

The energy and SCC markets may be coupled through **unrealistic operating conditions** in the pricing process, as hard constraints of units cannot be strictly satisfied.

Restricted pricing: *First*, the original SCC-constrained UC problem is solved, yielding the optimal commitment '$u*_g$'. *Then*, the problem is *re-solved* with binary variables *relaxed* to continuous values, while equality constraints are added to *fix them at the previously computed optimal values*:

$$u_g = u_g^* : (\lambda_{g,\text{commit}})$$ ← commitment price

A side payment to remunerate generators for staying online

This renders **SCC constraints non-binding**, with all related dual prices embedded within the commitment price, as part of uplift payments. Such all-or-nothing bundled pricing **lacks clear economic interpretability**. Moreover, assets **without commitment variables (e.g., synchronous compensators)** can provide SCC services yet receive no corresponding remuneration under this scheme.

Marginal unit pricing: This method is **not based on duality theory**. Instead, it evaluates the SCC value by solving and comparing optimal solutions of the UC problem.

- https://raw.githubusercontent.com/badber/Miscellany/master/Duality_KKT_shadow_prices.pdf
- https://en.wikipedia.org/wiki/Duality_(optimization)

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A new pricing method

A new pricing method

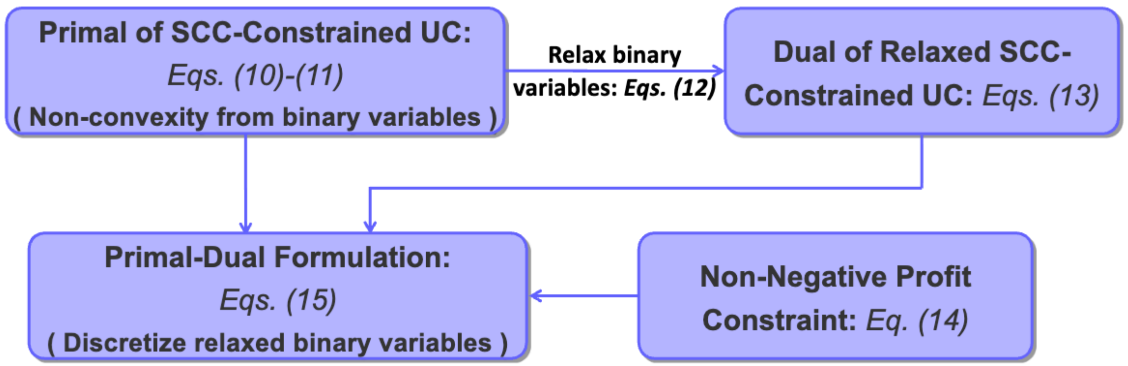
Primal-Dual formulation. It *preserves binary nature* and assigns prices that ensure *non-negative profits* for thermal units.

The method first **relaxes all binary variables** to continuous values.

Then **formulates the dual problem** along with constraints that explicitly guarantee **non-negative profits** for dispatched units.

Finally, it **enforces the relaxed variables back to discrete** values while solving a problem that **minimizes the duality gap**.

In this manner, service prices that deviate minimally from those under integrality relaxation can be derived and effectively provide generators with the proper incentives to remain in the market.



A new pricing method

Primal

$$\min_{V_{\mathrm{P}}} \sum_{g} \left(\mathrm{c}^{\mathrm{nl}}_g u_g + \mathrm{c}^{\mathrm{m}}_g P_g + C^{\mathrm{st}}_g\right) \tag{10a}$$

where:

$$V_{\mathrm{P}} = \left\{u_g, P_g, C^{\mathrm{st}}_g, P_c, \eta_m\right\} \tag{10b}$$

subject to:

$$\sum_g P_g + \sum_c P_c = \mathrm{P}^{\mathrm{D}} : (\lambda^{\mathrm{E}}) \tag{10c}$$
$$u_g \mathrm{P}^{\min}_g \le P_g \le u_g \mathrm{P}^{\max}_g : (\mu^{\min}_g, \mu^{\max}_g),\ \forall g \tag{10d}$$
$$C^{\mathrm{st}}_g \ge 0 : (\rho^{\mathrm{st}}_g),\ \forall g \tag{10e}$$
$$C^{\mathrm{st}}_g \ge (u_g - u_{g,0})\mathrm{c}^{\mathrm{st}}_g : (\sigma^{\mathrm{st}}_g),\ \forall g \tag{10f}$$
$$0 \le P_c \le \alpha_c \mathrm{P}^{\max}_c : (\zeta^{\min}_c, \zeta^{\max}_c),\ \forall c \tag{10g}$$
$$u_g \in \{0,1\},\ \forall g \tag{10h}$$

SCC constraint (2) : $(\lambda^{\mathrm{SCC}}_b),\ \forall b$ (10i)

McCormick envelopes for linearizing η_m, $\forall m$ (10j)

Relax binary variables

$$0 \le u_g \le 1 : (\psi^{\min}_g, \psi^{\max}_g),\ \forall g \tag{12a}$$
$$\eta_m \ge 0 : (\gamma^{\min}_{m,2}),\ \forall m \tag{12b}$$

Dual

$$\max_{V_{\mathrm{D}}}\ \mathrm{P}^{\mathrm{D}}\lambda^{\mathrm{E}} + \sum_b \Big(\mathrm{I}_{b_{\mathrm{lim}}} - \sum_c \mathrm{k}_{bc}\alpha_c\Big)\lambda^{\mathrm{SCC}}_b - \sum_c \alpha_c \mathrm{P}^{\max}_c \zeta^{\max}_c - \sum_g \psi^{\max}_g - \sum_m \gamma^{\min}_{m,1} - \sum_g u_{g,0}\mathrm{c}^{\mathrm{st}}_g \sigma^{\mathrm{st}}_g \tag{13a}$$

where:

$$V_{\mathrm{D}} = \Big\{\lambda^{\mathrm{E}}, \lambda^{\mathrm{SCC}}_b, \zeta^{\max}_c, \psi^{\max}_g, \gamma^{\max}_{m,1}, \gamma^{\max}_{m,2}, \gamma^{\min}_{m,1}, \mu^{\max}_g, \mu^{\min}_g, \sigma^{\mathrm{st}}_g\Big\} \tag{13b}$$

subject to:

$$\mathrm{c}^{\mathrm{nl}}_g - \sum_b \mathrm{k}_{bg}\lambda^{\mathrm{SCC}}_b - \mathrm{P}^{\max}_g \mu^{\max}_g + \mathrm{P}^{\min}_g \mu^{\min}_g + \mathrm{c}^{\mathrm{st}}_g \sigma^{\mathrm{st}}_g + h_g(\gamma^{\max}_{m,1}, \gamma^{\max}_{m,2}, \gamma^{\min}_{m,1}) + \psi^{\max}_g \ge 0,\ \forall g \tag{13c}$$
$$\mathrm{c}^{\mathrm{m}}_g - \lambda^{\mathrm{E}} + \mu^{\max}_g - \mu^{\min}_g \ge 0,\ \forall g \tag{13d}$$
$$1 - \sigma^{\mathrm{st}}_g \ge 0,\ \forall g \tag{13e}$$
$$-\lambda^{\mathrm{E}} + \zeta^{\max}_c \ge 0,\ \forall c \tag{13f}$$
$$\gamma^{\max}_{m,1} + \gamma^{\max}_{m,2} - \gamma^{\min}_{m,1} - \sum_b \mathrm{k}_{bm}\lambda^{\mathrm{SCC}}_b \ge 0,\ \forall m \tag{13g}$$
$$\{V_{\mathrm{D}} \mid V_{\mathrm{D}} \ne \lambda^{\mathrm{E}}\} \in \mathbb{R}_+,\ \forall b, g, c, m \tag{13h}$$

Primal-Dual formulation

$$\min_V\ (10a) - (13a) \tag{15a}$$

where:

$$V = \left\{V_{\mathrm{P}}, V_{\mathrm{D}}\right\} \tag{15b}$$

subject to:

Primal constraints: (10c)-(11) (15c)

Dual constraints: (13c)-(13h) (15d)

Non-negative profit constraint: (14) (15e)

Non-negative profit constraint

$$\underbrace{\lambda^{\mathrm{E}} P_g}_{\text{Energy revenue}} + \underbrace{\sum_b \lambda^{\mathrm{SCC}}_b \mathrm{k}_{bg} u_g + \sum_b \sum_{\{m \mid g \in m\}} \lambda^{\mathrm{SCC}}_b \mathrm{k}_{bm}\eta_m}_{\text{SCC revenue}} - \underbrace{(\mathrm{c}^{\mathrm{nl}}_g u_g + \mathrm{c}^{\mathrm{m}}_g P_g + C^{\mathrm{st}}_g)}_{\text{Operating cost}} \ge 0, \quad \forall g \tag{14}$$

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Prices under different pricing methods

Prices under different pricing methods

A single-period case to explain why restricted method is not suitable for pricing SCC.

TABLE IV
ENERGY PROFIT OF SGS UNDER DIFFERENT CONDITIONS (K€)

	Energy demand (GWh)	4.0	4.8	5.6	6.4	7.2	8.0
Restricted pricing	g_1-$b2$	-0.60	-0.56	1.58	1.58	5.22	9.87
	g_2-$b2$	-1.74	-1.70	0.43	0.43	4.08	8.73
	g_1-$b3$	-1.52	-1.50	0.37	0.37	3.56	7.62
	g_2-$b3$	0.00	0.00	-1.50	-1.50	1.69	5.76
	g_1-$b4$	-2.40	-2.39	0.00	-1.90	-0.60	2.07
	g_2-$b4$	0.00	0.00	0.00	-2.21	-1.38	1.29
	g_1-$b27$	-7.33	-7.33	0.00	0.00	0.00	0.00
	g_2-$b27$	0.00	0.00	-7.25	-7.25	-6.89	-6.22
	g_1-$b30$	-4.43	-4.43	-4.34	0.00	0.00	0.00
	g_2-$b30$	-4.41	-4.41	-4.32	-4.32	-4.16	-3.96

Solo energy revenue is insufficient to cover operating costs.

Although all thermal units can recover their costs via energy price and commitment price, the **needed SCC price is still absent**.

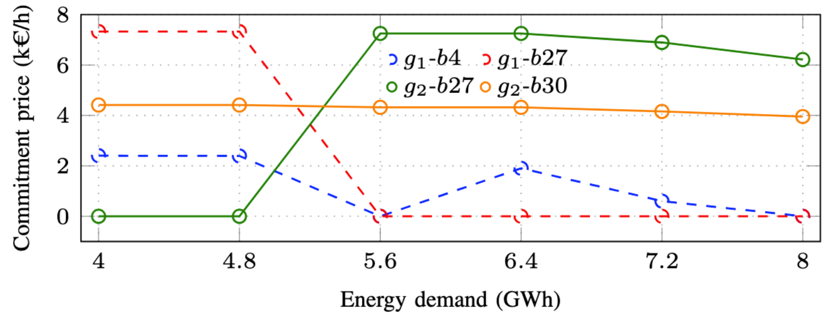

Fig. 6. Commitment price ($\lambda_{g,\text{commit}}$) for SGs under different demand levels. For visual clarity, the commitment price for other SGs is not shown, as they exhibit similar trends to g_1-$b4$ and g_1-$b27$. While the price for $2g$-$b5$ is zero, since they are not dispatched.

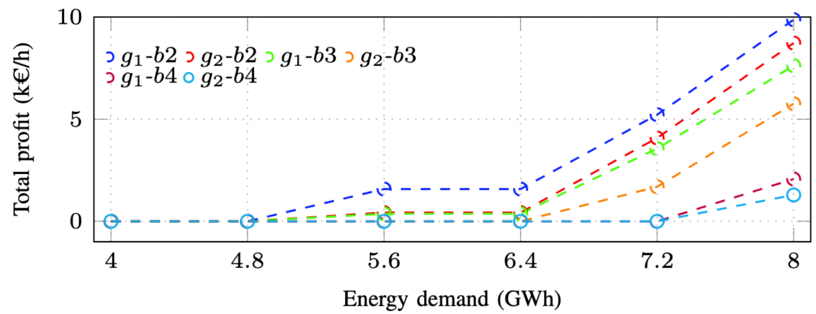

Fig. 7. Total profit (energy profit plus commitment price) for SGs under different demand levels, using restricted pricing. The profit for $2g$-$b5$ is zero since they are not dispatched. Meanwhile, the profit of the remaining SGs is also zero, because the commitment price exactly offsets their profit shortfall.

Prices under different pricing methods

A multi-period case to explain why binary nature should be respected and what the advantage of primal-dual formulation is.

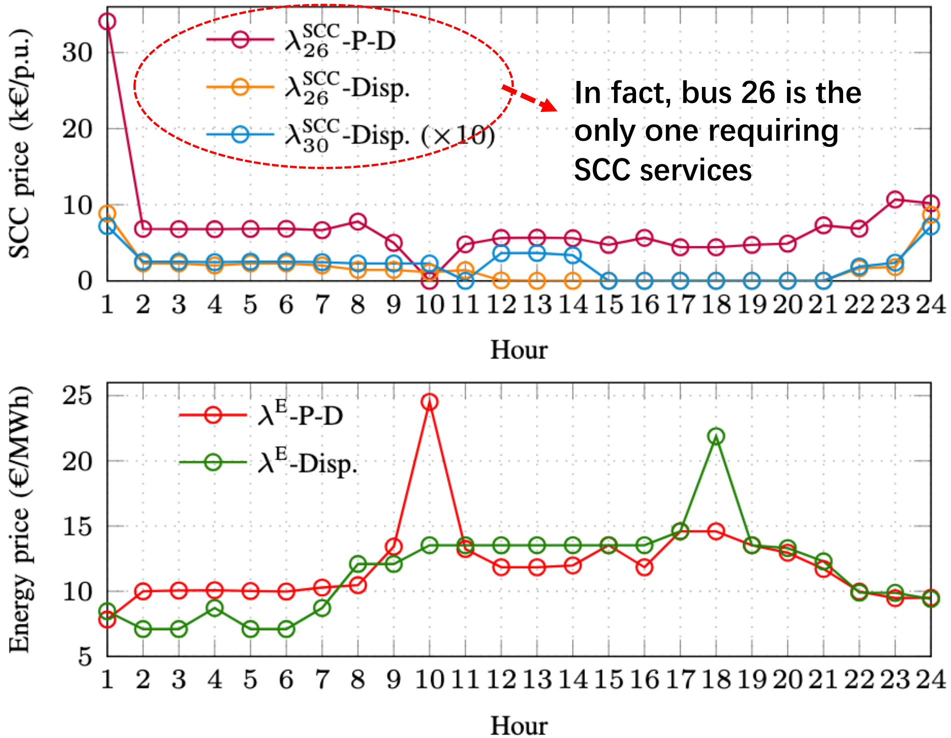

Fig. 9. Price profiles of SCC (upper) and energy (lower) over the complete market horizon. The SCC prices for other buses are zero in each case.

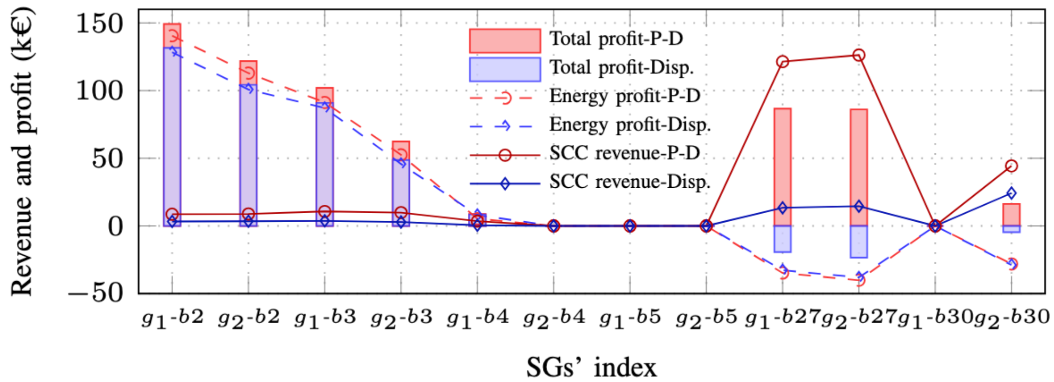

Fig. 10. Profitability of each SG under P-D and dispatchable pricing methods. Total profit is equal to the sum of energy profit and SCC revenue, in which the energy profit is energy revenue minus operating cost.

- The SCC and energy market can be tightly coupled
- Precise price signals
- Adequate SCC pricing

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