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

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Challenges & Opportunities: FERC Order 2222

**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

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.
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

**Ideal case for T&D co-operation:**

- **A single entity** can fully model, observe, and dispatch resources and networks in both T&D systems →
- **Optimal** 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
- **Unrealistic** → Currently no single entity can oversee both T&D systems
Ideal Case: T&D Coordination

**Ideal case for T&D co-operation (optimal but unrealistic):**

- Minimize total generation cost (generators & DERs)
- Total generation cost curve submitted by $i^{th}$ generator or DER

**Objective:**

$$\min_{\mathbf{p}} \left( \sum_{k \in \mathcal{N}_{\text{gen}}} c_{\text{gen}}^k \left( \mathbf{p}_{\text{gen}}^k \right) + \sum_{j \in \mathcal{N}_D} \sum_{i \in \mathcal{N}_{\text{der}}} c_{\text{der}}^{i,j} \left( \mathbf{p}_{\text{der}}^{i,j} \right) \right)$$

**Constraints:**

- **T-level** operating constraints (load balancing, congestion, etc.):
  $$\mathbf{p}_{\text{gen}}^{\text{gen}} \in S^T$$
- **D-level** operating constraints for each DSO (load balancing, congestion, voltage, etc.):
  $$\mathbf{p}_{\text{der}}^{i} \in S_{i,j}^{\text{D}}, \forall j \in \mathcal{N}_D$$
  $$\mathbf{p}_{\text{gen}}^{k} \in S_{k}^{\text{gen}}, \forall k \in \mathcal{N}_{\text{gen}}$$
  $$\mathbf{p}_{\text{der}}^{i,j} \in S_{i,j}^{\text{der}}, \forall i \in \mathcal{N}_{\text{der}}, j \in \mathcal{N}_D$$

**Optimal Decisions:**

Generator & DER dispatch outputs $\mathbf{p}$ (MW), locational marginal prices ($/\text{MWh}$)
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
Ideal Case Decomposition: Transmission-level

**Ideal case decomposition: T-level**

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

\[
\min \sum_{k \in N_{gen}} c_k^{gen}(p_k^{gen}) + \sum_{j \in N_D} c_{dso,j}(p_{dso,j})
\]

\[\text{s.t. } p_k^{gen} \in S^T_k, \forall k \in N_{gen} \]
\[p_j^{dso} \in S^D_j, \forall j \in N_D \]
\[p_k^{gen} \in S^{gen}_k, \forall k \in N_{gen} \]
\[p_j^{dso} \in S^{dso}_j, \forall j \in N_D \]

- Minimize total generation cost (generators & DERs) DSOs
- T-level operating constraints (load balancing, congestion, etc.)
- D-level operating constraints for each DSO (load balancing, congestion, voltage, etc.)
- Generator upper/lower limits
- DER upper/lower limits
- DSO

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

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

Minimnal total generation costs of all DERs

$$c_{i}^{DSO} = \min_{p^{der}} \sum_{i \in N} c_{i,j}^{der}(p_{i,j}^{der})$$

S.t.

$$p_{i,j}^{DSO} = \sum_{i \in N_{der}} p_{i,j}^{der} = \sum_{i \in N_{j}} f_{i,j} - L_{k,j}$$

DSO power balance equation at ISO-DSO coupling point

DER upper/lower limits

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

The true/lowest cost $c_{i}^{DSO*} ($) of generating $p_{i}^{DSO}$ (MW) of real power from DSO 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

DSO cost curve submitted 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

Minimnal total generation costs of all DERs

$$c_{i}^{DSO} = \min_{p^{der}} \sum_{i \in N} c_{i,j}^{der}(p_{i,j}^{der})$$

S.t.

$$p_{i,j}^{DSO} = \sum_{i \in N_{der}} p_{i,j}^{der} = \sum_{i \in N_{j}} f_{i,j} - L_{k,j}$$

DSO power balance equation at ISO-DSO coupling point

DER upper/lower limits

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

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

Each point $(p_{i}^{DSO}, c_{i}^{DSO*})$ on this curve:
Proposed T&D market coordination (before ISO market clearing):

1. DSO collects incremental cost curve from each (aggregated) DER, $d_{i,j}^{DER}(p_{i,j}^{DER})$

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)

4. DSO converts the DSO’s total generation cost curve $c_{i}^{DSO}(p_{i}^{DSO})$ to the DSO’s incremental generation cost curve $d_{i}^{DSO}(p_{i}^{DSO})$

5. DSO submits the DSO’s incremental generation cost curve $d_{i}^{DSO}(p_{i}^{DSO})$ to ISO
Proposed T&D market coordination (after ISO market clearing):

1. ISO clears the wholesale market and sends out each DSO’s wholesale dispatch signal \( p_{iDSO}^* \) (MW), wholesale locational marginal price (LMP) \( \pi_{iDSO}^* \) ($/MWh) \rightarrow total wholesale payment to DSO = \( p_{iDSO}^* \times \lambda_{iDSO}^* \) ($)

2. DSO re-dispatches the wholesale dispatch signal \( p_{jDSO}^* \) and wholesale payment \( p_{jDSO}^* \times \lambda_{jDSO}^* \) to obtain the retail dispatch signal \( p_{jDER}^* \) and retail LMP \( \lambda_{jDER}^* \) for each DER

Decomposed T-level & D-level dispatch and pricing \rightarrow 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 - $p_j^{DSO^*}$

Optimal DSO decision solved at $p_j^{DSO^*} = p_j^{DSO}$:

Optimal retail dispatch signal for each DER:
- $p_{DER^*} = [p_1^{DER^*}, ..., p_j^{DER^*}, ..., p_n^{DER^*}]$

**Data exchange from ISO to DSO (after ISO market clearing):**
- Optimal wholesale dispatch for $j^{th}$ DSO - $p_j^{DSO^*}$

**Optimal DSO decision solved at $p_j^{DSO^*} = p_j^{DSO}$:**

- $p_{DER^*} = [p_1^{DER^*}, ..., p_j^{DER^*}, ..., p_n^{DER^*}]$

**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

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

- **Optimal DSO power balance equation at ISO-DSO coupling point**

- **DER upper/lower limits**

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

\[
\begin{align*}
\min_{p^{der}, p^{dso}_j} & \sum_{i \in \mathcal{N}_{der}} c_{i,j}^{der} (p_{i,j}^{der}) - \lambda_j^{dso^*} p^{dso}_j \\
\text{s.t.} & \quad p^{dso}_j = \sum_{i \in \mathcal{N}_{der}} p_{i,j}^{der} + \sum_{l \in \mathcal{N}_{f_k}} f_{l,j} - L_{k,j} \\
& \quad p_{i,j}^{der} \in S_{i,j}^{der}, \forall i \in \mathcal{N}_{der} \quad \text{DER upper/lower limits} \\
& \quad p_j^{dso} \in S_j^D \quad \text{D-level operating constraints for } j^{th} \text{ DSO} \\
& \quad (\text{voltage violations, congestions, load balancing})
\end{align*}
\]

DSO power balance equation at ISO-DSO coupling point

Optimal DSO decision solved at \( \lambda_j^{DSO^*} = \)

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

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
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

Theoretical justifications for optimal T&D coordination:

**Lemma 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 $\rightarrow$ needs to be convex functions

DSO cost curve submitted to ISO $\rightarrow$ convex function guaranteed

DSO parametric programming

Feasible region defined by DSO-level constraints $\rightarrow$ needs to be a convex set
**Theoretical justifications for optimal T&D coordination:**

**Theorem 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.** 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.
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*). This equality implies that the DSO is always revenue adequate.

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

![Diagram of illustrative example system]

**Figure 1. Illustrative example system.**

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

<table>
<thead>
<tr>
<th>Participant</th>
<th>( P_{\text{min}} ) (MW)</th>
<th>( P_{\text{max}} ) (MW)</th>
<th>Offering price ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_1 )</td>
<td>0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>( G_2 )</td>
<td>0</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>( DDG_1 )</td>
<td>0</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>( DDG_2 )</td>
<td>0</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

**Marginal unit (in ISO)**

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

<table>
<thead>
<tr>
<th>Participant</th>
<th>( P_{\text{min}} ) (MW)</th>
<th>( P_{\text{max}} ) (MW)</th>
<th>Offering price ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_1 )</td>
<td>0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>( G_2 )</td>
<td>0</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>( DDG_1 )</td>
<td>0</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>( DDG_2 )</td>
<td>0</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

**Marginal unit (in DSO)**
Case Studies – Small Illustrative Example

**Ideal (but unrealistic) case:**

\[
\text{Min}_P \quad c_1 p_1^g + c_2 p_2^g + c_1^{ddg} p_1^{ddg} + c_2^{ddg} p_2^{ddg}
\]

\[\text{s.t.} \quad p_1^g - F_1 + F_2 = 0 \quad \left[\lambda_1^{WM}\right] \tag{13a}\]

\[p_2^g - F_2 = 0 \quad \left[\lambda_2^{WM}\right] \tag{13b}\]

\[p_1^{ddg} + F_1 - L = 0 \quad \left[\lambda_3^{WM}\right] \tag{13c}\]

\[p_2^{ddg} - f_1 - p_1^{ddg} = 0 \quad \left[\lambda_1^{DP}\right] \tag{13d}\]

\[f_1 - f_2 = 0 \quad \left[\lambda_2^{DP}\right] \tag{13e}\]

\[p_2^{ddg} - f_2 = 0 \quad \left[\lambda_2^{DP}\right] \tag{13f}\]

\[0 \leq p_1^g \leq 10 \tag{13g}\]

\[0 \leq p_2^g \leq 10 \tag{13h}\]

\[0 \leq p_1^{ddg} \leq 1 \tag{13i}\]

\[0 \leq p_2^{ddg} \leq 1 \tag{13j}\]

\[-20 \leq F_1 \leq 20 \tag{13k}\]

\[-20 \leq F_2 \leq 20 \tag{13l}\]

\[-2 \leq f_1 \leq 2 \tag{13m}\]

\[-2 \leq f_2 \leq 2 \tag{13n}\]

- **T&D-level resources**
- **T-level power balance**
- **T&D coupling power balance**
- **D-level power balance**
- **T-level resource constraints (generator upper/lower limits)**
- **D-level resource constraints (DER upper/lower limits)**
- **T-level line flow constraints**
- **D-level line flow constraints**

**Figure 1. Illustrative example system.**
Case Studies – Small Illustrative Example

T&D coordination case – DSO bidding

\[
\begin{align*}
\text{Min}_{p_{\text{dso}}} & \quad 15p_1^{\text{ddg}} + 5p_2^{\text{ddg}} \\
\text{s.t.} & \quad p_1^{\text{ddg}} + f_1 - p_{\text{dso}}^{\text{dso}} = 0 \\
& \quad f_1 - f_2 = 0 \\
& \quad p_2^{\text{ddg}} - f_2 = 0 \\
& \quad -2 \leq f_1 \leq 2 \\
& \quad -2 \leq f_2 \leq 2 \\
& \quad 0 \leq p_1^{\text{ddg}} \leq 1 \\
& \quad 0 \leq p_2^{\text{ddg}} \leq 1
\end{align*}
\]

- **D-level resources**
- **D-level power balance**
- **D-level line flow constraints**
- **D-level resource constraints (DER upper/lower limits)**

DSO parametric programming

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

\[
\begin{align*}
\text{Min}_P & \quad c_1^g p_1^g + c_2^g p_2^g + 5 p_1^{ds} + 15 p_2^{ds} \\
\text{s.t.} & \quad p_1^g - F_1 + F_2 = 0 \\
& \quad p_2^g - F_2 = 0 \\
& \quad p_1^{ds} + p_2^{ds} + F_1 - L = 0 \\
0 & \leq p_1^g \leq 10 \\
0 & \leq p_2^g \leq 10 \\
-20 & \leq F_1 \leq 20 \\
-20 & \leq F_2 \leq 20 \\
0 & \leq p_1^{ds} \leq 1 \\
0 & \leq p_2^{ds} \leq 1
\end{align*}
\]

(15a) \( T \)-level generators & DSOs
(15b) \( T \)-level power balance
(15c) \( T \)-level power balance
(15d) \( T \)-level resource constraints (generator upper/lower limits)
(15e) \( T \)-level resource constraints (DSO upper/lower limits)
(15f) \( T \)-level line flow constraints
(15g)
(15h)
(15i)
(15j)

Case 1 [marginal unit in ISO]: \( p_1^g = 10 \text{MW}, p_2^g = 4 \text{MW}, p_1^{ds} = 1 \text{MW}, p_2^{ds} = 0 \text{MW}, \text{ISO price} = 12\$/\text{MWh} \)

Case 2: [marginal unit in DSO]: \( p_1^g = 10 \text{MW}, p_2^g = 4 \text{MW}, p_1^{ds} = 1 \text{MW}, p_2^{ds} = 0.5 \text{MW}, \text{ISO price} = 15\$/\text{MWh} \)
Case Studies – Small Illustrative Example

T&D coordination case – DSO dispatch

\[ \text{Min}_{p_{ddg}} \quad 15p_{1}^{ddg} + 5p_{2}^{ddg} \]  \hspace{1cm} (14a)

s.t. \hspace{1cm} \begin{align*}
    p_{1}^{ddg} + f_{1} - p_{dso}^{*} &= 0 \quad \text{(14b)} \\
    f_{1} - f_{2} &= 0 \quad \text{(14c)} \\
    p_{2}^{ddg} - f_{2} &= 0 \quad \text{(14d)} \\
    -2 &\leq f_{1} \leq 2 \quad \text{(14e)} \\
    -2 &\leq f_{2} \leq 2 \quad \text{(14f)} \\
    0 &\leq p_{1}^{ddg} \leq 1 \\
    0 &\leq p_{2}^{ddg} \leq 1
\end{align*} 

D-level resources

D-level power balance

D-level line flow constraints

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

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]: \( p_{1}^{ddg} = 0 \text{MW}, p_{2}^{ddg} = 1 \text{MW}, DSO \text{ price} = 15\$/\text{MWh} \) \( \times \)

- Case 2: [marginal unit in DSO]: \( p_{1}^{ddg} = 0.5 \text{MW}, p_{2}^{ddg} = 1 \text{MW}, DSO \text{ price} = 15\$/\text{MWh} \) \( \checkmark \)
Case Studies – Small Illustrative Example

T&D coordination case – DSO pricing

\[
\begin{align*}
\text{Min}_P & \quad 15p_1^{ddg} + 5p_2^{ddg} - LMP^* p^{dso} \\
\text{s.t.} & \quad p_1^{ddg} + f_1 - p^{dso} = 0 \\
& \quad f_1 - f_2 = 0 \\
& \quad p_2^{ddg} - f_2 = 0 \\
& \quad -2 \leq f_1 \leq 2 \\
& \quad -2 \leq f_2 \leq 2 \\
& \quad 0 \leq p_1^{ddg} \leq 1 \\
& \quad 0 \leq p_2^{ddg} \leq 1 \\
\end{align*}
\]

D-level resources

D-level power balance

D-level line flow constraints

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

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, \( p_1^{ddg} = 0 \text{MW}, p_2^{ddg} = 1 \text{MW}, p^{dso} = 1 \text{MW} \)

- Case 2: [marginal unit in DSO]: DSO price = 15$/MWh, \( p_1^{ddg} \in [0,1] \text{MW}, p_2^{ddg} = 1 \text{MW}, p^{dso} \in [1,2] \text{MW} \), 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
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.
Case Studies – Large Test Case

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

![Graph showing total cost function for the 240 node test system.](image1)

![Graph showing bid in marginal cost function for the 240 node test system.](image2)

**TABLE IV**

240 NODE BREAKPOINTS AND MARGINAL COSTS DATA

<table>
<thead>
<tr>
<th>Breakpoint index</th>
<th>Breakpoint coordinate value (MW,$/h)</th>
<th>Marginal cost index</th>
<th>Marginal cost value ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₁</td>
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<td>P₂</td>
<td>(-1.587, -26.213)</td>
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<tr>
<td>P₇</td>
<td>(-0.642, -10.413)</td>
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<td>20.333</td>
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<td>21</td>
</tr>
<tr>
<td>P₉</td>
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<td>(0.363, 11.124)</td>
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<td>P₁₅</td>
<td>(0.939, 25.605)</td>
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<tr>
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<td>P₁₇</td>
<td>(1.263, 34.608)</td>
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<td>P₁₈</td>
<td>(1.389, 38.178)</td>
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</table>
T&D-level optimal dispatches & prices (identical in ideal case and T&D coordination case):

- 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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