Cooperative approach for multi-area power system security taking advantage of grid flexibility

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Research

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'Cooperative game' inspired approach for multi-area power system security management taking advantage of grid flexibilities

Efthymios Karangelos[1] and Patrick Panciatici[2]

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This paper advocates for a progressive rethinking of the day-ahead/intra-day power system security management practice in the low-carbon energy transition era. As a starting point, the need for coordination between multi-area transmission system operators in order to efficiently exploit the value of grid flexibility towards operating the low-carbon, multi-area power system securely and economically is emphasized. On this basis, the core proposal of this paper is the adoption of a new approach to day-ahead/intra-day multi-area power system security management, inspired by the principles of cooperative game theory. The proposed approach relies on counterfactual analysis to evaluate the (positive and/or negative) impact of each distinctive control area to the common security of the multi-area system, thus providing clear economic incentives to achieve the required coordination. This proposal is not a marginal approach and notably facilitates the integration of more detailed physical modelling (including the non-convexities of the power system) in the inter-TSO settlement of the multi-area interconnected system security management cost. The proposed framework allows some level of subsidiarity and the definition of hedging products to cover ex-post costs. Further from the blueprint of the proposed approach, the paper presents a demonstrative implementation in the context of static

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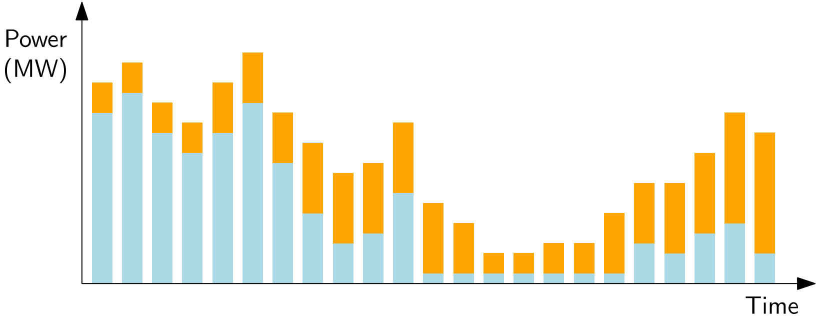
Presentation Overview

1. Background & motivation.
2. Problem set-up.
3. Proposed approach.
4. Demonstrative implementation.
5. Closing discussion.

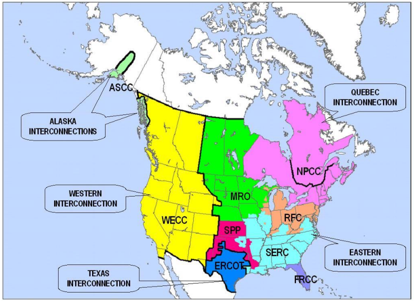
1. Background & motivation

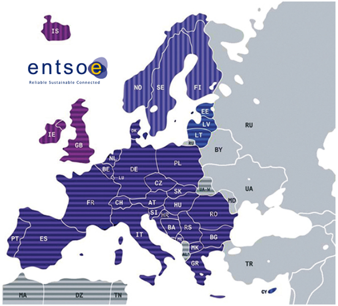
Research theme



- Renewable power generation is **intermittent** and **uncertain**!
- How to make the most of what the HV transmission grid has to offer?

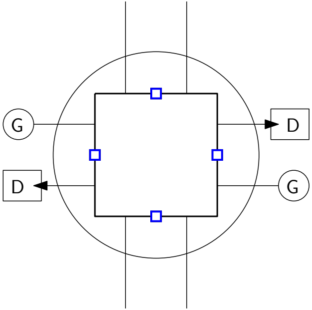
Using the grid to survive intermittency?

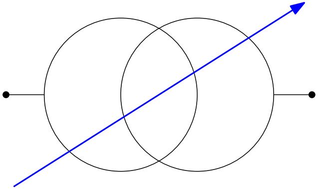




- Wider transmission system interconnections allow sharing of reserve/balancing resources between the multi-area grid System Operators (SOs).

Using the grid to survive uncertainty?

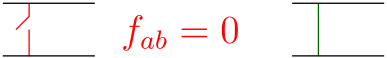




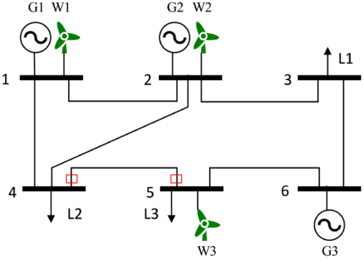
- Grid flexibility allows managing power flow through active grid components, *e.g.*,
  - topology optimization: line-switching, bus-splitting merging;
  - phase-shifting transformers.

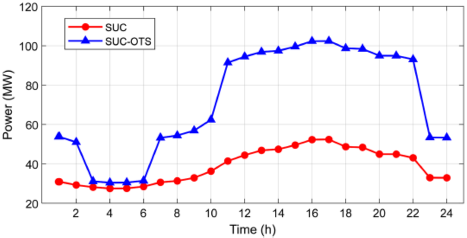
Grid flexibility – *e.g.* topology optimization [1]

- Controlling power flow through the bus incidence.



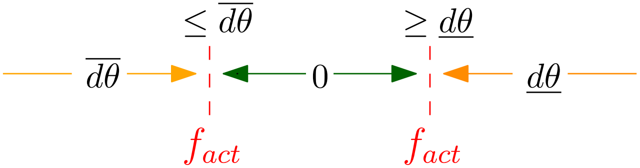
$$f_{ab} = 0 \qquad \theta_a = \theta_b$$

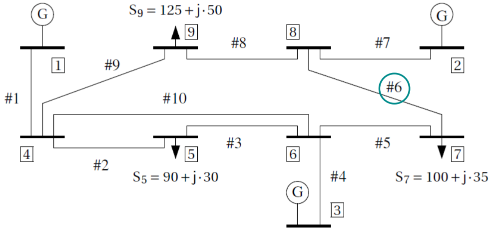


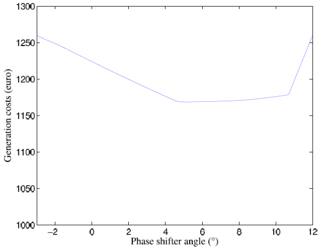


Grid flexibility – *e.g.* phase-shifting transformers [2]

- Controlling power flow through the voltage angle difference.







How do we presently use the grid?

Multi-area interconnections

- All control areas are physically linked into a single XL-system.
- Markets reach beyond the (electrical/national) borders of a single control area.

Grid flexibility

- SOs prefer "non-costly" grid flexibility for security management.
- not explicitly modeled in (nodal/zonal) markets...

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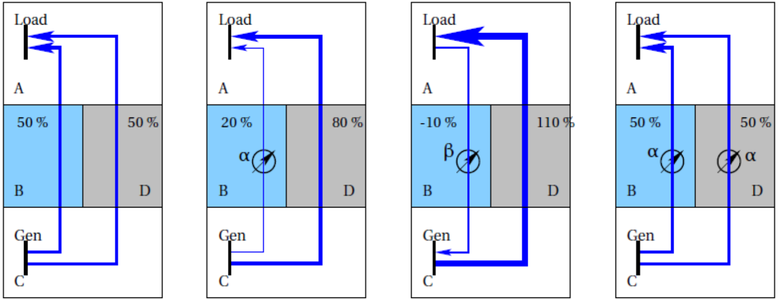
Grid flexibility

- SOs prefer "non-costly" grid flexibility for security management.
- not explicitly modeled in (nodal/zonal) markets...
  - complexity is beyond the linear/convex assumptions of electricity markets;
  - *e.g.*, several binary variables to represent breaker positions at each bus of the "bus-branch" model;
  - redefining risks, locational prices, financial transmission rights, *etc.*.

Multi-area interconnections & grid flexibility

- It's all about SO coordination, *e.g.* [2]



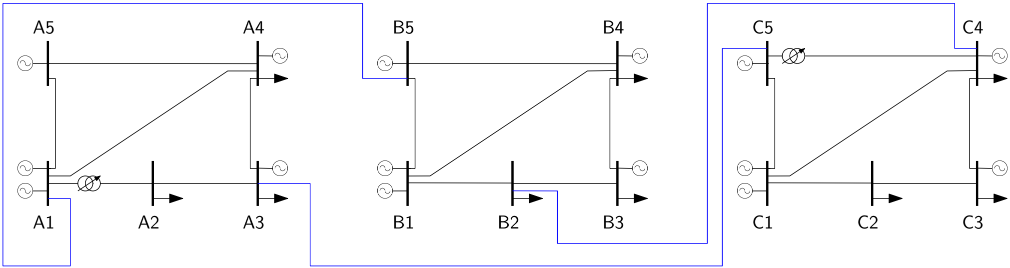
(A) (B) (C) (D)

(C) In the short-term, the blue area SO causes an overload in the gray area.

(D) In the long-term, both SOs have invested to go back to (A).

2. Problem set-up

Overview



We place ourselves in a post-market timeframe . . .

✓ Market actors have traded through forward, day-ahead and intra-day markets.

✓ Market actors have also offered redispatching/balancing resources to SOs.

- SOs have to secure the physical execution of the market transactions.

Notation

Fixed parameters

$\bar{\mathbf{y}}$: physical characteristics of the grid (*e.g.*, impedances, thermal ratings, *etc.*);

$\bar{\mathbf{m}}$: the market positions of the grid users (generators & loads);

Available resources (variables)

$\mathbf{r} \in \mathcal{R}(\bar{\mathbf{m}})$: redispatching generation & load – offered by the market actors;

$\mathbf{g} \in \times_{a=1}^{A} \mathcal{G}^a$: intra-area grid flexibility, *i.e.* breaker positions, PST settings *etc.*

Grid-state (variable)

$\mathbf{x} = f\left(\bar{\mathbf{m}}, \bar{\mathbf{y}}, \mathbf{r}, \mathbf{g}\right)$: nodal voltages, power flows, served load demand, *etc.*;

– over the whole multi-area grid.

Multi-area security management

Primary mission

- SOs have to secure the physical execution of the market transactions.

Cooperative approach

- Jointly minimizing the costs of resources over the whole system.

Multi-area security management

Primary mission

- SOs have to secure the physical execution of the market transactions.

$\mathcal{X}^a$: the security domain of any single system area.

$$\Rightarrow \mathbf{x} = f\left(\bar{\mathbf{m}}, \bar{\mathbf{y}}, \mathbf{r}, \mathbf{g}\right) \in \bigcap_{a=1}^{A} \mathcal{X}^a.$$

Cooperative approach

- Jointly minimizing the costs of resources over the whole system.

$\mathbf{C}^{\mathcal{A}}\left(\mathbf{x}, \mathbf{r}, \bar{\mathbf{m}}\right)$: a mutually acceptable cost function:

  - short-run (direct) cost of the resources SOs get from the market participants;
  - grid flexibility has negligible short-run costs (*e.g.*, wear & tear).

Cooperative multi-area system security mgmt

$$(\mathbf{x}^\star, \mathbf{r}^\star, \mathbf{g}^\star) \in \arg\min_{\mathbf{r},\mathbf{g},\mathbf{x}} \mathbf{C}^{\mathcal{A}}(\mathbf{x}, \mathbf{r}, \bar{\mathbf{m}})$$

$$\textit{subject to}:$$

$$\mathbf{x} = f(\bar{\mathbf{m}}, \bar{\mathbf{y}}, \mathbf{r}, \mathbf{g}) \in \bigcap_{a=1}^{A} \mathcal{X}^a, \tag{1}$$

$$\mathbf{g} \in \times_{a=1}^{A} \mathcal{G}^a,$$

$$\mathbf{r} \in \mathcal{R}(\bar{\mathbf{m}}).$$

- Considerable research efforts in solving these decision making problems in centralized/distributed manner (*e.g.*, large-scale SCOPF [3]);

Cooperative multi-area system security mgmt

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- Considerable research efforts in solving these decision making problems in centralized/distributed manner (*e.g.*, large-scale SCOPF [3]);

- How to **share** the multi-area security mgmt cost $\mathbf{C}^{\mathcal{A}}(\mathbf{x}^\star, \mathbf{r}^\star, \bar{\mathbf{m}})$?

  $\rightarrow$ promoting inter-SO coordination to exploit grid flexibility.

3. Proposed approach

How to share the multi-area security mgmt cost $\mathbf{C}^{\mathcal{A}}(\mathbf{x}^{\star}, \mathbf{r}^{\star}, \bar{\mathbf{m}})$?

- ~~Shadow prices of linear programming problems reflect the (locational) value of securely delivering electricity.~~
- Security management is a **non-linear, non-convex** optimization problem;

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- Security management is a **non-linear, non-convex** optimization problem;
- Its cost depends on the **synthesis** of all intra-area grid properties:
  - physical parameters $\bar{\mathbf{y}}$;
  - security criteria $\bigcap_{a=1}^{A} \mathcal{X}^a$;
  - use of grid flexibility $\mathbf{g} \in \times_{a=1}^{A} \mathcal{G}^a$.

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  - use of grid flexibility $\mathbf{g} \in \times_{a=1}^{A} \mathcal{G}^a$.
- **Reflect/reward intra-area grid properties at the inter-SO settlement level!**

How to do that? – counterfactual analysis

What-if . . .

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1. we were not restricted by the intra-area physical parameters and security criteria of any single area?

   $\rightarrow$ measuring the economic loss due to the fixed intra-area features.

How to do that? – counterfactual analysis

What-if . . .

1. we were not restricted by the intra-area physical parameters and security criteria of any single area?

   → measuring the economic loss due to the fixed intra-area features.

2. we were not sharing the intra-area grid flexibility of any single area?

   → measuring the economic benefit from intra-area grid flexibility sharing.

Economic loss indicator

What if we **were not restricted** by the intra-area physical parameters and security criteria of any single area?

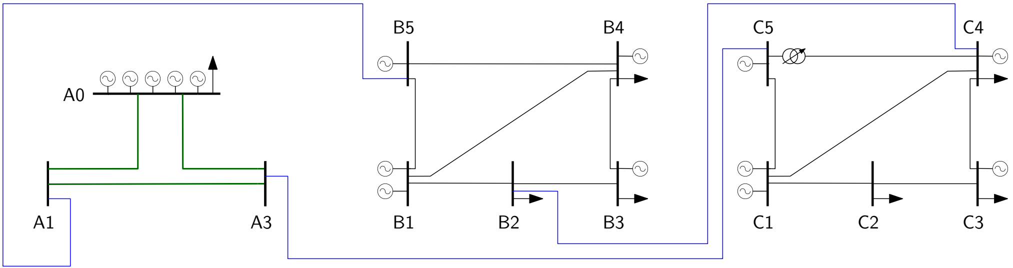
---

1. Formulate per-area a **relaxation** of the multi-area security mgmt problem;
   - denote its optimal cost $\mathbf{C}^{\mathcal{A}}\left(\mathbf{x}^{\star}_{/a}, \mathbf{r}^{\star}_{/a}, \bar{\mathbf{m}}\right)$.
2. Measure the loss with respect to the full problem (1) solution:

$$L_a = \mathbf{C}^{\mathcal{A}}\left(\mathbf{x}^{\star}_{/a}, \mathbf{r}^{\star}_{/a}, \mathbf{m}\right) - \mathbf{C}^{\mathcal{A}}\left(\mathbf{x}^{\star}, \mathbf{r}^{\star}, \mathbf{m}\right) \leq 0, \tag{2}$$

   - a relaxation can only lead to a lower/equal optimal cost.
3. Repeat over all areas.

How to get a relaxation?



Modeling a control area as an "ideal medium" ...

- All generators & loads connected to a single super-node;
- all intra-area links have variable impedance & inifinite capacity;
- no intra-area security restrictions and contingency events.

Economic benefit indicator

What if we **were not sharing** the intra-area grid flexibility of any single area?

---

1. Formulate a **restriction** by modeling a **non-cooperative** control area;
   - denote this optimal cost as $\mathbf{C}^{\mathcal{A}}\left(\mathbf{x}^{\star}_{+a}, \mathbf{r}^{\star}_{+a}, \bar{\mathbf{m}}\right)$.
2. Measure the benefit with respect to the full problem (1) solution:

$$B_a = \mathbf{C}^{\mathcal{A}}\left(\mathbf{x}^{\star}_{+a}, \mathbf{r}^{\star}_{+a}, \mathbf{m}\right) - \mathbf{C}^{\mathcal{A}}\left(\mathbf{x}^{\star}, \mathbf{r}^{\star}, \mathbf{m}\right) \geq 0. \tag{3}$$

   - non-zero only if the grid flexibility of an area is also used for the rest of the system.
3. Repeat over all areas.

How to model a non-cooperative control area?

1. Find how the autonomous SO would use its grid flexibility;
   - reducing all external control areas to an "ideal medium".

2. Restrict to these autonomous decisions & resolve the multi-area problem.

$$\left(\mathbf{x}^{\star}_{+a}, \mathbf{r}^{\star}_{+a}, \mathbf{g}^{\star}_{+a}\right) \in \arg\min_{\mathbf{r},\mathbf{g},\mathbf{x}} \mathbf{C}^{\mathcal{A}}\left(\mathbf{x}, \mathbf{r}, \bar{\mathbf{m}}\right)$$

$$\textit{subject to}:$$

$$\mathbf{x} = f\left(\bar{\mathbf{m}}, \bar{\mathbf{y}}, \mathbf{x}, \mathbf{r}, \mathbf{g}\right) \in \bigcap_{a'=1}^{A} \mathcal{X}^{a'}, \tag{4}$$

$$\mathbf{g} \in \times_{a'=1}^{A} \mathcal{G}^{a'},$$

$$\mathbf{g}^{\mathbf{a}} = \bar{\mathbf{g}}^{\mathbf{a}},$$

$$\mathbf{r} \in \mathcal{R}(\bar{\mathbf{m}}).$$

Multi-area power system security with grid flexibility

Let's recap ...

- It's all about inter-SO cooperation.
- Security management cost relies on all intra-area grid properties and usage of grid flexibility.
- Counterfactual analysis to evaluate the economic loss & benefit contributed by any single area.

Multi-area power system security with grid flexibility

Let's recap . . .

- It's all about inter-SO cooperation.
- Security management cost relies on all intra-area grid properties and usage of grid flexibility.
- Counterfactual analysis to evaluate the economic loss & benefit contributed by any single area.
- How to use these indicators for inter-SO settlement?
  - intra-area settlements at the discretion of local regulation.

Inter-SO settlement scheme

Net impact indicator

- Summing the economic loss & benefit per area,

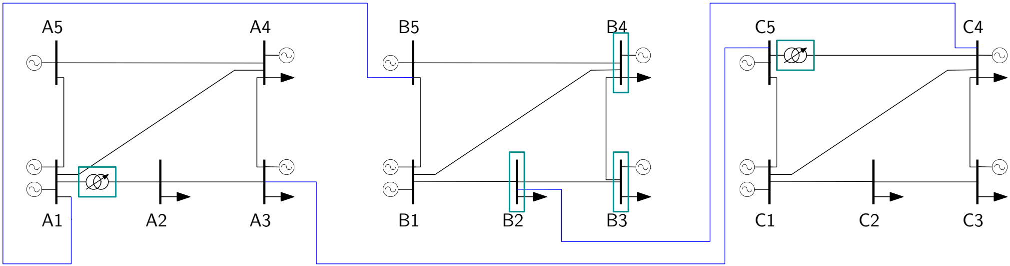
$$N_a = L_a + B_a \quad \forall a \in A, \tag{5}$$

Cost allocation approach

- Areas with positive net impact provide value to the whole system;
  - $\rightarrow$ collect revenues equal to the respective net impact indicators;
- Areas with negative net impact create costs for the whole system;
  - $\rightarrow$ pay security mgmt cost + total positive net impact;
  - $\rightarrow$ pro-rata of negative net impact.

4. Demonstrative implementation

Test system overview



- A 3-area system based on the 5PJM matpower case, designed for demonstration;
- 3 identical interconnections, with capacity of 1.5 pu;
- area A has increased marginal generation costs (+200 money pu) and area C has reduced marginal generation costs (-200 mpu);
- grid flexibility: 2x PST [(A1–A2);(C4–C5)], 3x bus-splitting breakers [B2,B3,B4].

Preventive/corrective N-1 Security Constrained OPF

- Seeking to avoid loss of load after any single branch outage;
- objective is to minimize generation redispatching cost wrt the market baseline.

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- Pre-contingency controls:
  - generation redispatching;
  - bus splitting/merging;
  - PST flow threshold.
- Post-contingency controls:
  - bus splitting/merging;
  - PST operating mode.

Preventive/corrective N-1 Security Constrained OPF

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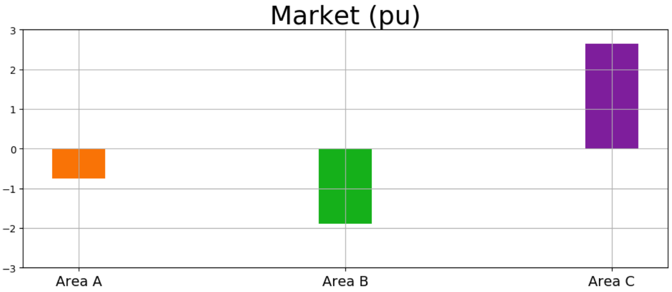
- Post-contingency controls:
  - bus splitting/merging;
  - PST operating mode.

- Mixed-Integer Linear Programming (MILP) problem:
  - DC power flow approximation;
  - integer variables for grid flexibility.

Baseline "market" dispatch & redispatching resources



- Baseline dispatch using a DC-OPF subject to interconnection capacity constraints;
- all units offering the available headroom (capacity - market dispatch) as upward redispatch potential for a marginal generation (fuel) cost;
- and the available floor-room (market dispatch - minimum stable generation) as downward redispatch potential for free.

Power flow control through grid flexibility

- Increased use of interconnection capacity (more inter-area congestion).

No Flexibility		Grid Flexibility	
Contingency	Congestion	Contingency	Congestion
A1 – A4	A4 – A5	A1 – A5	A4 – A5
A1 – A5	A4 – A5	C1 – C4	C4 – C5
B1 – B4	B4 – B5	C1 – C2	C4 – C5
B1 – B5	A4 – B5	C1 – C5	C4 – C5; **A3 – C5**
A1 – A5	**A3 – C5**	B1 – B5	**A1 – B5**
		A3 – C5	**A1 – B5**

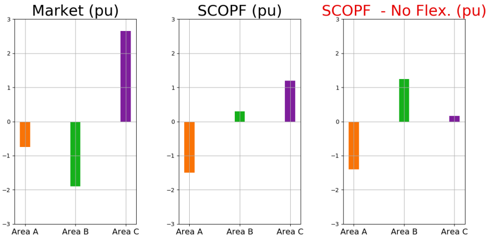
Network congestion overview

Economic value of grid flexibility

- Secure import/export positions closer to the market dispatch.
- Grid flexibility allows to use more the cheap generation from area C.

	Cost ($)
Market	43752
SCOPF	25038
SCOPF - No Flex.	29675 (+18.5%)

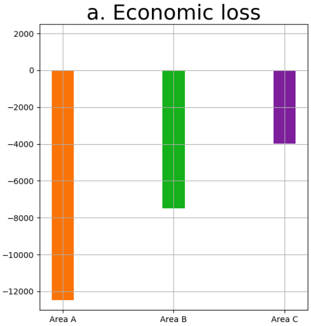
Multi-area system costs



Net export positions per system area

Counterfactual analysis (1/2)

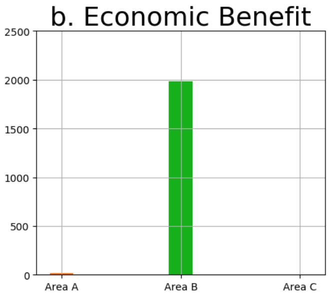
What if we **were not restricted** by the intra-area physical parameters and security criteria of any single area?



- Area C has the smallest negative impact on the multi-area system security cost;
  - cheap generation is locally available;
- Area A & B indicators relate to securing interconnections;
  - larger evitable costs.

Counterfactual analysis (2/2)

What if we **were not sharing** the intra-area grid flexibility of any single area?

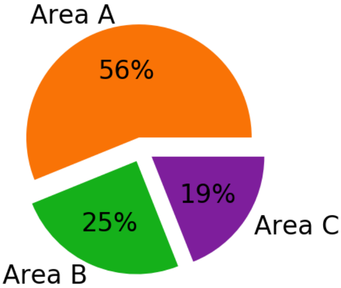


- Sharing area B grid flexibility creates value to the multi-area system;
  - SO would autonomously use a different topology;
- Area C grid flexibility serves intra-area purpose.

Inter-SO cost settlement

Area	Net Impact
A	-12464
B	-5518
C	-3935

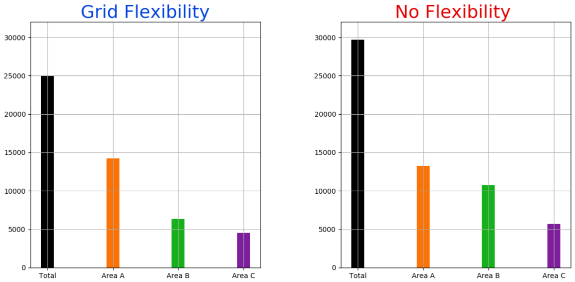
Net impact indicators



Cost allocation coefficients

- SOs to pay redispatching costs pro-rata.

SO gains from grid flexibility



Security management costs ($)

A smaller share of a smaller cost

- Area B SO gains from the multi-area system security cost reduction;
- and, from the value it creates by sharing its flexibility.

5. Closing discussion

Multi-area power system security with grid flexibility

Cooperative approach overview

1. Sharing of all resources & grid flexibilities of the different SO control areas.
   – Jointly minimize the multi-area system interconnected security cost.
2. Inter-SO settlement based on each control area impact.
   – Counterfactual analysis of each SO costs & benefits to the multi-area system.
3. Intra-area settlements.
   – As per the local regulations.

Cooperative approach for multi-area power system security with grid flexibility

Why?

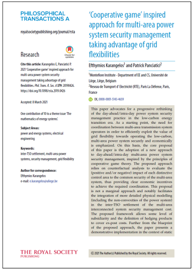
- Inter-SO cooperation is necessary to make the most of interconnections & grid flexibility.
- Inter-SO settlement can provide the incentives ...
  - sharing existing grid flexibility in the short-term;
  - mutually beneficial investments on grid flexibility in the long-term.
- Counterfactual analysis is non-marginal;
  - no limitations on detailed physical modeling (non-convexities/non-linearities).
- Intra-area settlement rules, hedging products, *etc.* can be designed in any way.

Cooperative approach for multi-area power system security with grid flexibility

From demonstrative to real-life applications

- Computational efficiency of counterfactual analysis steps.
- Short-term winners & losers under the new settlement.
- Long-term rewards & coordinated investment benefits.
- Work-in-progress. . .

To find out more . . .



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Research

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One contribution of 10 to a theme issue 'The mathematics of energy systems'.

Subject Areas:
power and energy systems, electrical engineering

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This paper advocates for a progressive rethinking of the day-ahead/intra-day power system security management practice in the low-carbon energy transition era. As a starting point, the need for coordination between multi-area transmission system operators in order to efficiently exploit the value of grid flexibility towards operating the low-carbon, multi-area power system securely and economically is emphasized. On this basis, the core proposal of this paper is the adoption of a new approach to day-ahead/intra-day multi-area power system security management, inspired by the principles of cooperative game theory. The proposed approach relies on counterfactual analysis to evaluate the (positive and/or negative) impact of each distinctive control area to the common security of the multi-area system, thus providing clear economic incentives to achieve the required coordination. This proposal is not a marginal approach and notably facilitates the integration of more detailed physical modelling (including the non-convexities of the power system) in the inter-TSO settlement of the multi-area interconnected system security management cost. The proposed framework allows some level of subsidiarity and the definition of hedging products to cover ex-post costs. Further from the blueprint of the proposed approach, the paper presents a demonstrative implementation in the context of static

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Thanks for your attention

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