Transmission and Distribution (T&D) Coordination for DER Market Participation

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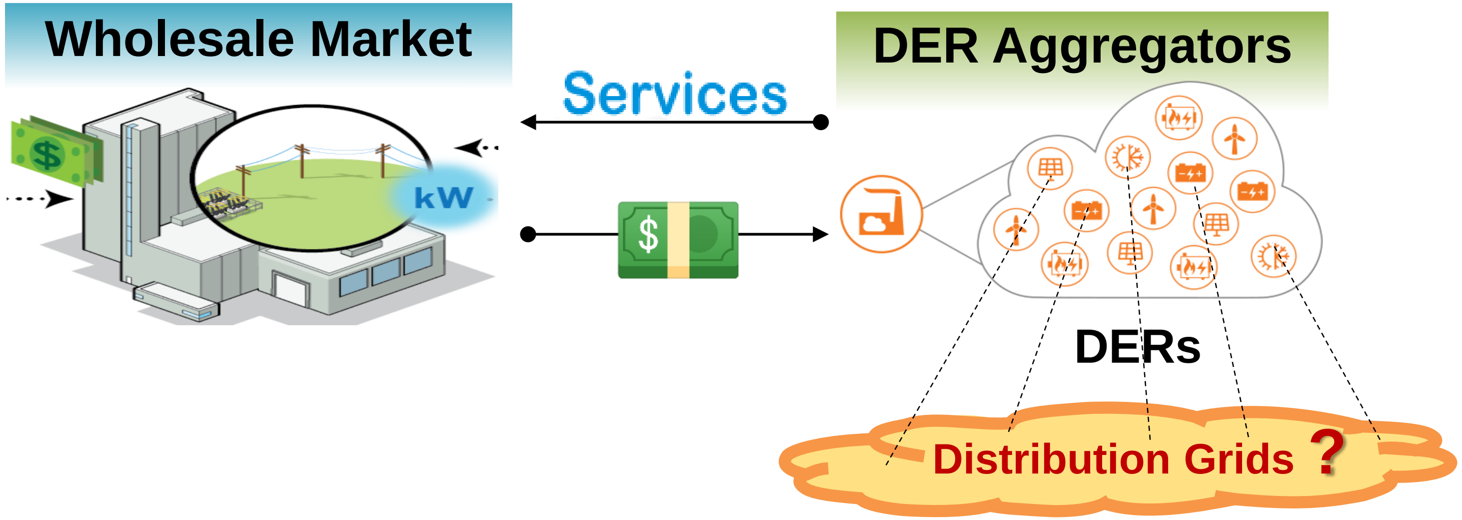
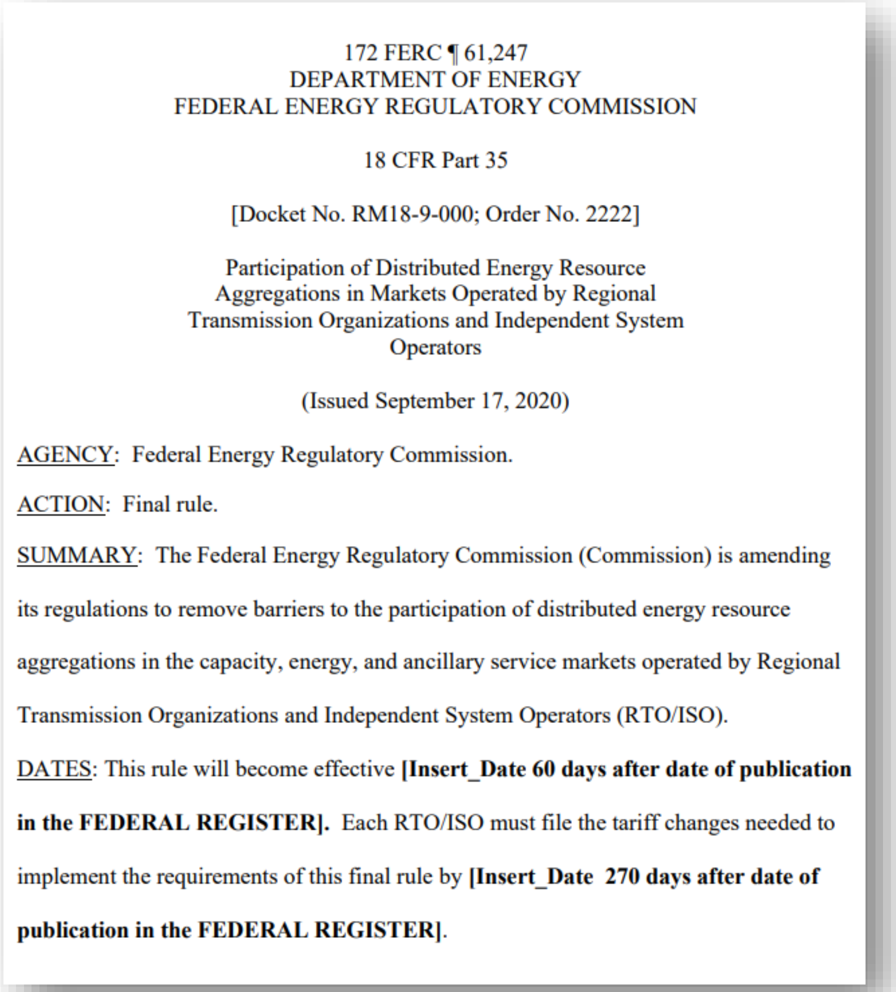
PSERC Webinar
September 20, 2023

Challenges & Opportunities: FERC Order 2222



FERC Order 2222



172 FERC ¶ 61,247
DEPARTMENT OF ENERGY
FEDERAL ENERGY REGULATORY COMMISSION

18 CFR Part 35

[Docket No. RM18-9-000; Order No. 2222]

Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators

(Issued September 17, 2020)

AGENCY: Federal Energy Regulatory Commission.

ACTION: Final rule.

SUMMARY: The Federal Energy Regulatory Commission (Commission) is amending its regulations to remove barriers to the participation of distributed energy resource aggregations in the capacity, energy, and ancillary service markets operated by Regional Transmission Organizations and Independent System Operators (RTO/ISO).

DATES: This rule will become effective **[Insert_Date 60 days after date of publication in the FEDERAL REGISTER]**. Each RTO/ISO must file the tariff changes needed to implement the requirements of this final rule by **[Insert_Date 270 days after date of publication in the FEDERAL REGISTER]**.

DER wholesale market participation

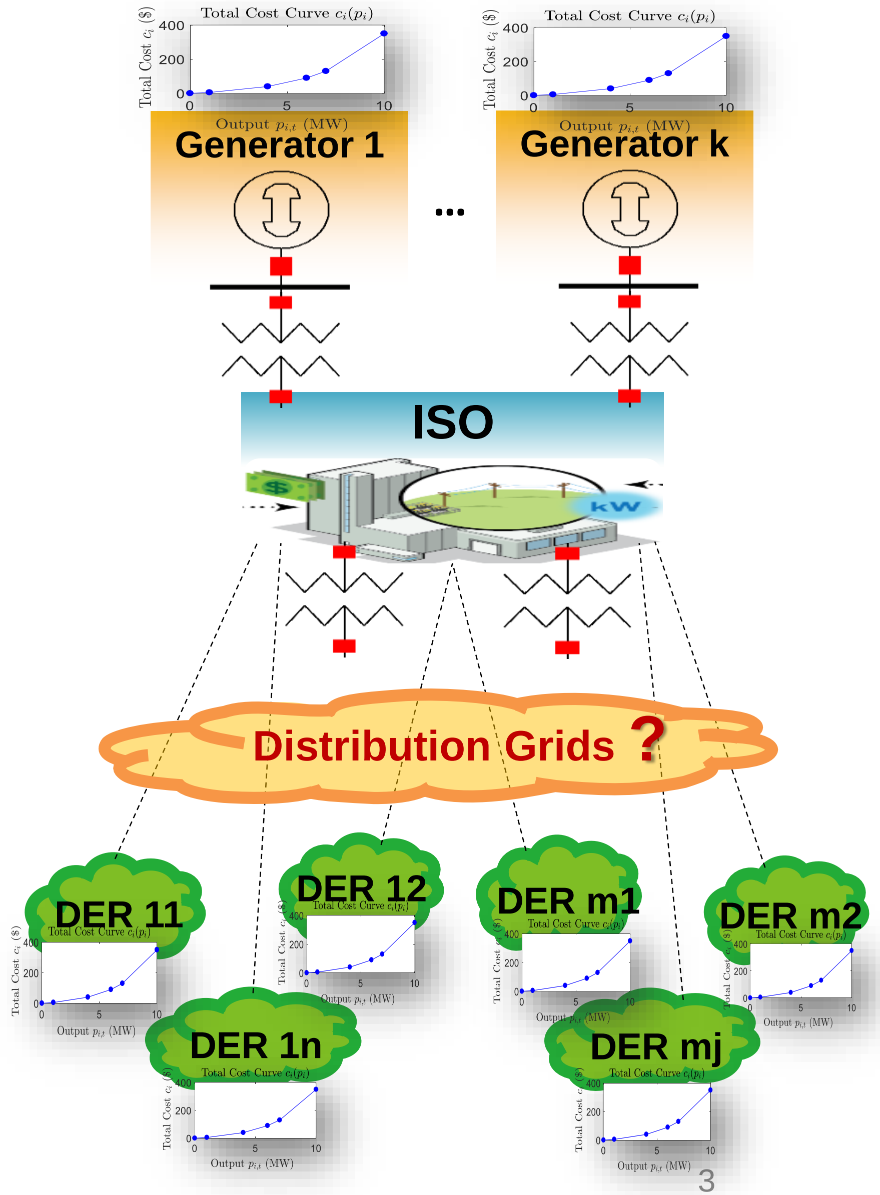
- FERC Order 2222
- Full market participation of DER aggregators
- T&D coordination for DER market participation

*https://www.ferc.gov/media/ferc-order-no-2222-fact-sheet

Challenges & Opportunities: DER Market Participation

DER wholesale market participation

- Many (aggregated) DERs enter the ISO market as small generators
- DERs are physically located in distribution grids
- ISO cannot observe distribution grids
- Mismatch between ISO market and physical models
- Computation burden, convergence, price oscillations for ISO market clearing
- Voltage/thermal violations or outages in distribution grids



* Y. Chen, T. Zheng, X. Wang, and S. Oren, "DER Market Integration: Opportunities and Challenges," in Panel session at 2020 IEEE Power and Energy Society General Meeting, 2020.

Challenges & Opportunities: T&D Coordination

Practical requirements for T&D coordination

- T&D operation should be coordinated with minimal T&D communications
- For data ownership and model confidentiality: no exchange of T&D system models
- For smooth transition from today's established ISO markets, no or minimal changes to ISO's existing market operations
- Guarantee optimal T&D operation while satisfying all the operating constraints for the entire T&D systems.

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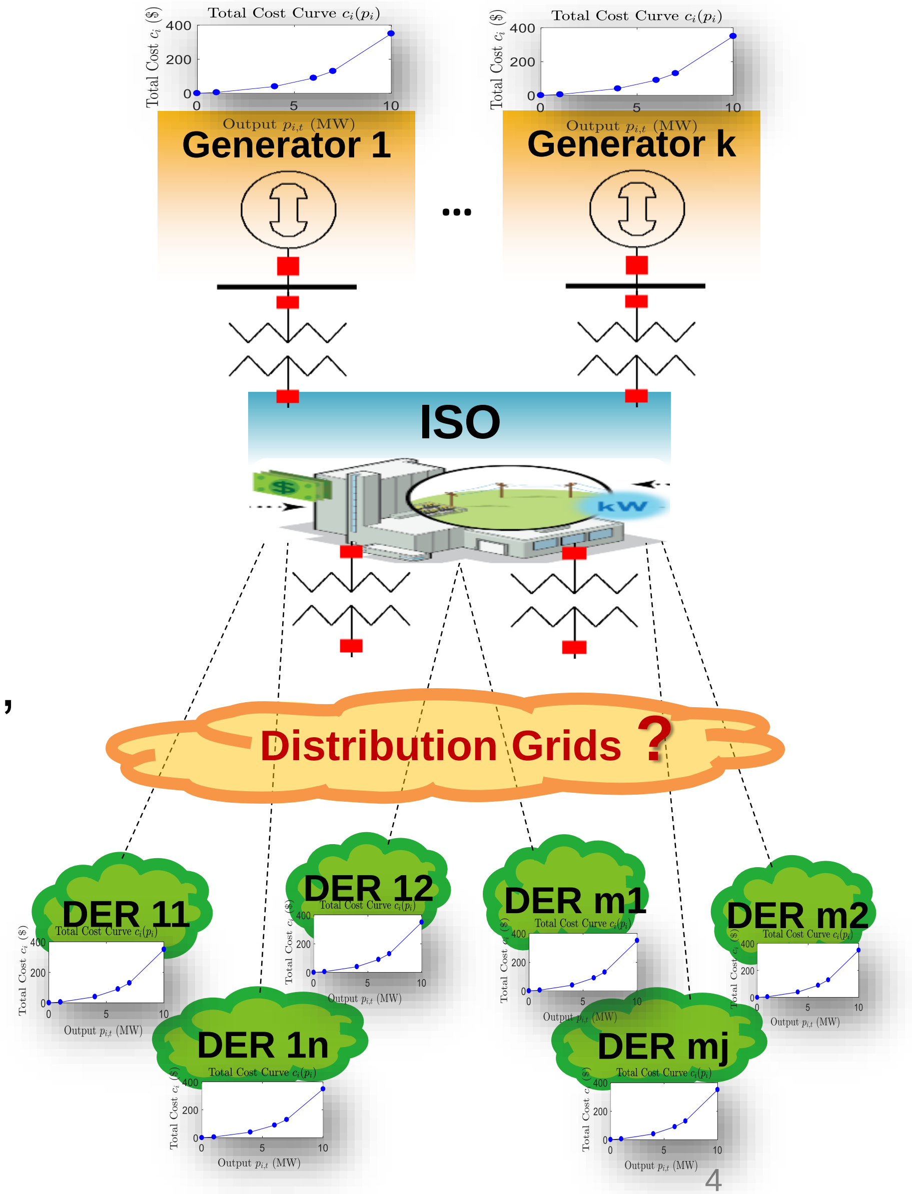
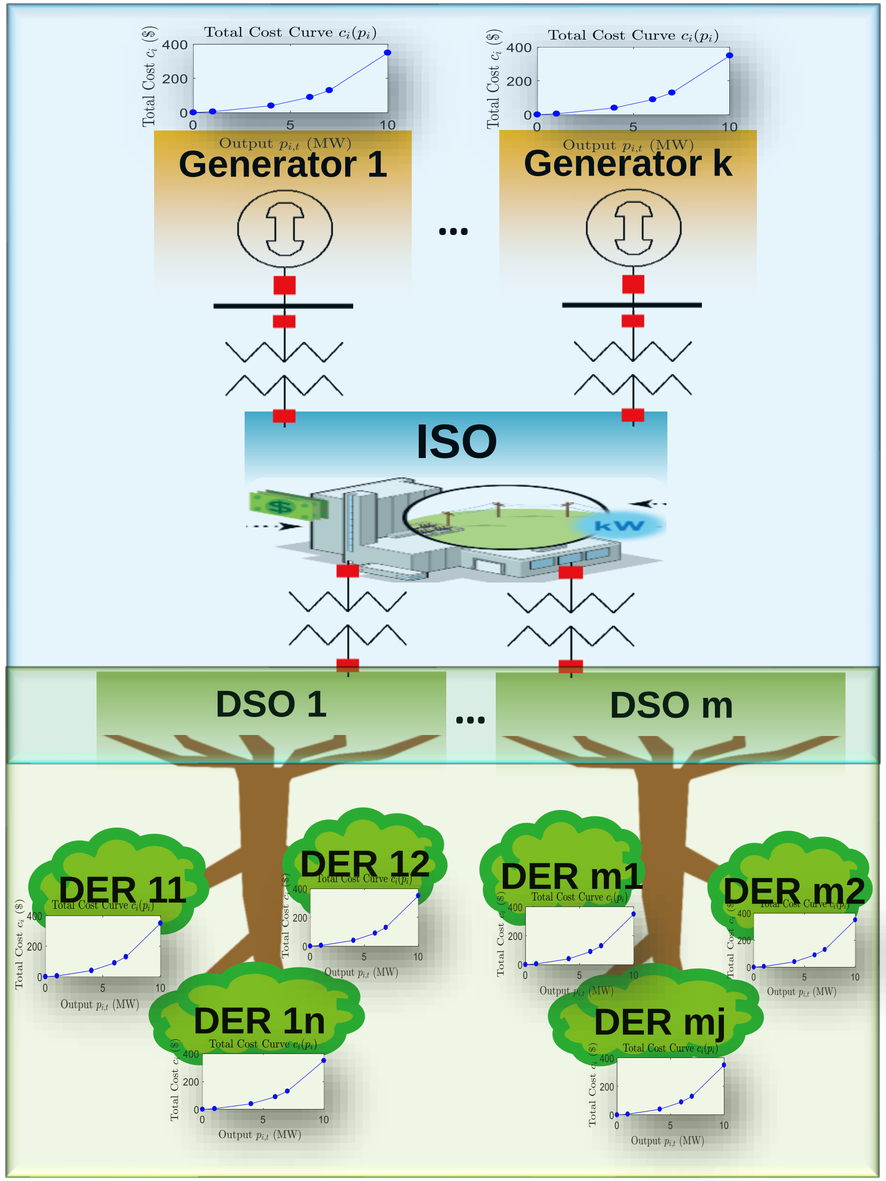


Existing Works: T&D Coordination

Existing works for T&D coordination

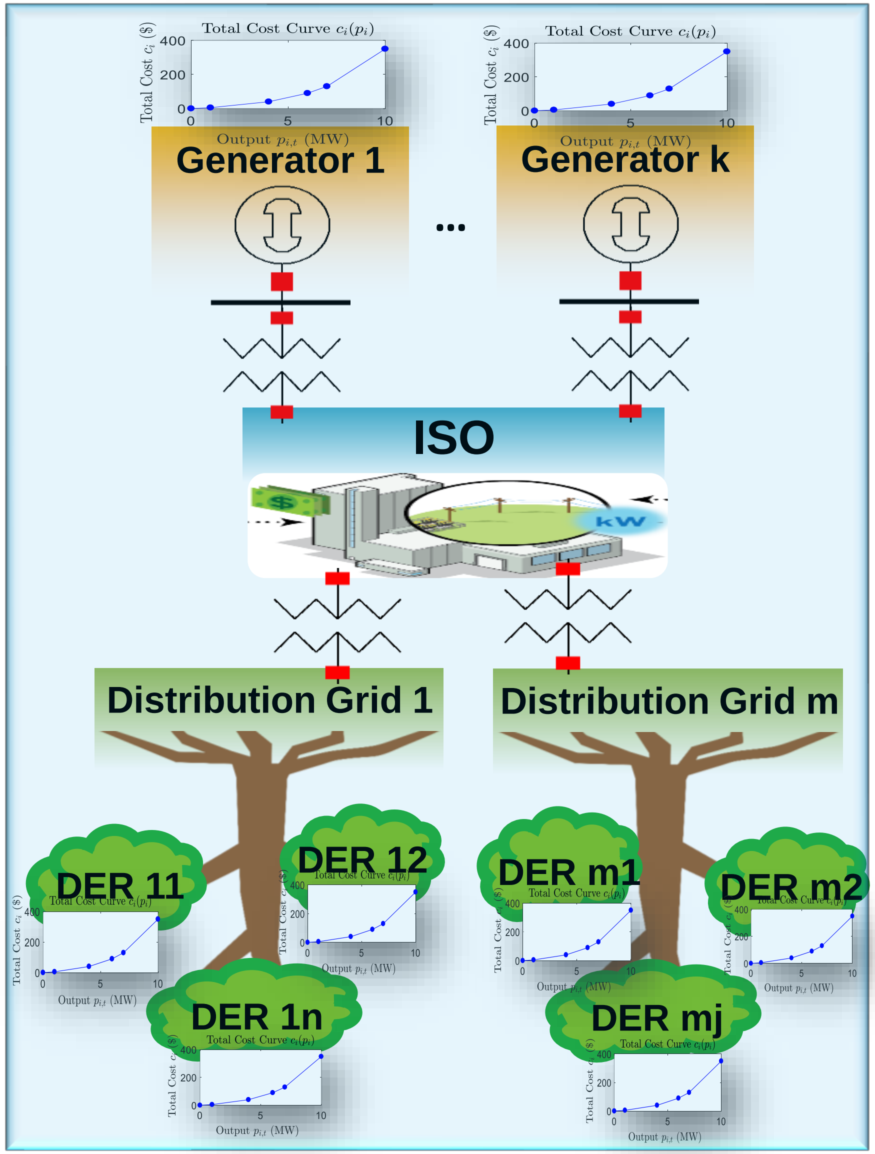
- Bi-level optimization, feasible region projection, etc.
  - ✓ Exchanging T&D grid models → data ownership/confidentiality, increased ISO modeling/computation efforts
- Decentralized/Distributed optimization
  - ✓ Decompose the ideal (unrealistic) optimization model/computation across the ISO and DSOs
  - ✓ Coupled T&D iterative optimization solution process, exchanging T&D intermediate values during iterations
  - ✓ Need to change existing ISO market clearing procedure
  - ✓ High communication demands between T&D



Ideal Case: T&D Coordination

⏩ <u>Ideal case</u> for T&D co-operation:

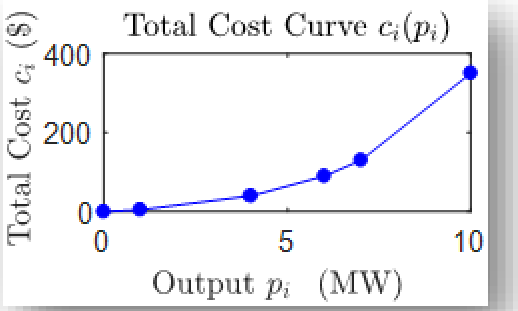
- A single entity can fully model, observe, and dispatch resources and networks in both T&D systems →
- <u>Optimal</u> T&D co-operation can be easily achieved by letting the single entity:
  1) dispatch and pay/price all the T&D-level resources (generators & DERs)
  2) satisfy all the T&D-level operating constraints
  3) minimize total operating cost of all the T&D-level resources
- <u>Unrealistic</u> → Currently no single entity can oversee both T&D systems



Ideal Case: T&D Coordination

<u>Ideal case</u> for T&D co-operation (optimal but unrealistic):

Total generation cost curve submitted by i^{th} generator or DER



$$\min_{\boldsymbol{p}} \sum_{k\in\mathcal{N}_{gen}} \boxed{c_k^{gen}(p_k^{gen})} + \sum_{j\in\mathcal{N}_D}\sum_{i\in\mathcal{N}_{der}} \boxed{c_{i,j}^{der}(p_{i,j}^{der})}$$

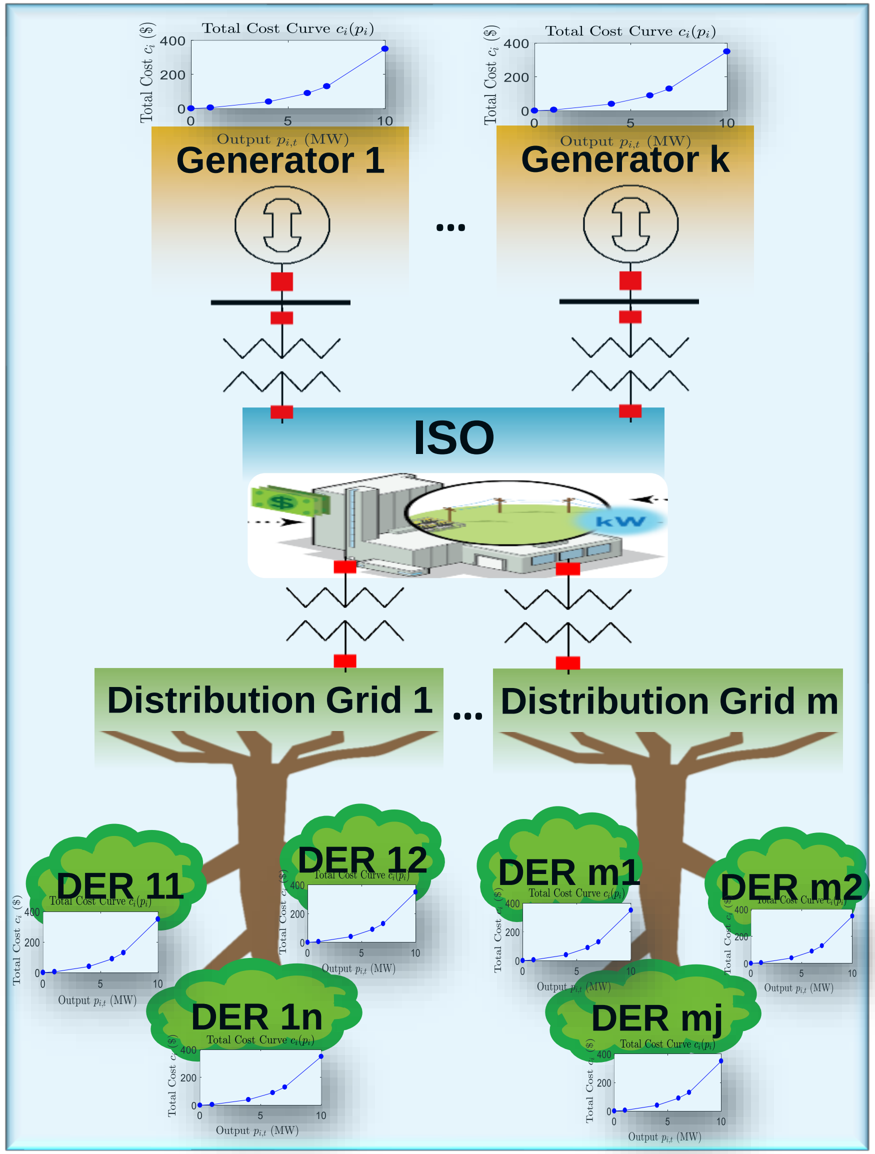
Minimize total generation cost (generators & DERs)

s.t. $\boldsymbol{p}^{gen} \in S^T$ → T-level operating constraints (load balancing, congestion, etc.)

$\boldsymbol{p}_j^{der} \in S_j^D, \forall j \in \mathcal{N}_D$ → D-level operating constraints for each DSO (load balancing, congestion, voltage, etc.)

$p_k^{gen} \in S_k^{gen}, \forall k \in \mathcal{N}_{gen}$ → Generator upper/lower limits

$p_{i,j}^{der} \in S_{i,j}^{der}, \forall i \in \mathcal{N}_{der}, j \in \mathcal{N}_D$ → DER upper/lower limits

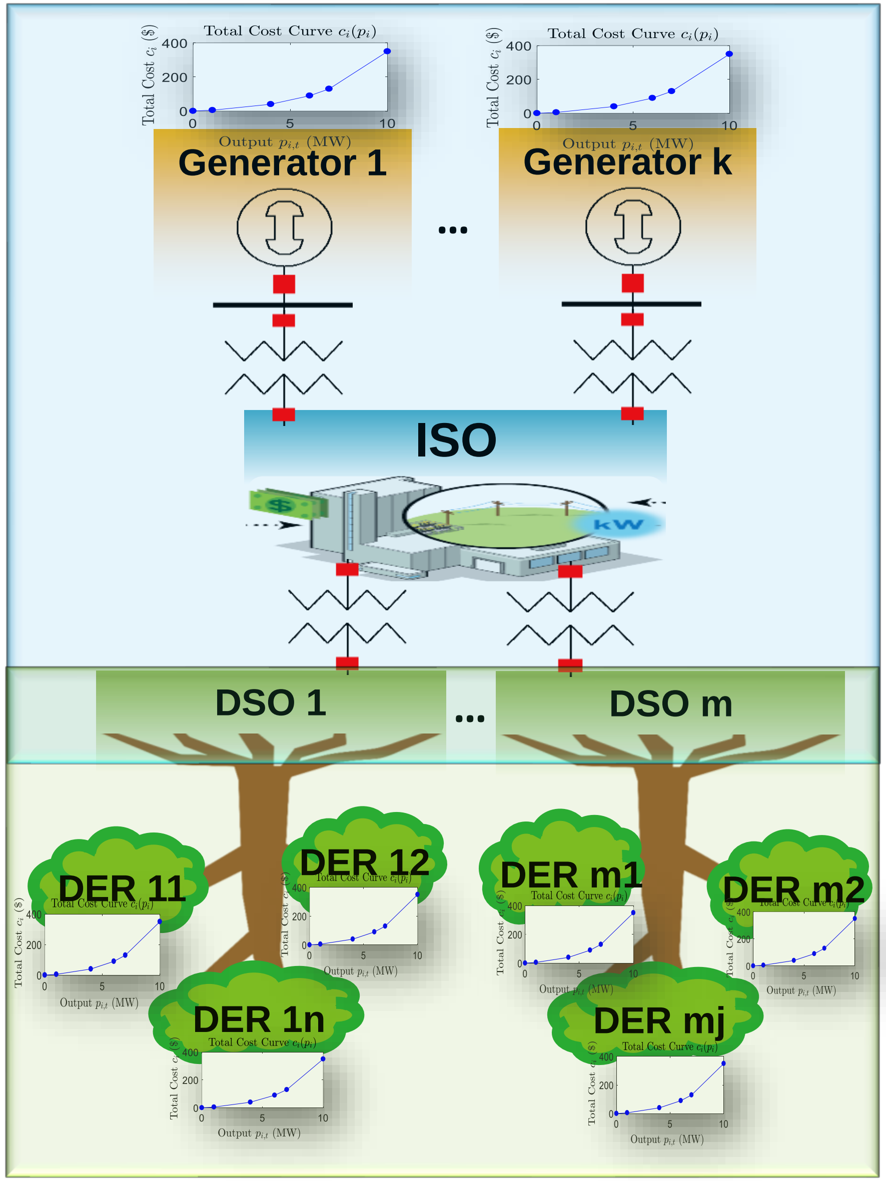


Optimal Decisions: Generator & DER dispatch outputs $\boldsymbol{p}$ (MW), locational marginal prices ($/MWh)

Proposed Work: T&D Coordination

Proposed T&D market coordination:

- ISO and DSOs operate T&D markets separately
- Decompose the ideal case (optimal but unrealistic) optimization model/computation across the ISO and DSOs
  - ✓ No T&D grid model exchange
  - ✓ No change to existing ISO market clearing procedure
  - ✓ Completely decoupled T&D solution process → no iterative T&D communications
  - ✓ Only exchange the minimal amount of public data → minimized T&D communication burden
  - ✓ Decomposed T&D market clearing outcomes are identical to the ideal case market clearing outcomes.



Ideal Case Decomposition: Transmission-level

Ideal case decomposition: T-level

- No change to existing ISO market clearing procedure

- No exchange of DSO grid models

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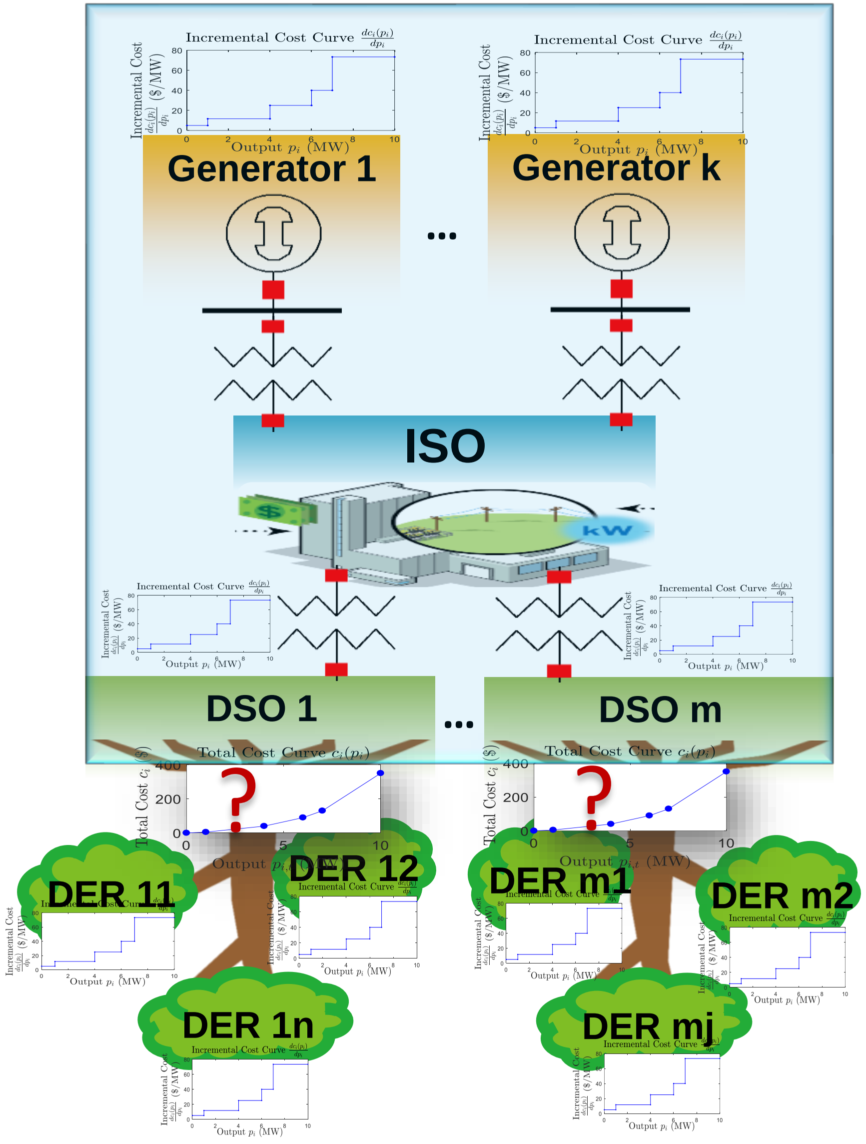
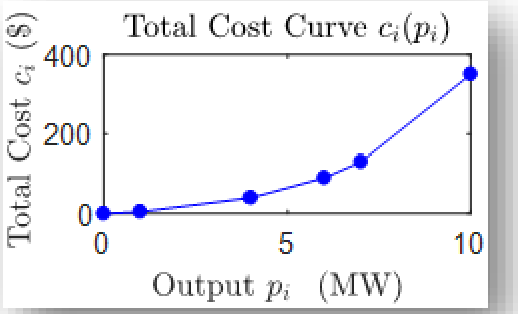


Ideal Case Decomposition: Transmission-level

Ideal case decomposition: T-level

Total generation cost curve submitted by i^{th} generator or ~~DER~~ DSO



$$\min_{\boxed{p}} \sum_{k\in\mathcal{N}_{gen}} \boxed{c_k^{gen}(p_k^{gen})} + \sum_{j\in\mathcal{N}_D} \boxed{c_{,j}^{dso}(p_{,j}^{dso})}$$

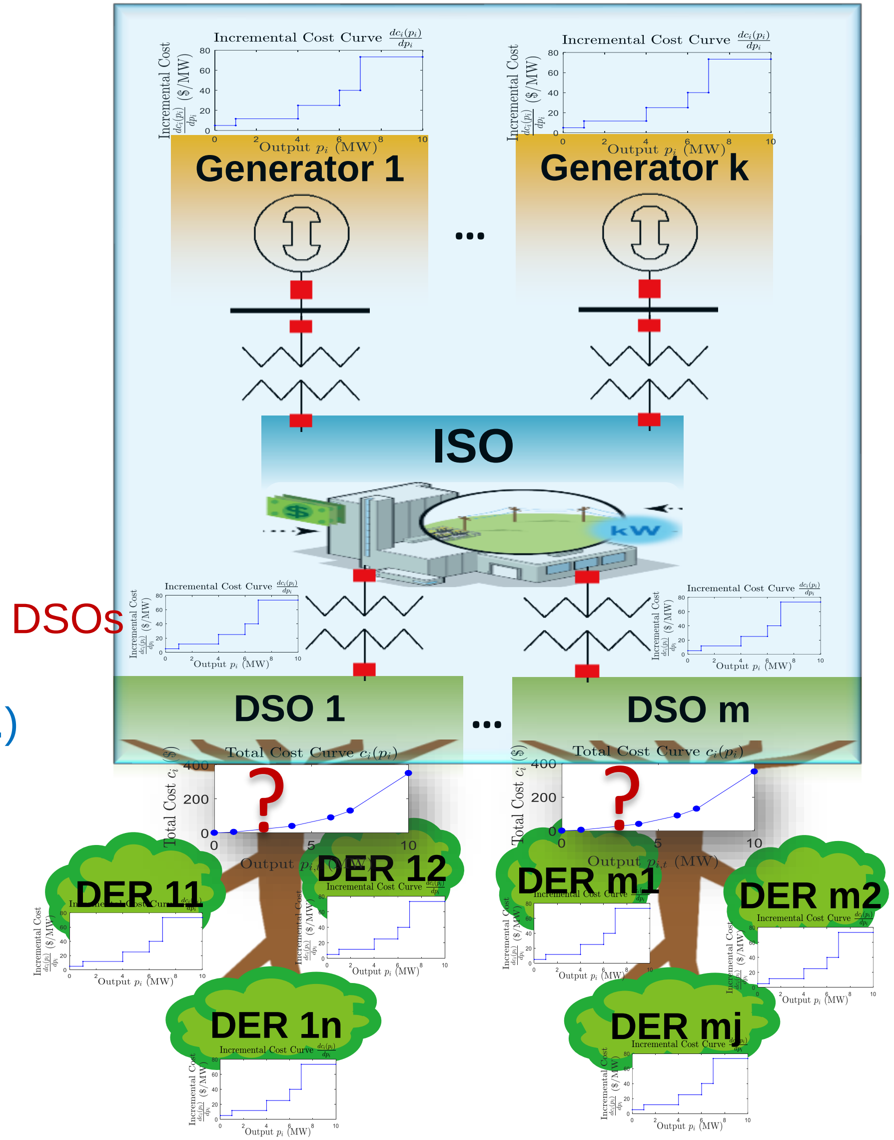
Minimize total generation cost (generators & ~~DERs~~) DSOs

s.t. $\boldsymbol{p}^{gen} \in S^T$ → T-level operating constraints (load balancing, congestion, etc.)

$\cancel{\boldsymbol{p}_j^{der} \in S_j^D, \forall j \in \mathcal{N}_D}$ → ~~D-level operating constraints for each DSO (load balancing, congestion, voltage, etc.)~~

$p_k^{gen} \in S_k^{gen}, \forall k \in \mathcal{N}_{gen}$ → Generator upper/lower limits

$p_{,j}^{dso} \in S_{,j}^{dso}, \forall j \in \mathcal{N}_D$ → ~~DER~~ DSO upper/lower limits

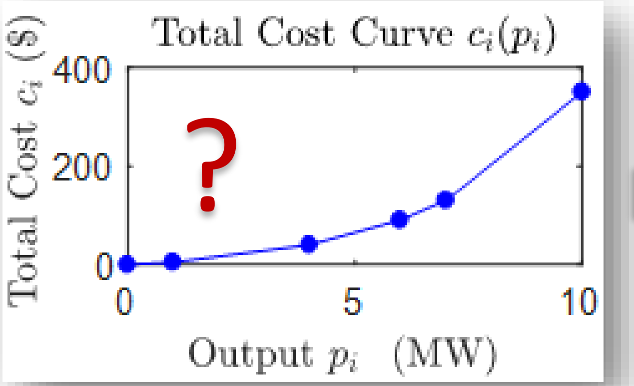


Optimal Decisions: Generator & ~~DER~~ DSO dispatch outputs $\boldsymbol{p}$ (MW), locational marginal prices ($/MWh)

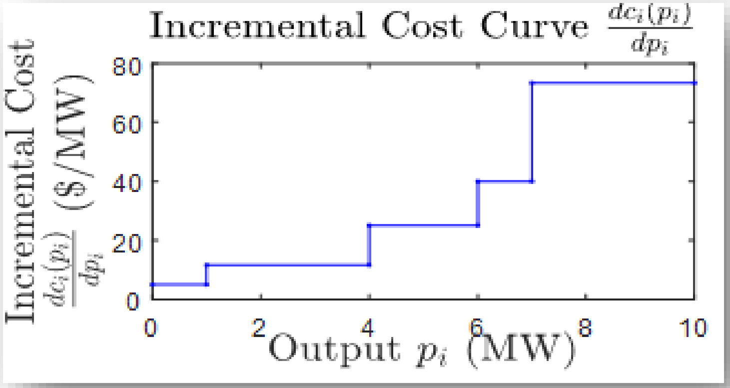
Before ISO Market Clearing: Data Exchange from DSO to ISO

Data exchange from DSO to ISO:

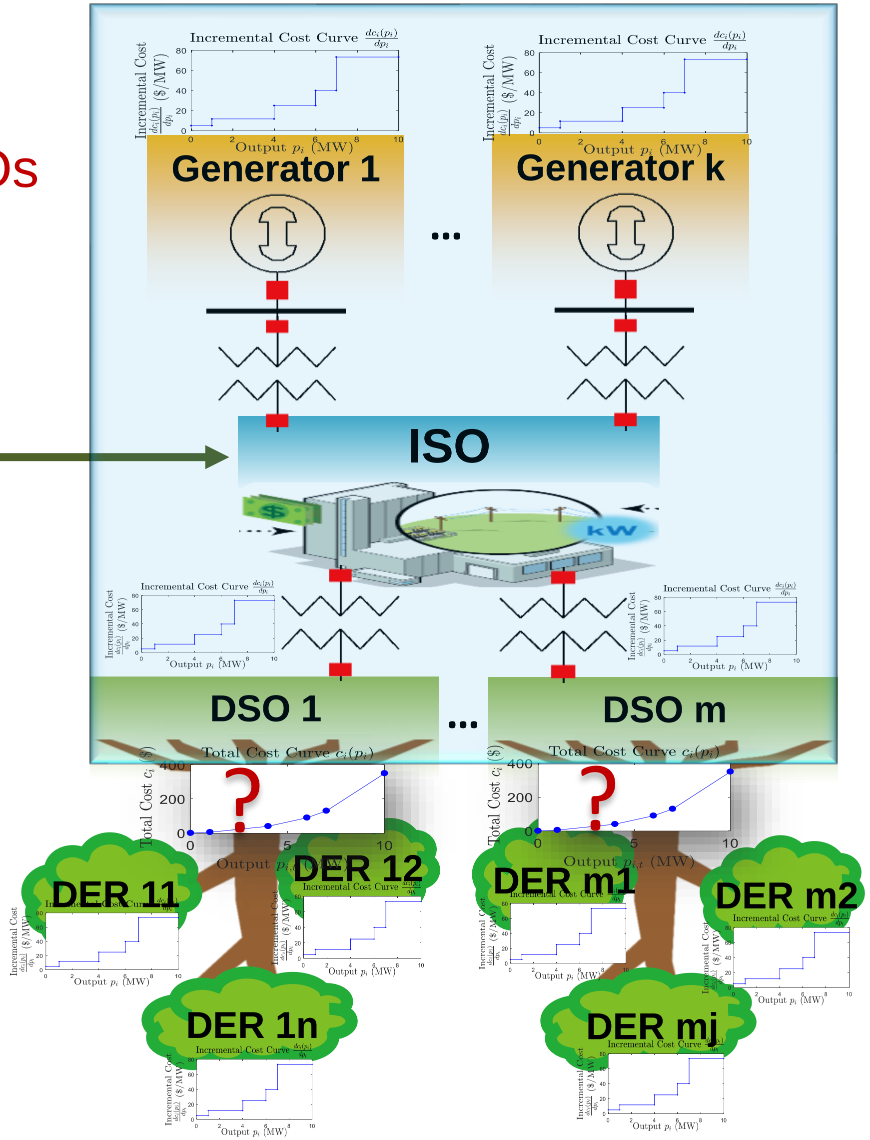
- ISO requests incremental cost curves from all generators and DSOs



Total generation cost curve $c_i(p_i)$ submitted by i^{th} DSO



Incremental/Marginal generation cost curve $\frac{dc_i(p_i)}{dp_i}$ submitted by i^{th} DSO

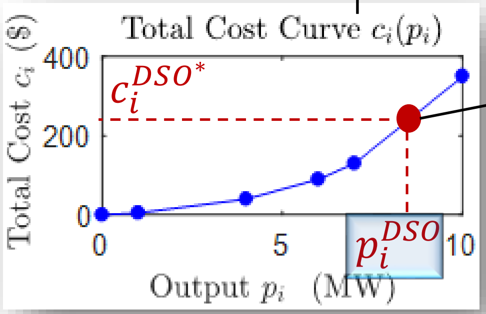


- DSO obtains its total generation cost curve (converted to DSO incremental cost curve), after collecting incremental cost curves from all the (aggregated) DERs in the DSO territory → How?

Ideal Case Decomposition: Distribution-level (Bidding)

Ideal case decomposition: D-level (bidding)

DSO cost curve submitted to ISO



Each point (p_i^{DSO}, c_i^{DSO*}) on this curve:

The true/lowest cost c_i^{DSO*} ($) of generating p_i^{DSO} (MW) of real power from DSO to ISO

Total generation cost curve $c_i^{DSO}(p_i^{DSO})$ submitted by i^{th} (non-profit) DSO to ISO

Cost curves submitted by DERs to DSO

$$c_j^{dso*}(p_j^{dso}) = \min_{p^{der}} \sum_{i\in\mathcal{N}} c_{i,j}^{der}(p_{i,j}^{der})$$

Miniminal total generation costs of all DERs = true/lowest DSO generation cost c_i^{DSO*}

s.t.

$$p_j^{dso} = \sum_{i\in\mathcal{N}_{der_k}} p_{i,j}^{der} + \sum_{l\in\mathcal{N}_{f_k}} f_{l,j} - L_{k,j}$$

DSO power balance equation at ISO-DSO coupling point

$$p_{i,j}^{der} \in S_{i,j}^{der}, \forall i \in \mathcal{N}_{der}$$

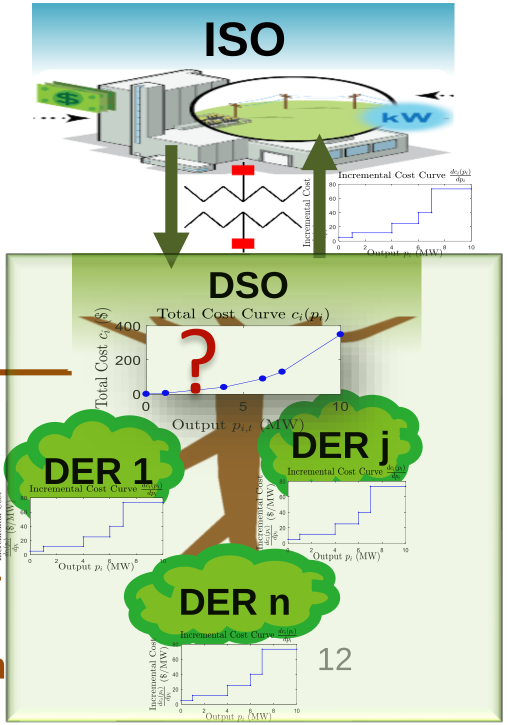
DER upper/lower limits

$$\boldsymbol{p}_j^{der} \in S_j^D$$

D-level operating constraints for j^{th} DSO (voltage violations, congestions, load balancing)

Optimal Decisions: DER dispatch outputs $\boldsymbol{p}^{DER}$ (MW)

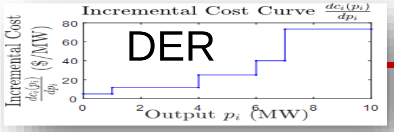
Inelastic load 1
⋮
Inelastic load m



T&D Coordination for DER Market Integration

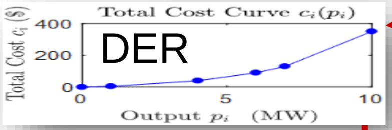
Proposed T&D market coordination (before ISO market clearing):

1. DSO collects incremental cost curve from each (aggregated) DER, $\frac{dc_j^{DER}(p_j^{DER})}{dp_j^{DER}}$



Integrate

2. DSO constructs total cost curve for each (aggregated) DER, $c_j^{DER}(p_j^{DER})$



3. DSO runs parametric programming to obtain the DSO's total generation cost curve $c_i^{DSO}(p_i^{DSO})$ (true/lowest generation costs at all possible DSO generation levels)

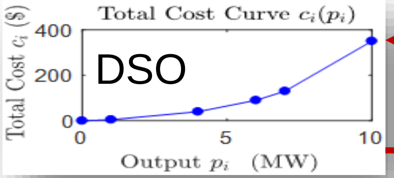
$$c_j^{dso*}(p_j^{dso}) = \min_{p^{der}} \sum_{i \in \mathcal{N}} c_{i,j}^{der}(p_{i,j}^{der})$$

$$\text{s.t.} \quad p_j^{dso} = \sum_{i \in \mathcal{N}_{der_k}} p_{i,j}^{der} + \sum_{l \in \mathcal{N}_{f_k}} f_{l,j} - L_{k,j}$$

$$p_{i,j}^{der} \in S_{i,j}^{der}, \forall i \in \mathcal{N}_{der}$$

$$\boldsymbol{p}_j^{der} \in S_j^{D}$$

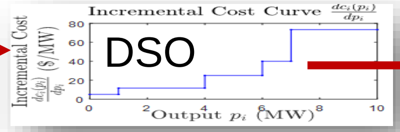
DSO parametric programming



Derivative

4. DSO converts the DSO's total generation cost curve $c_i^{DSO}(p_i^{DSO})$ to the DSO's incremental generation cost curve $\frac{dc_i^{DSO}(p_i^{DSO})}{dp_i^{DSO}}$

5. DSO submits the DSO's incremental generation cost curve $\frac{dc_i^{DSO}(p_i^{DSO})}{dp_i^{DSO}}$ to ISO



DSO bids To ISO

T&D Coordination for DER Market Integration

Proposed T&D market coordination (after ISO market clearing):

1. ISO clears the wholesale market and sends out each DSO's wholesale dispatch signal $p_i^{DSO^*}$ (MW), wholesale locational marginal price (LMP) $\pi_i^{DSO^*}$ (\$/MWh) → total wholesale payment to DSO = $p_i^{DSO^*} \times \lambda_i^{DSO^*}$(\$)

2. DSO re-dispatch the wholesale dispatch signal $p_i^{DSO^*}$ and wholesale payment $p_j^{DSO^*} \times \lambda_j^{DSO^*}$ to obtain the retail dispatch signal $p_j^{DER^*}$ and retail LMP $\lambda_j^{DER^*}$ for each DER

D-level (dispatch) **D-level (pricing)**

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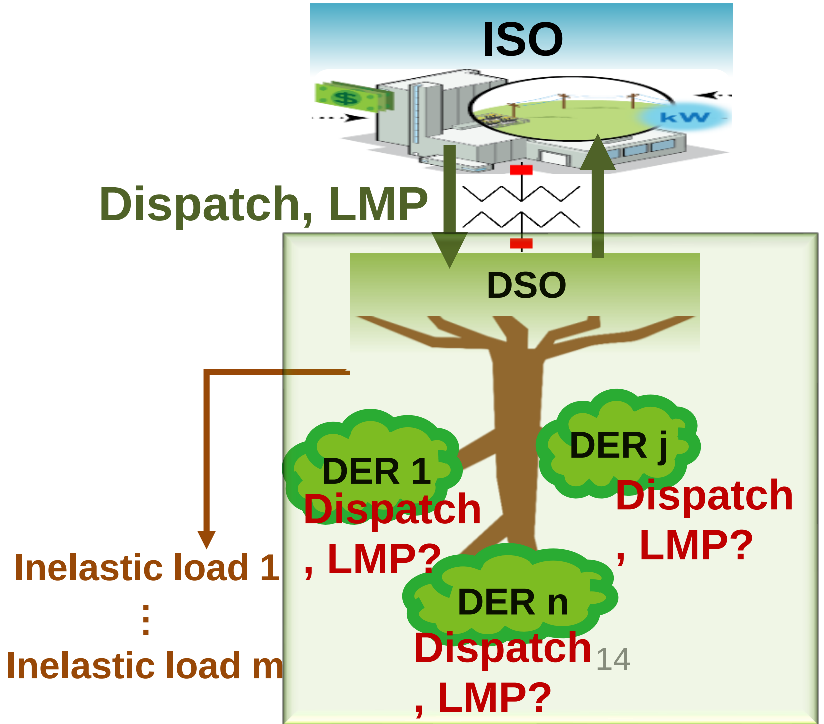
Decomposed T-level & D-level dispatch and pricing →

identical to the dispatch and pricing in the ideal (but unrealistic) case



Ideal Case Decomposition: D-level (Dispatch)

Ideal case decomposition: D-level (dispatch) after ISO market clearing

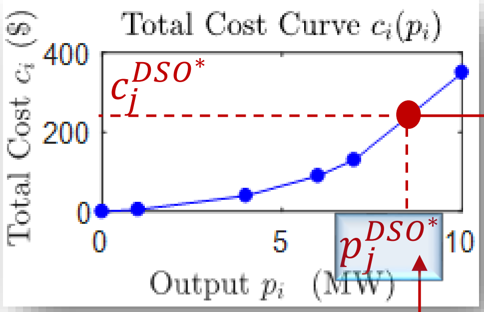
Data exchange from ISO to DSO (after ISO market clearing):

Optimal wholesale dispatch for j^{th} DSO - $\boxed{p_j^{DSO^*}}$

Optimal DSO decision solved at $\boxed{\boldsymbol{p_j^{DSO*}}} =$

Optimal retail dispatch signal for each DER:

$$\boldsymbol{p^{DER^*}} = [p_1^{DER^*}, \dots, p_j^{DER^*}, \dots, p_n^{DER^*}]$$



DSO's optimal wholesale dispatch signal $p_j^{DSO^*}$ (by ISO market clearing)

$$c_j^{dso*}\left(\boxed{p_j^{dso^*}}\right) = \min_{\boxed{\boldsymbol{p^{der}}}} \sum_{i\in\mathcal{N}} c_{i,j}^{der}\left(p_{i,j}^{der}\right)$$

$$\text{s.t.} \quad \boxed{p_j^{dso^*}} = \sum_{i\in\mathcal{N}_{der_k}} p_{i,j}^{der} + \sum_{l\in\mathcal{N}_{f_k}} f_{l,j} - L_{k,j}$$

→ DSO power balance equation at ISO-DSO coupling point

$$p_{i,j}^{der} \in S_{i,j}^{der}, \forall i \in \mathcal{N}_{der}$$

→ DER upper/lower limits

$$\boldsymbol{p_j^{der}} \in S_j^D$$

→ D-level operating constraints for j^{th} DSO (voltage violations, congestions, load balancing)

- **In the DSO parametric-programming-based bidding model:**

1. Fix ISO-DSO coupling parameter p_j^{DSO} at the ISO market clearing solution ($p_j^{DSO} = p_j^{DSO*}$)
2. Solve the (non-parametric) optimization problem for optimal retail dispatch signals of DERs

Ideal Case Decomposition: D-level (pricing)

Ideal case decomposition: D-level (pricing) after ISO market clearing

Data exchange from ISO to DSO (after ISO market clearing):

Optimal wholesale LMP (price) for j^{th} DSO - $\boxed{\lambda_j^{DSO^*}}$

$$\min_{p^{der}, p_j^{dso}} \sum_{i \in \mathcal{N}_{der}} c_{i,j}^{der}(p_{i,j}^{der}) - \boxed{\lambda_j^{dso*}} p_j^{dso}$$

$$\text{s.t.} \quad p_j^{dso} = \sum_{i \in \mathcal{N}_{der_k}} p_{i,j}^{der} + \sum_{l \in \mathcal{N}_{f_k}} f_{l,j} - L_{k,j}$$

DSO power balance equation at ISO-DSO coupling point

$$p_{i,j}^{der} \in S_{i,j}^{der}, \forall i \in \mathcal{N}_{der}$$

DER upper/lower limits

$$\boldsymbol{p}_j^{der} \in S_j^D$$

D-level operating constraints for j^{th} DSO (voltage violations, congestions, load balancing)

Optimal DSO decision solved at $\boldsymbol{\lambda_j^{DSO*}}$ =

Optimal retail price (D-LMP, **dual variable**) for each DER: $\boldsymbol{\lambda^{DER^*}} = [\lambda_1^{DER^*}, \ldots, \lambda_j^{DER^*}, \ldots, \lambda_n^{DER^*}]$

T&D Coordination for DER Market Integration

Proposed T&D market coordination (after ISO market clearing):

1. ISO sends the optimal wholesale dispatch and price signals to each DSO (p_j^{DSO*} and λ_j^{DSO*})

2. DSO runs the D-level dispatch model to obtain D-level dispatch signals for all the (aggregated) DERs

3. DSO runs the D-level pricing model to obtain D-level price signals for all the (aggregated) DERs

D-level (dispatch model)

$$c_j^{dso*}\boxed{(p_j^{dso*})} = \min_{\boldsymbol{p}^{der}} \sum_{i \in \mathcal{N}} c_{i,j}^{der}(p_{i,j}^{der})$$

$$\text{s.t.} \quad \boxed{p_j^{dso*}} = \sum_{i \in \mathcal{N}_{der_k}} p_{i,j}^{der} + \sum_{l \in \mathcal{N}_{f_k}} f_{l,j} - L_{k,j}$$

$$p_{i,j}^{der} \in S_{i,j}^{der}, \forall i \in \mathcal{N}_{der}$$

$$\boldsymbol{p}_j^{der} \in S_j^D$$

D-level (pricing model)

$$\min_{\boldsymbol{p}^{der}, p_j^{dso}} \sum_{i \in \mathcal{N}_{der}} c_{i,j}^{der}(p_{i,j}^{der}) - \boxed{\lambda_j^{dso*}} p_j^{dso}$$

$$\text{s.t.} \quad p_j^{dso} = \sum_{i \in \mathcal{N}_{der_k}} p_{i,j}^{der} + \sum_{l \in \mathcal{N}_{f_k}} f_{l,j} - L_{k,j}$$

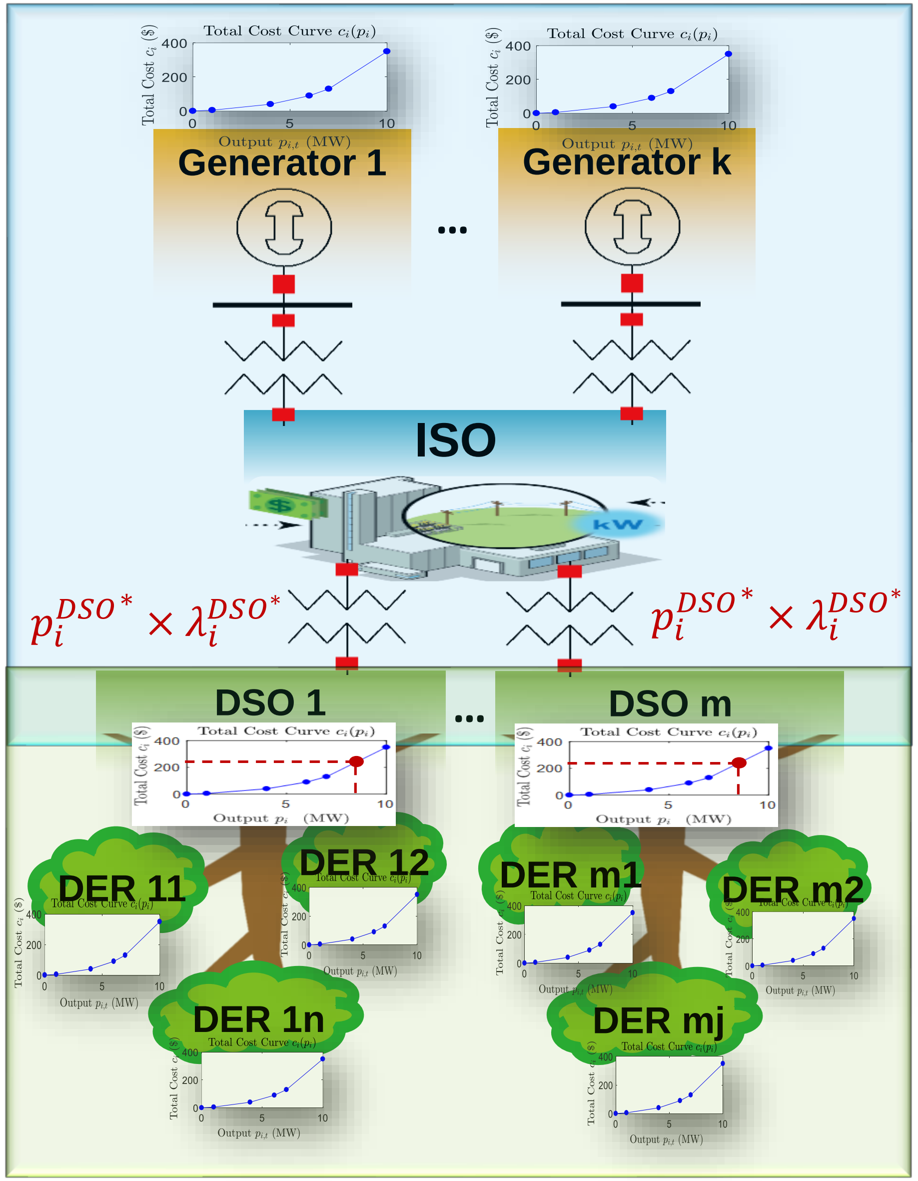
$$p_{i,j}^{der} \in S_{i,j}^{der}, \forall i \in \mathcal{N}_{der}$$

$$\boldsymbol{p}_j^{der} \in S_j^D$$

T&D Coordination for DER Market Integration

Proposed T&D market coordination:

- ISO and DSOs to operate T&D operations separately
  - ✓ Only exchange the minimal amount of public data:
    - ▪ DSO to ISO: DSO's incremental cost curve
    - ▪ ISO to DSO: DSO's wholesale dispatch and price
  - ✓ No change to existing ISO market clearing procedure
  - ✓ No iterative T&D communications
  - ✓ Decomposed T&D market clearing outcomes (including T&D-level dispatches and prices) are identical to the ideal integrated market clearing outcomes.
  - ✓ No T&D-level constraint violations
  - ✓ Minimize T&D-level total generation cost



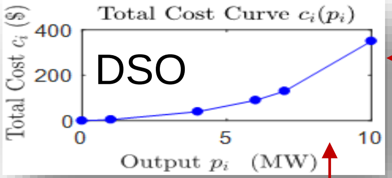
- M. Mousavi, and M. Wu, 'Transmission and Distribution Coordination for DER-rich Energy Markets: A Parametric Programming Approach'. https://arxiv.org/pdf/2306.08258.pdf

T&D Coordination for DER Market Integration

Theoretical justifications for optimal T&D coordination:

Lemma 1. [1] *The optimal bid-in cost function from DSO to ISO, $c_j^{dso}(p_j^{dso})$, is a convex function of parameter p_j^{dso}, if the following conditions are all satisfied: 1) the bid-in cost function submitted by each aggregator $c_{i,j}^{agg}(p_{i,j}^{agg})$ is a convex function; 2) the operating constraints of each DER aggregator define a convex set $S_{i,j}^{agg}$; and 3) the system-wide distribution grid constraints define a convex set S_j^{Dis}.*

DER cost curves submitted to DSO → <u>needs to be convex functions</u>



$$\boxed{c_j^{dso*}(p_j^{dso})} = \min_{p^{der}} \sum_{i\in\mathcal{N}} \boxed{c_{i,j}^{der}(p_{i,j}^{der})}$$

$$\text{s.t.} \quad p_j^{dso} = \sum_{i\in\mathcal{N}_{der_k}} p_{i,j}^{der} + \sum_{l\in\mathcal{N}_{f_k}} f_{l,j} - L_{k,j}$$

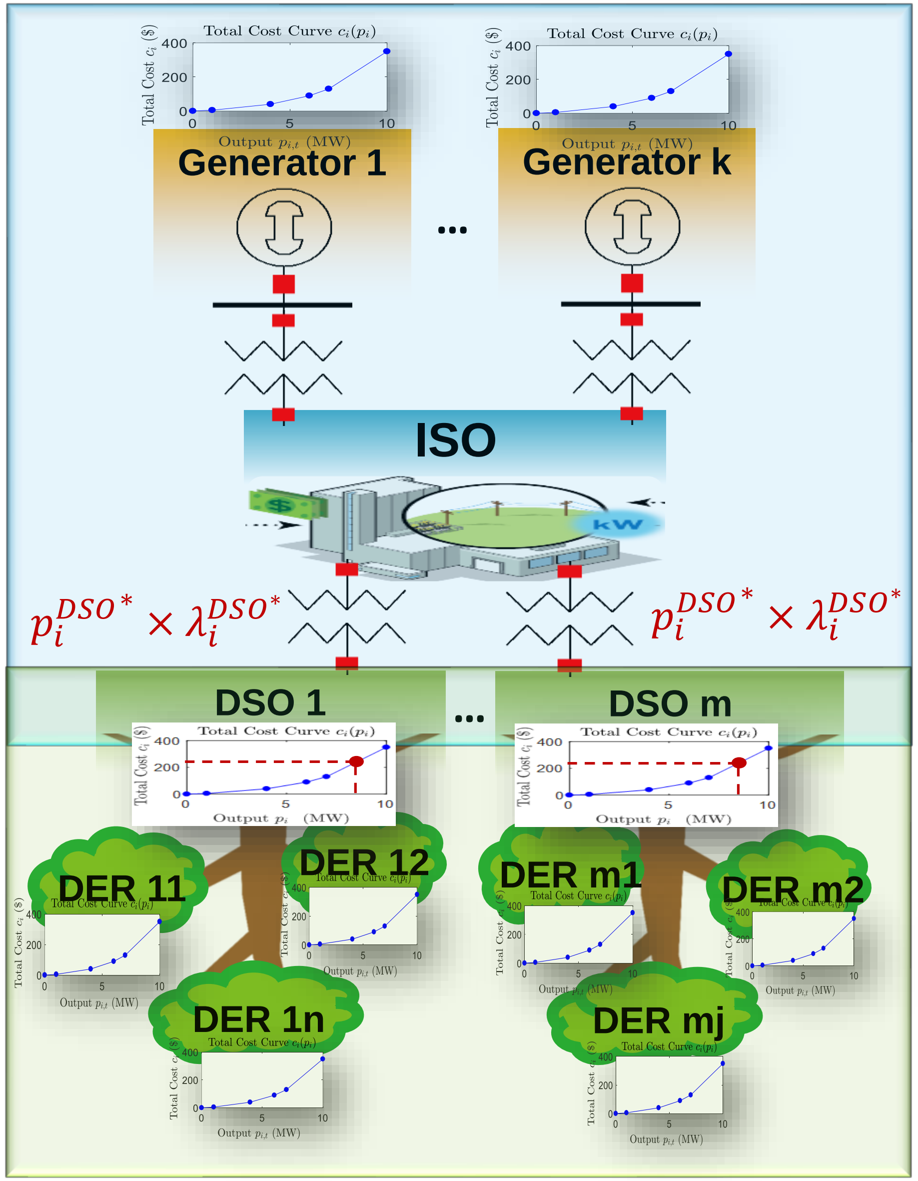
$$p_{i,j}^{der} \in S_{i,j}^{der}, \forall i \in \mathcal{N}_{der}$$

$$p_j^{der} \in S_j^D$$

DSO parametric programming

DSO cost curve submitted to ISO → <u>convex function guaranteed</u>

Feasible region defined by DSO-level constraints → <u>needs to be a convex set</u>



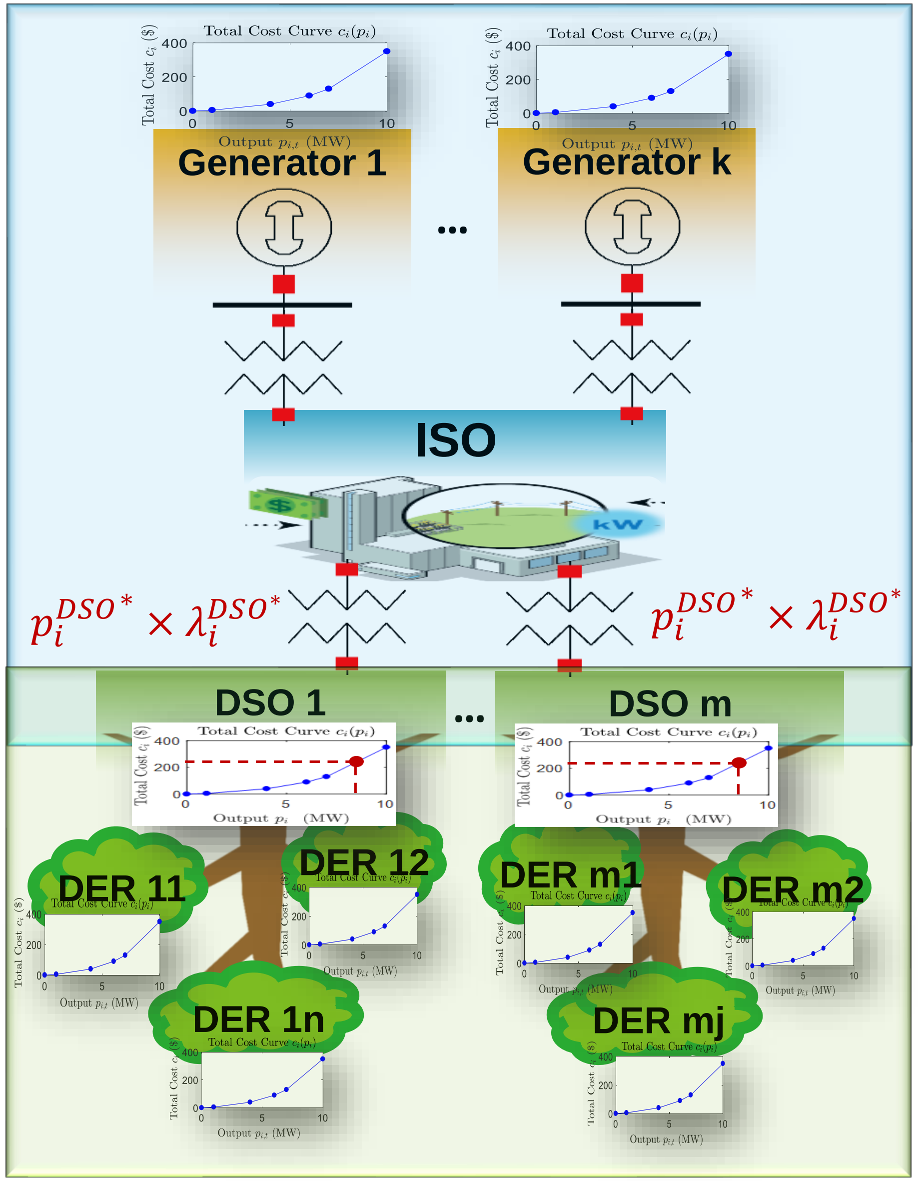
T&D Coordination for DER Market Integration

Theoretical justifications for optimal T&D coordination:

Theorem 1. [1] *The optimal dispatches for all the ISO-level and DSO-level market participants under the ISO-DSO coordination framework in (2)-(3) are identical to those under the ideal case in (1).*

Theorem 2. [1] *The optimal payments and LMPs (or D-LMPs) for all the ISO-level and DSO-level market participants under the ISO-DSO coordination framework in (2)-(4) are identical to those under the ideal case in (1).*

Optimality of T&D coordination: Decomposed T&D market clearing outcomes (including T&D-level dispatches and prices) are identical to the integrated market clearing outcomes of the ideal (but unrealistic) case.

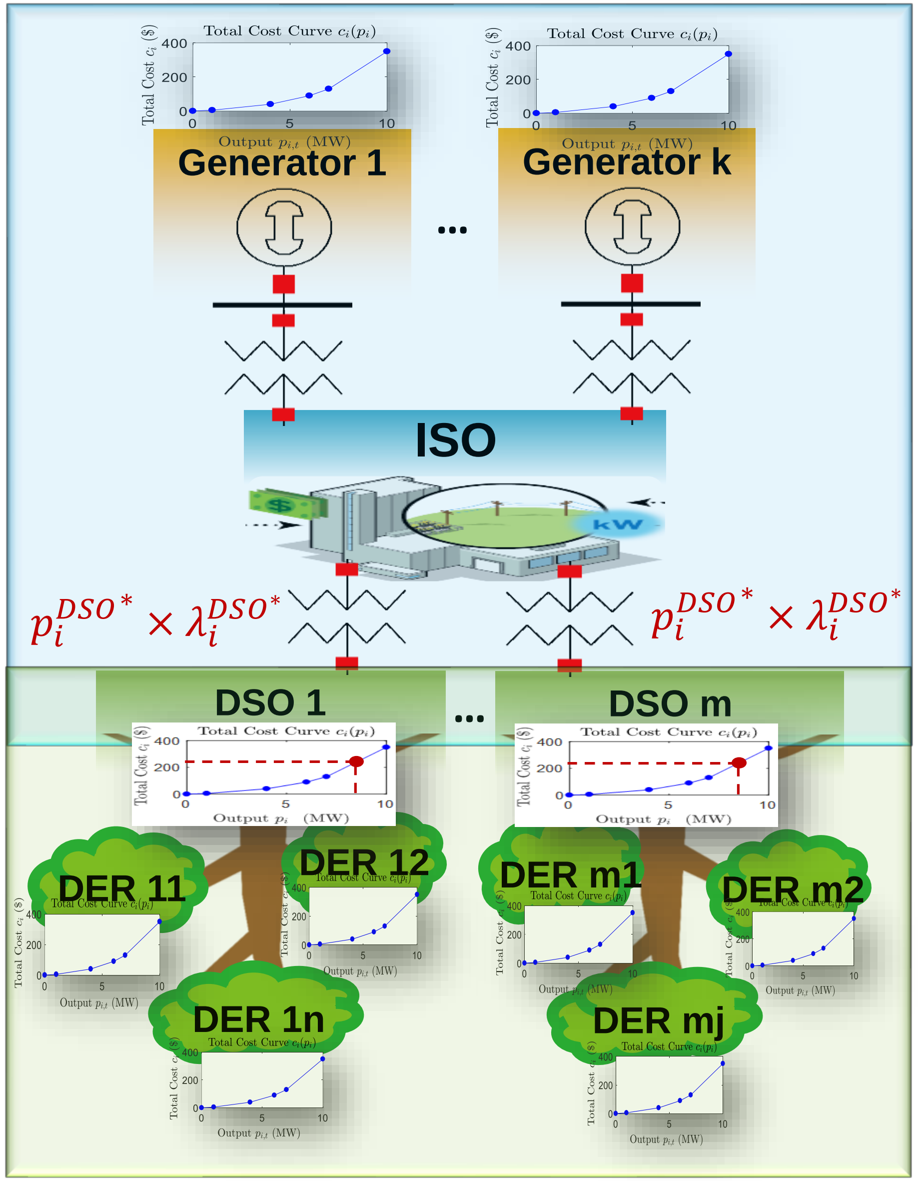


T&D Coordination for DER Market Integration

Theoretical justifications for optimal T&D coordination:

Lemma 1. *The price cleared by the DSO (i.e., the D-LMP) at the ISO-DSO coupling substation node in the distribution system (dual variable corresponding to substation node balance constraint) will always be equal to the price at the same node in the wholesale market cleared by the ISO (LMP_j^*). This equality implies that the DSO is always revenue adequate.*

DSO revenue adequacy: DSO will not lose money by providing T&D coordination



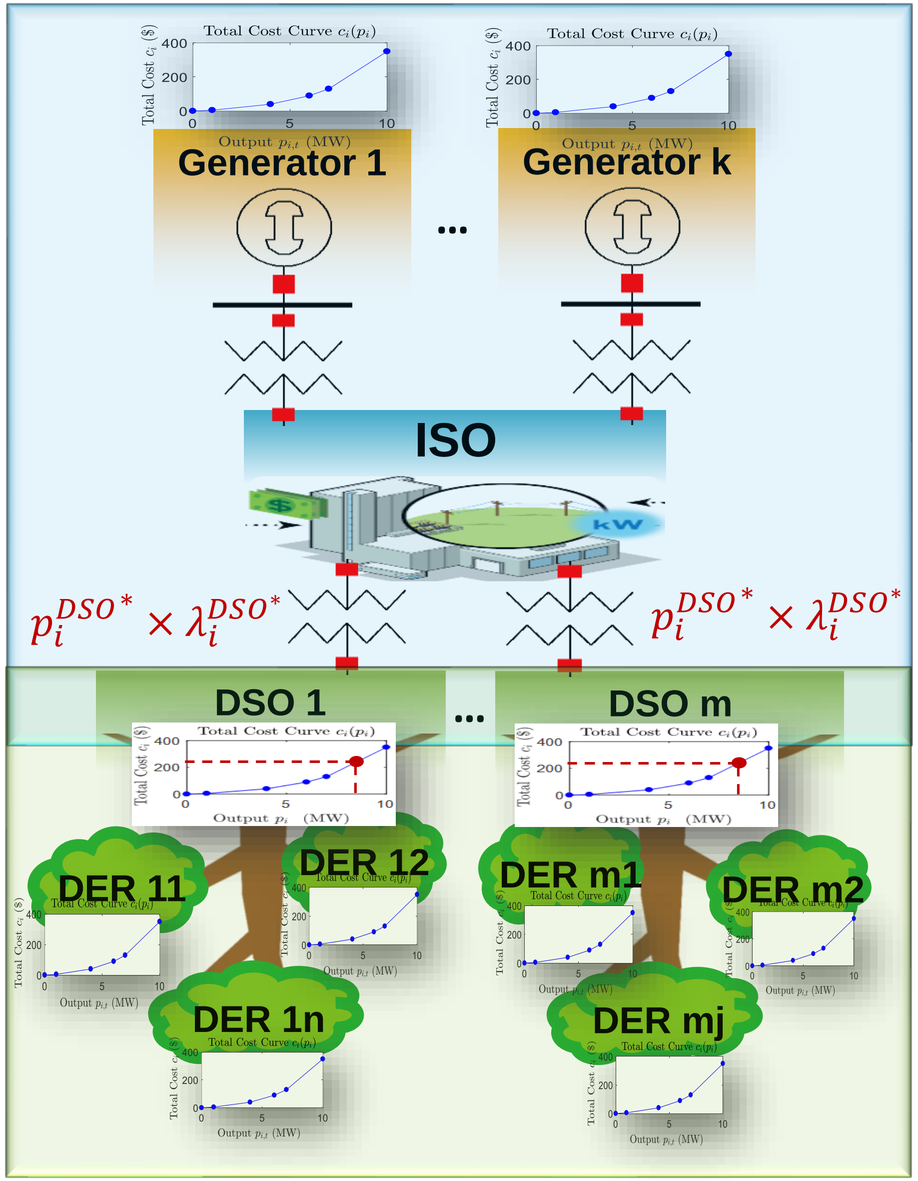
T&D Coordination for DER Market Integration

Theoretical justifications for optimal T&D coordination:

Lemma 2. *If the marginal unit is located within the distribution system, at the ISO-DSO coupling substation, the DSO dispatch problem in (3) results in the same D-LMP as the wholesale LMP determined by the ISO, which is also the same D-LMP determined by the DSO pricing problem in (4). However, if the marginal unit is located in the transmission system, at the ISO-DSO coupling substation, the D-LMP determined by the DSO dispatch problem in (3) could be different from the wholesale LMP determined by the ISO, and also could be different from the D-LMP determined by the DSO pricing problem in (4).*

Separate DSO dispatch and pricing models:

- DSO dispatch model will give correct D-level dispatch signals (but not correct D-level price signals) to DERs



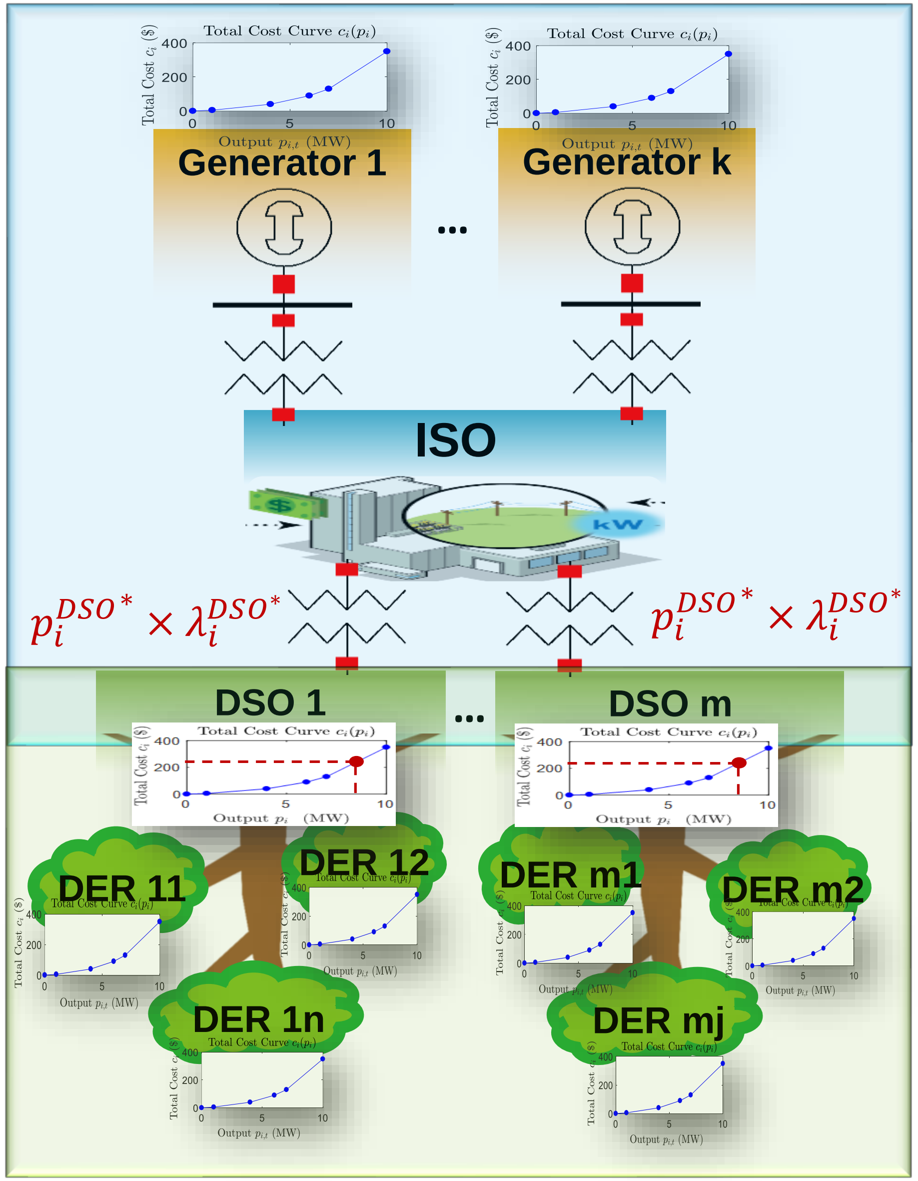
T&D Coordination for DER Market Integration

Theoretical justifications for optimal T&D coordination:

Lemma 3. *If the marginal unit is located in the transmission system, at the ISO-DSO coupling substation, the DSO pricing problem in (4) results in the same dispatch as the wholesale dispatch determined by the ISO problem, which is also the same dispatch determined by the DSO dispatch problem in (3). However, if the marginal unit is located in the distribution system, at the ISO-DSO coupling substation, the dispatch determined by the DSO pricing problem in (4) could be different from the wholesale dispatch determined by the ISO problem, and also could be different from the dispatch determined by the DSO dispatch problem in (3).*

Separate DSO dispatch and pricing models:

- DSO pricing model will give correct D-level price signals (but not correct D-level dispatch signals) to DERs



Case Studies – Small Illustrative Example

Test case description:

- **Case 1:** marginal unit in ISO (DSO firm load L = 15 MW)
- **Case 2:** marginal unit in DSO (DSO firm load L = 11.5 MW)

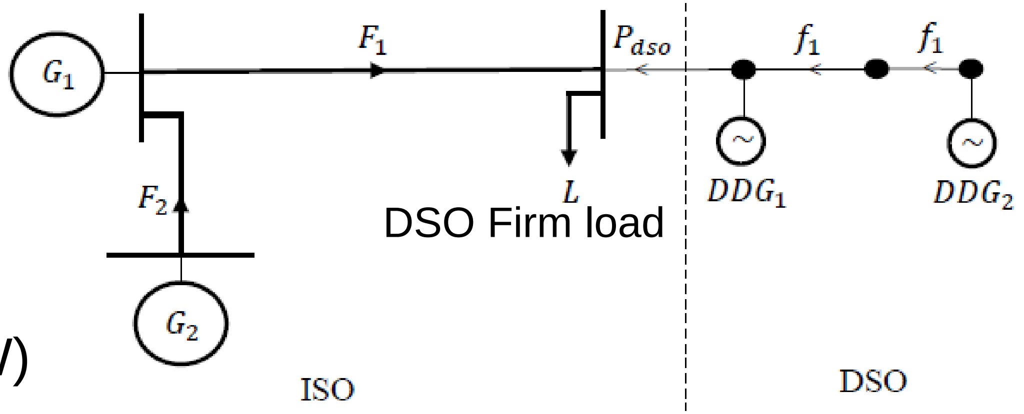


Figure 1. Illustrative example system.

Table 1. Bidding data for the conventional generators and DDGs in the illustrative example: Case 1

Participant	Pmin (MW)	Pmax (MW)	Offering price ($/MWh)
G_1	0	10	10
G_2	0	10	12
DDG_1	0	1	15
DDG_2	0	1	5

Marginal unit (in ISO)

Table 2. Bidding data for the conventional generators and DDGs in the illustrative example: Case 2

Participant	Pmin (MW)	Pmax (MW)	Offering price ($/MWh)
G_1	0	10	10
G_2	0	10	20
DDG_1	0	1	15
DDG_2	0	1	5

Marginal unit (in DSO)

Case Studies – Small Illustrative Example

Ideal (but unrealistic) case:

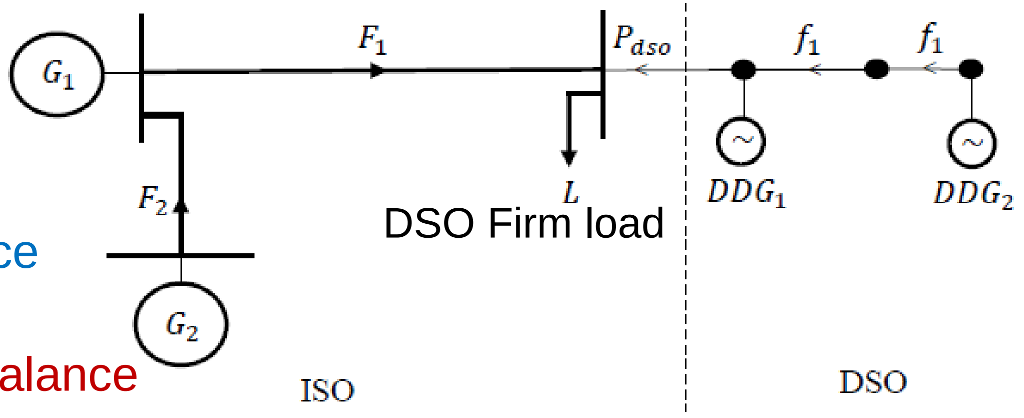


Figure 1. Illustrative example system.

$$\text{Min}_{\boldsymbol{P}} \quad c_1^g p_1^g + c_2^g p_2^g + c_1^{ddg} p_2^{ddg} + c_2^{ddg} p_2^{ddg} \qquad (13a)$$

T&D-level resources

$$s.t. \quad p_1^g - F_1 + F_2 = 0 \qquad [\lambda_1^{WM}] \qquad (13b)$$

$$p_2^g - F_2 = 0 \qquad [\lambda_2^{WM}] \qquad (13c)$$

T-level power balance

$$p^{dso} + F_1 - L = 0 \qquad [\lambda_3^{WM}] \qquad (13d)$$

T&D coupling power balance

$$p_1^{ddg} + f_1 - p^{dso} = 0 \qquad [\lambda_1^D] \qquad (13e)$$

$$f_1 - f_2 = 0 \qquad [\lambda_2^D] \qquad (13f)$$

$$p_2^{ddg} - f_2 = 0 \qquad [\lambda_3^D] \qquad (13g)$$

D-level power balance

$$0 \le p_1^g \le 10 \qquad (13h)$$

$$0 \le p_2^g \le 10 \qquad (13i)$$

T-level resource constraints (generator upper/lower limits)

$$0 \le p_1^{ddg} \le 1 \qquad (13j)$$

$$0 \le p_2^{ddg} \le 1 \qquad (13k)$$

D-level resource constraints (DER upper/lower limits)

$$-20 \le F_1 \le 20 \qquad (13l)$$

$$-20 \le F_2 \le 20 \qquad (13m)$$

T-level line flow constraints

$$-2 \le f_1 \le 2 \qquad (13n)$$

$$-2 \le f_2 \le 2 \qquad (13o)$$

D-level line flow constraints

Case Studies – Small Illustrative Example

T&D coordination case – DSO bidding

$$\boxed{c^{dso}(p^{dso})} = \mathrm{Min}_{\mathbf{p}^{ddg}} \quad 15p_1^{ddg} + 5p_2^{ddg} \qquad (14a)$$

D-level resources

$$\text{s.t.} \quad p_1^{ddg} + f_1 - p^{dso} = 0 \qquad (14b)$$

$$f_1 - f_2 = 0 \qquad (14c)$$

$$p_2^{ddg} - f_2 = 0 \qquad (14d)$$

D-level power balance

$$-2 \le f_1 \le 2 \qquad (14e)$$

$$-2 \le f_2 \le 2 \qquad (14f)$$

D-level line flow constraints

$$0 \le p_1^{ddg} \le 1$$

$$0 \le p_2^{ddg} \le 1$$

D-level resource constraints (DER upper/lower limits)

DSO parametric programming

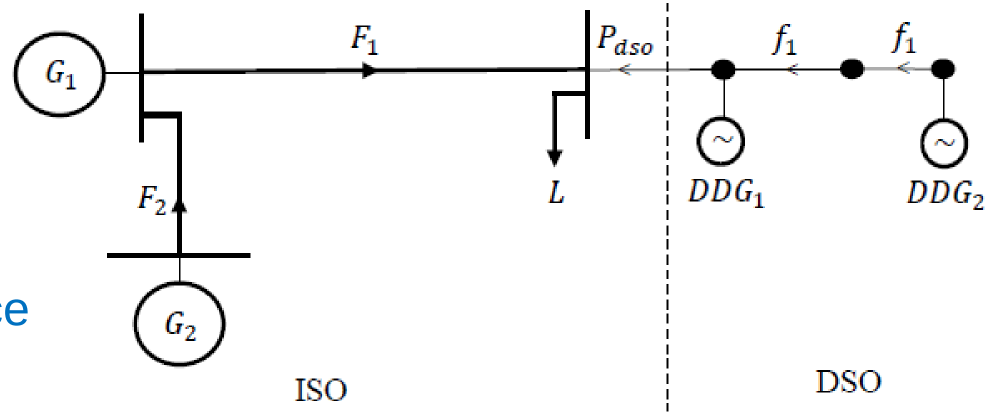
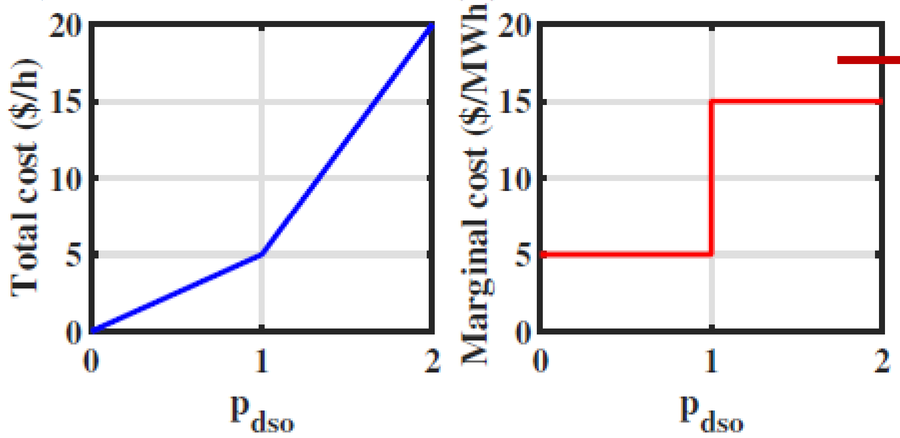


Figure 1. Illustrative example system.



DSO bids To ISO

DSO bid-in total (blue) cost function and marginal (red) cost function for Case 1 and Case 2 (to be submitted to the ISO)

Case Studies – Small Illustrative Example

T&D coordination case – ISO market clearing

$$\text{Min}_{\boldsymbol{P}} \quad c_1^g p_1^g + c_2^g p_2^g + 5p_1^{dso} + 15p_2^{dso} \qquad (15a)$$

T-level generators & DSOs

$$s.t. \quad p_1^g - F_1 + F_2 = 0 \qquad [\lambda_1^{WM}] \qquad (15b)$$

$$p_2^g - F_2 = 0 \qquad [\lambda_2^{WM}] \qquad (15c)$$

T-level power balance

$$p_1^{dso} + p_2^{dso} + F_1 - L = 0 \qquad [\lambda_3^{WM}] \qquad (15d)$$

T&D coupling power balance

$$0 \le p_1^g \le 10 \qquad (15e)$$

$$0 \le p_2^g \le 10 \qquad (15f)$$

T-level resource constraints (generator upper/lower limits)

$$-20 \le F_1 \le 20 \qquad (15g)$$

$$-20 \le F_2 \le 20 \qquad (15h)$$

T-level line flow constraints

$$0 \le p_1^{dso} \le 1 \qquad (15i)$$

$$0 \le p_2^{dso} \le 1 \qquad (15j)$$

T-level resource constraints (DSO upper/lower limits)

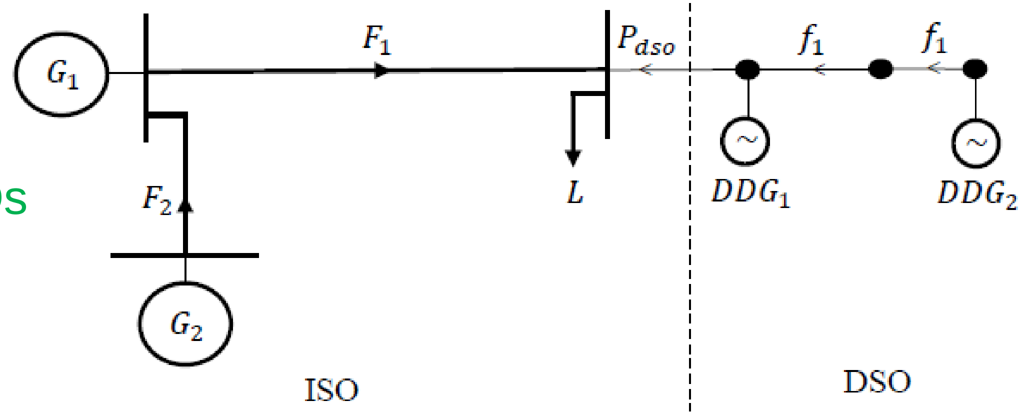


Figure 1. Illustrative example system.

- **Case 1 [marginal unit in ISO]:** $p_1^g = 10MW, p_2^g = 4MW, p_1^{dso} = 1MW, p_2^{dso} = 0MW, ISO\ price = 12\$/MWh$
- **Case 2: [marginal unit in DSO]:** $p_1^g = 10MW, p_2^g = 4MW, p_1^{dso} = 1MW, p_2^{dso} = 0.5MW, ISO\ price = 15\$/MWh$

Case Studies – Small Illustrative Example

T&D coordination case – DSO dispatch

$$\text{Min}_{\boldsymbol{p}^{ddg}} \quad 15p_1^{ddg} + 5p_2^{ddg} \qquad (14a)$$

D-level resources

$$\text{s.t.} \quad p_1^{ddg} + f_1 - \boxed{p^{dso*}} = 0 \qquad (14b)$$

$$f_1 - f_2 = 0 \qquad (14c)$$

$$p_2^{ddg} - f_2 = 0 \qquad (14d)$$

D-level power balance

$$-2 \le f_1 \le 2 \qquad (14e)$$

$$-2 \le f_2 \le 2 \qquad (14f)$$

D-level line flow constraints

$$0 \le p_1^{ddg} \le 1$$

$$0 \le p_2^{ddg} \le 1$$

D-level resource constraints (DER upper/lower limits)

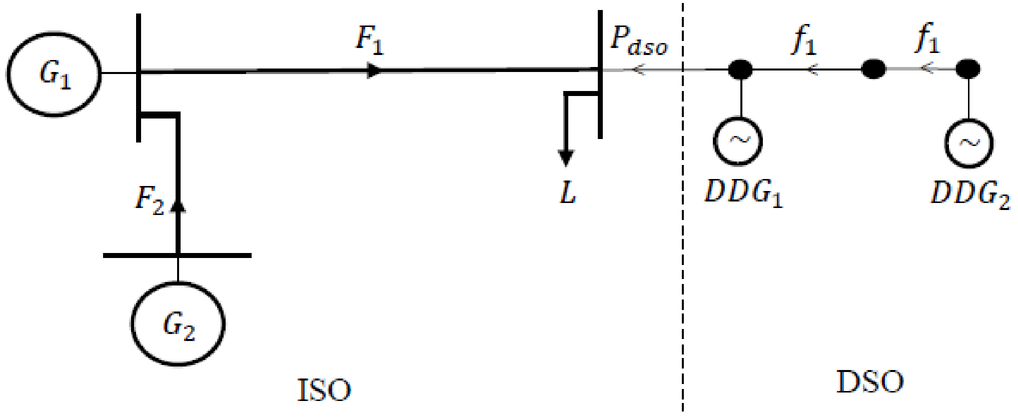


Figure 1. Illustrative example system.

Wholesale dispatch for this DSO (cleared by ISO): 1 MW in Case 1; 1.5 MW in Case 2

- **Case 1 [marginal unit in ISO]:** $p_1^{ddg} = 0MW, p_2^{ddg} = 1MW, DSO\ price = 15\$/MWh$ ✗
- **Case 2: [marginal unit in DSO]:** $p_1^{ddg} = 0.5MW, p_2^{ddg} = 1MW, DSO\ price = 15\$/MWh$ ✓

Case Studies – Small Illustrative Example

T&D coordination case – DSO pricing

$$\text{Min}_{\boldsymbol{P}} \quad 15p_1^{ddg} + 5p_2^{ddg} - \boxed{LMP^*} p^{dso} \qquad (16a)$$

D-level resources

$$\text{s.t.} \quad p_1^{ddg} + f_1 - p^{dso} = 0 \qquad (16b)$$

$$f_1 - f_2 = 0 \qquad (16c)$$

$$p_2^{ddg} - f_2 = 0 \qquad (16d)$$

D-level power balance

$$-2 \le f_1 \le 2 \qquad (16e)$$

$$-2 \le f_2 \le 2 \qquad (16f)$$

D-level line flow constraints

$$0 \le p_1^{ddg} \le 1$$

$$0 \le p_2^{ddg} \le 1$$

D-level resource constraints (DER upper/lower limits)

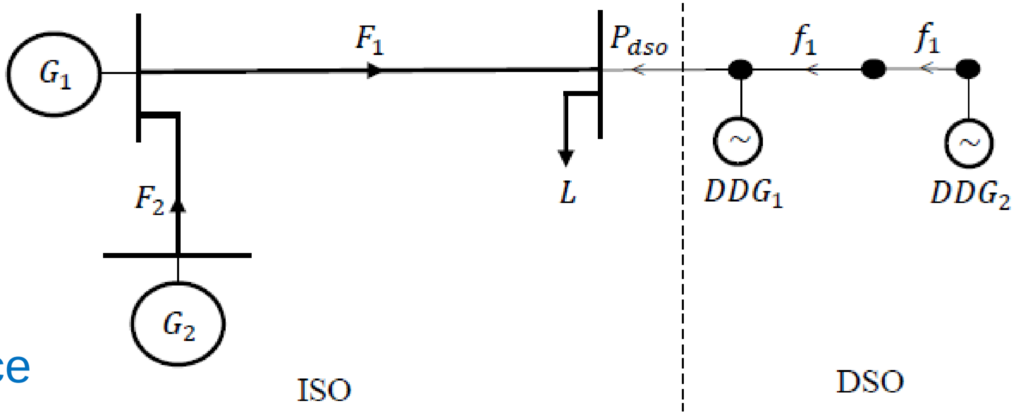


Figure 1. Illustrative example system.

Wholesale price for this DSO (cleared by ISO): 12 $/MWh in Case 1; 15 $/MWh in Case 2

- **Case 1 [marginal unit in ISO]:** $DSO\ price = 12\$/MWh, p_1^{ddg} = 0MW, p_2^{ddg} = 1MW,\ p^{dso} = 1MW$
- **Case 2: [marginal unit in DSO]:** $DSO\ price = 15\$/MWh,\ p_1^{ddg} \in [0,1]MW, p_2^{ddg} = 1MW, p^{dso} \in [1,2]MW$, degeneracy

Case Studies – Large Test Case

Test case description:

- **1 ISO connected with 2 DSOs (balanced + unbalanced)**
- **ISO**: IEEE-118 bus transmission system
- **DSO 1:** 33-node balanced distribution system, with 1 demand response aggregator (DRAG), 4 dispatchable distributed generation aggregators (DDGAGs), 2 renewable energy aggregators (REAGs)
- **DSO 2**: 240-node unbalanced distribution system, with 10 DRAGs, 10 DDGAGS, 4 REAGs

TABLE I
DSO MARKET PARTICIPANTS DATA FOR THE 33-NODE TEST SYSTEM

Participant	Pmin (MW)	Pmax (MW)	Offering price ($/MWh)
DDGAG 1	0	0.5	20
DDGAG 2	0	1	10
DDGAG 3	0	1.2	15
DDGAG 4	0	2	24
DRAG	0	2	28

TABLE III
DSO MARKET PARTICIPANTS INFORMATION FOR 240-NODE TEST SYSTEM

Participant	Capacity (MW)	Price ($/MWh)	Participant	Capacity (MW)	Price ($/MWh)
DDGAG 1	0.25 A	20	DRAG 1	0.15 A	28
DDGAG 2	0.25 A	10	DRAG 2	0.15 A	29
DDGAG 3	0.25 B	15	DRAG 3	0.15 B	30
DDGAG 4	0.25 B	24	DRAG 4	0.15 B	27
DDGAG 5	0.25 C	14	DRAG 5	0.15 C	26
DDGAG 6	0.25 C	15	DRAG 6	0.15 C	25
DDGAG 7	0.25 A	16	DRAG 7	0.15 A	24
DDGAG 8	0.25 B	17	DRAG 8	0.15 B	22
DDGAG 9	0.25 C	18	DRAG 9	0.15 C	22
DDGAG 10	0.25 A	19	DRAG 10	0.15 A	23

Case Studies – Large Test Case

- **Bids submitted by DSO 1 – 33 node balanced distribution system:**

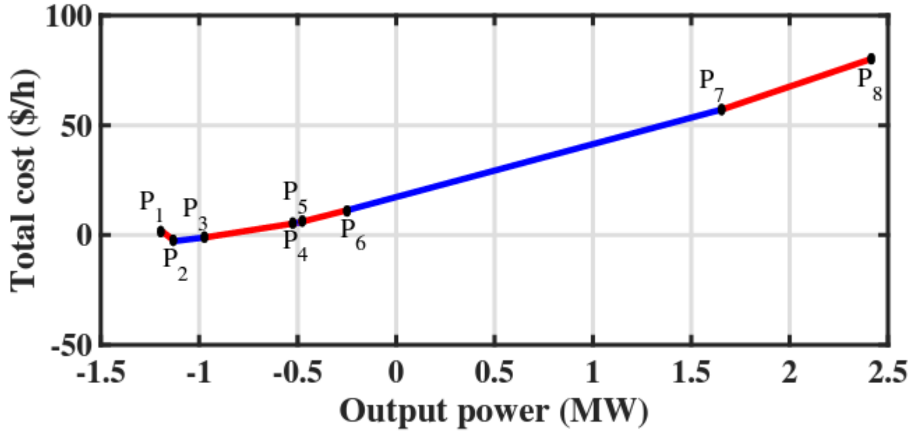


Fig. 5. Total cost function of the 33 node test system.

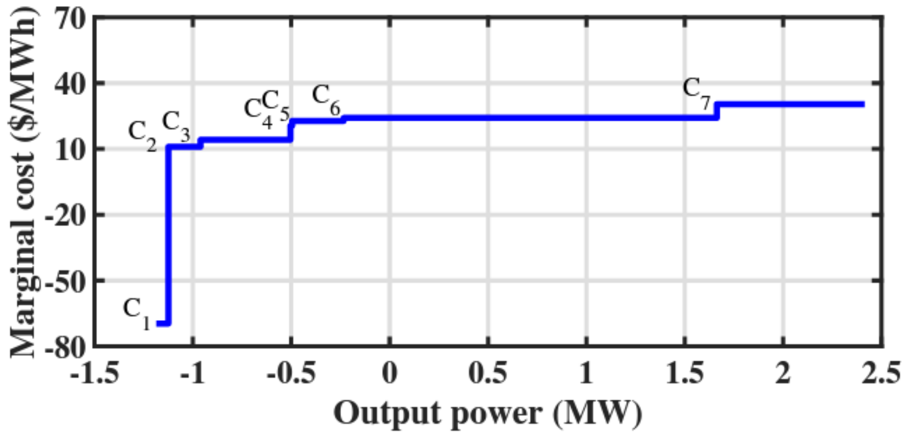


Fig. 6. Bid-in marginal cost function of the 33 node test system.

TABLE II

33-NODE TEST SYSTEM BREAKPOINTS AND MARGINAL COSTS DATA

Breakpoint index	Breakpoint coordinate value (MW,$/h)	Marginal cost index	Marginal cost value ($/MWh)
P_1	(-1.18654,1.54166)	C_1	-69.6072
P_2	(-1.12498, -2.74336)	C_2	10.9555
P_3	(-0.961451, -0.951813)	C_3	14.1388
P_4	(-0.504623, 5.50717)	C_4	20.5587
P_5	(-0.495727, 5.69006)	C_5	22.8007
P_6	(-0.233645, 11.6657)	C_6	24.1164
P_7	(1.66269, 57.3985)	C_7	30.3739
P_8	(2.4175, 80.325)		

Case Studies – Large Test Case

Bids submitted by DSO 2 – 240 node unbalanced distribution system:

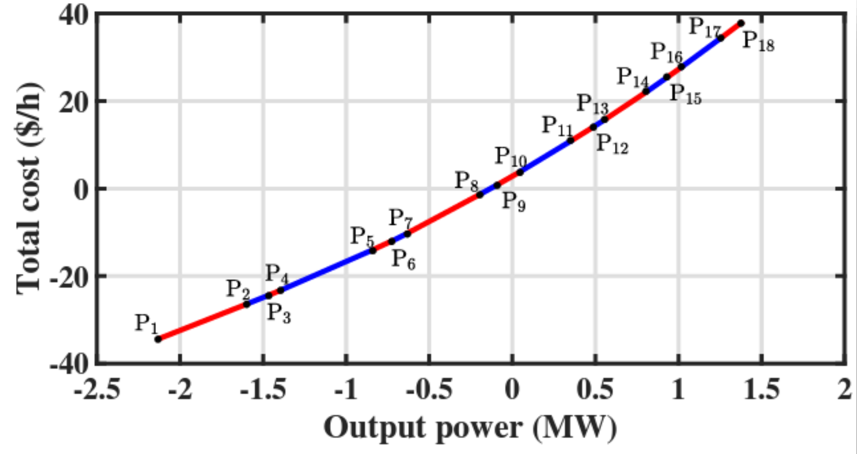


Fig. 7. Total cost function of the 240 node test system.

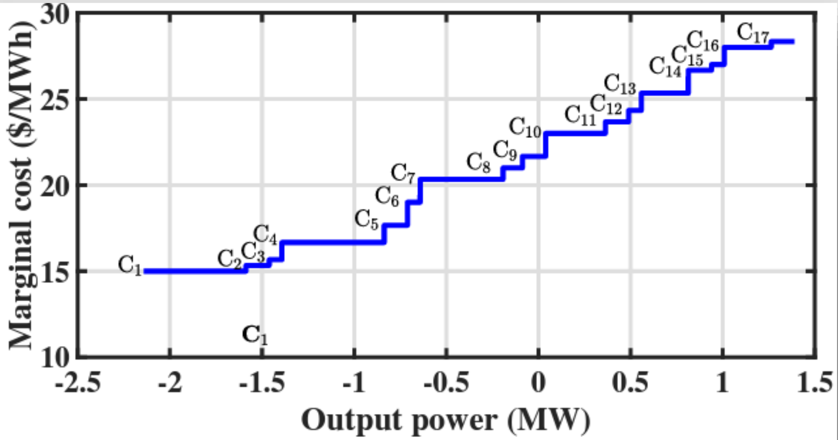


Fig. 8. Bid in marginal cost function of the 240 node test system.

TABLE IV
240 NODE BREAKPOINTS AND MARGINAL COSTS DATA

Breakpoint index	Breakpoint coordinate value (MW,$/h)	Marginal cost index	Marginal cost value ($/MWh)
P_1	(-2.142,-34.538)	C_1	15
P_2	(-1.587, -26.213)	C_2	15.333
P_3	(-1.461, -24.281)	C_3	15.667
P_4	(-1.392, -23.2)	C_4	16.667
P_5	(-0.837, -13.95)	C_5	17.667
P_6	(-0.711, -11.724)	C_6	19
P_7	(-0.642, -10.413)	C_7	20.333
P_8	(-0.192,-1.263)	C_8	21
P_9	(-0.087, 0.942)	C_9	21.667
P_{10}	(0.039, 3.672)	C_{10}	23
P_{11}	(0.363, 11.124)	C_{11}	23.667
P_{12}	(0.489, 14.106)	C_{12}	24.333
P_{13}	(0.558, 15.785)	C_{13}	25.333
P_{14}	(0.813, 22.245)	C_{14}	26.667
P_{15}	(.939,25.605)	C_{15}	27
P_{16}	(1.008, 27.468)	C_{16}	28
P_{17}	(1.263, 34.608)	C_{17}	28.333
P_{18}	(1.389, 38.178)		

Case Studies – Large Test Case

T&D-level optimal dispatches & prices (identical in ideal case and T&D coordination case):

TABLE V
IDEAL CASE AND ISO-DSO COORDINATION CASE DISPATCH

Total wholesale market generators' dispatch			
6601.1 MW			
33 node test system dispatches			
Participant	Dispatch (MW)	Participant	Dispatch (MW)
DDGAG 1	0	DDGAG 3	1.2
DDGAG 2	0.7102	DDGAG 4	0
DRAG	0.6998		
240 node test system dispatches			
Participant	Dispatch (MW)	Participant	Dispatch (MW)
DDGAG 1	0.065 A	DRAG 1	0.15 A
DDGAG 2	0.25 A	DRAG 2	0.15 A
DDGAG 3	0.25 B	DRAG 3	0.15 B
DDGAG 4	0 B	DRAG 4	0.15 B
DDGAG 5	0.25 C	DRAG 5	0.15 C
DDGAG 6	0.25 C	DRAG 6	0.15 C
DDGAG 7	0.25 A	DRAG 7	0.15 A
DDGAG 8	0.25 A	DRAG 8	0.15 A
DDGAG 9	0.25 B	DRAG 9	0.15 B
DDGAG 10	0.023 C	DRAG 10	0.15 C

- Wholesale LMP = 20.24 \$/MWh (no transmission-level congestion)
- Distribution LMP at ISO-DSO coupling point for 33-node balanced distribution system = 20.24 \$/MWh
- Distribution LMP at ISO-DSO coupling point for 240-node unbalanced distribution system = 20 \$/MWh (for Phase A), 21.71 \$/MWh (for Phase B), 19 \$/MWh (for Phase C) → Average distribution LMP for three phases = 20.24 \$/MWh

Conclusions

Optimal T&D coordination for DER Market Participation

- T&D operation are coordinated with minimal T&D communications and data exchange
- For data ownership and model confidentiality: no exchange of T&D system models
- For smooth transition from today's established ISO markets, no change to ISO's existing market clearing procedure
- Guarantee optimal T&D operation while satisfying all the operating constraints for the entire T&D systems
- Extendable to 3-phase unbalanced DSOs

Future Work

Optimal T&D coordination for DER Market Participation

- Fast algorithms for solving the parametric-programming-based DSO bidding problem
- Multi-interval market clearing

Transmission and Distribution (T&D) Coordination for DER Market Participation

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