Demand response aggregators in microgrid energy trading

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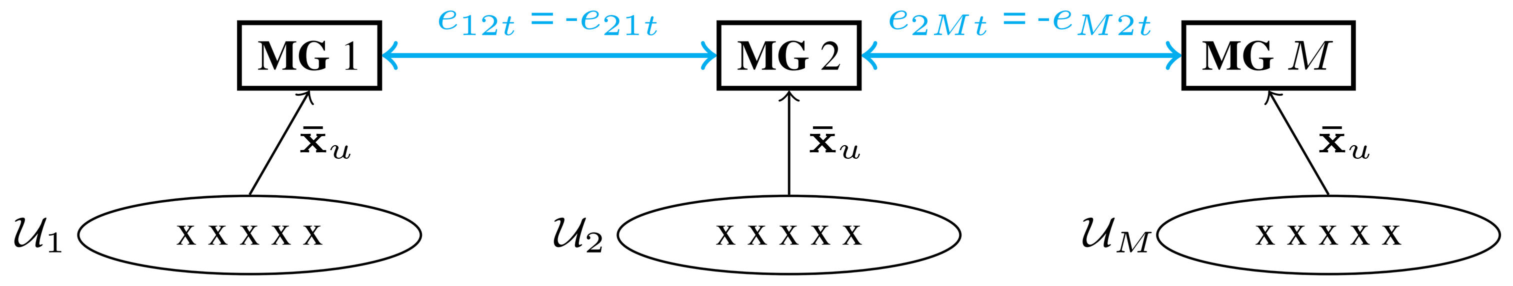
Motivation

- The smart grid will be composed of smaller grids, known as MicroGrids (MGs), in which energy is locally generated and consumed.
  - MGs can operate in islanded mode, i.e., without connection to the main grid.
  - MGs improve reliability in power delivery and efficiency of energy usage.
- Demand Response (DR) programs are another alternative for reducing costs at the MG.
  - Low energy consumers have been traditionally ignored in DR programs due to their reduced impact.
  - *DR Aggregators (AGs)* have recently appeared as new market agents, capable of controlling and managing compounds of small energy consumers, granting omnipresent access to DR programs.

Energy trading without demand response



Problem formulation:

Each MG designs its energy generation and trading strategy, $\mathbf{y}_m = [\mathbf{g}_m,\ \mathbf{e}_m]$, to maximize its own benefit, i.e., the difference between incomes and costs (generation + energy transfer costs):

$$q_m\left(\sum_{u\in\mathcal{U}_m} \mathbf{1}_{LT}^{\mathsf{T}}\bar{\mathbf{x}}_u\right) - \underbrace{\left(\mathbf{1}_T^{\mathsf{T}}\mathbf{c}_m(\mathbf{g}_m) + \mathbf{1}_{T|\mathcal{M}_m|}^{\mathsf{T}}\gamma_m(\mathbf{e}_m)\right)}_{f_m(\mathbf{y}_m)}. \quad (1)$$

Design constraints:

1. The energy generated by the m-th MG must satisfy $\mathbf{g}_m \in \mathcal{G}_m \triangleq \{\mathbf{g}_m \in \mathbb{R}^T : g_{mt} \in [0, \hat{G}_m], \forall t\}$.
2. The traded energy must satisfy $\mathbf{e}_m \in \mathcal{E}_m \triangleq \{\mathbf{e}_m \in \mathbb{R}^{T|\mathcal{M}_m|} : e_{mm't} \in [\check{E}_{mm'}, \hat{E}_{mm'}], \forall t\}$, where $\check{E}_{mm'} \leq 0$ and $\hat{E}_{mm'} \geq 0$ limit the maximum energy sold and bought by MG m to/from MG m', respectively.
3. MG pairs $(m, m') \in \mathcal{M}$ must reach consensus on the traded energy, i.e.,
$$e_{mm't} = -e_{m'mt}, \quad \forall (m,m') \in \mathcal{M}, \forall t \in \mathcal{T}.$$
4. Load balancing: $g_{mt} = \sum_{u\in\mathcal{U}_m} \mathbf{1}_L^{\mathsf{T}}\bar{\mathbf{x}}_{ut} - \mathbf{1}_{|\mathcal{M}_m|}^{\mathsf{T}}\mathbf{e}_{mt}, \forall m, t$.

M-player Generalized Nash Equilibrium Problem (GNEP):

The m-th MG revenue maximization problem can be written as follows:

$$\min_{\mathbf{y}_m \in \mathcal{Y}_m(\mathbf{e}_{-m})} f_m(\mathbf{y}_m), \quad (2)$$

where the feasible set of MG m, $\mathcal{Y}_m$, is coupled with the strategy of the other MGs, $\mathbf{e}_{-m} \triangleq (\mathbf{e}_{m'})_{m'\in\mathcal{M}_m}$:

$$\mathcal{Y}_m(\mathbf{e}_{-m}) \triangleq \left\{\mathbf{g}_m \in \mathcal{G}_m, \mathbf{e}_m \in \mathcal{E}_m : g_{mt} = \sum_{u\in\mathcal{U}_m} \mathbf{1}_L^{\mathsf{T}}\bar{\mathbf{x}}_{ut} - \mathbf{1}_{|\mathcal{M}_m|}^{\mathsf{T}}\mathbf{e}_{mt}, \forall t, e_{mm't} + e_{m'mt} = 0, \forall m' \in \mathcal{M}_m, \forall t\right\}.$$

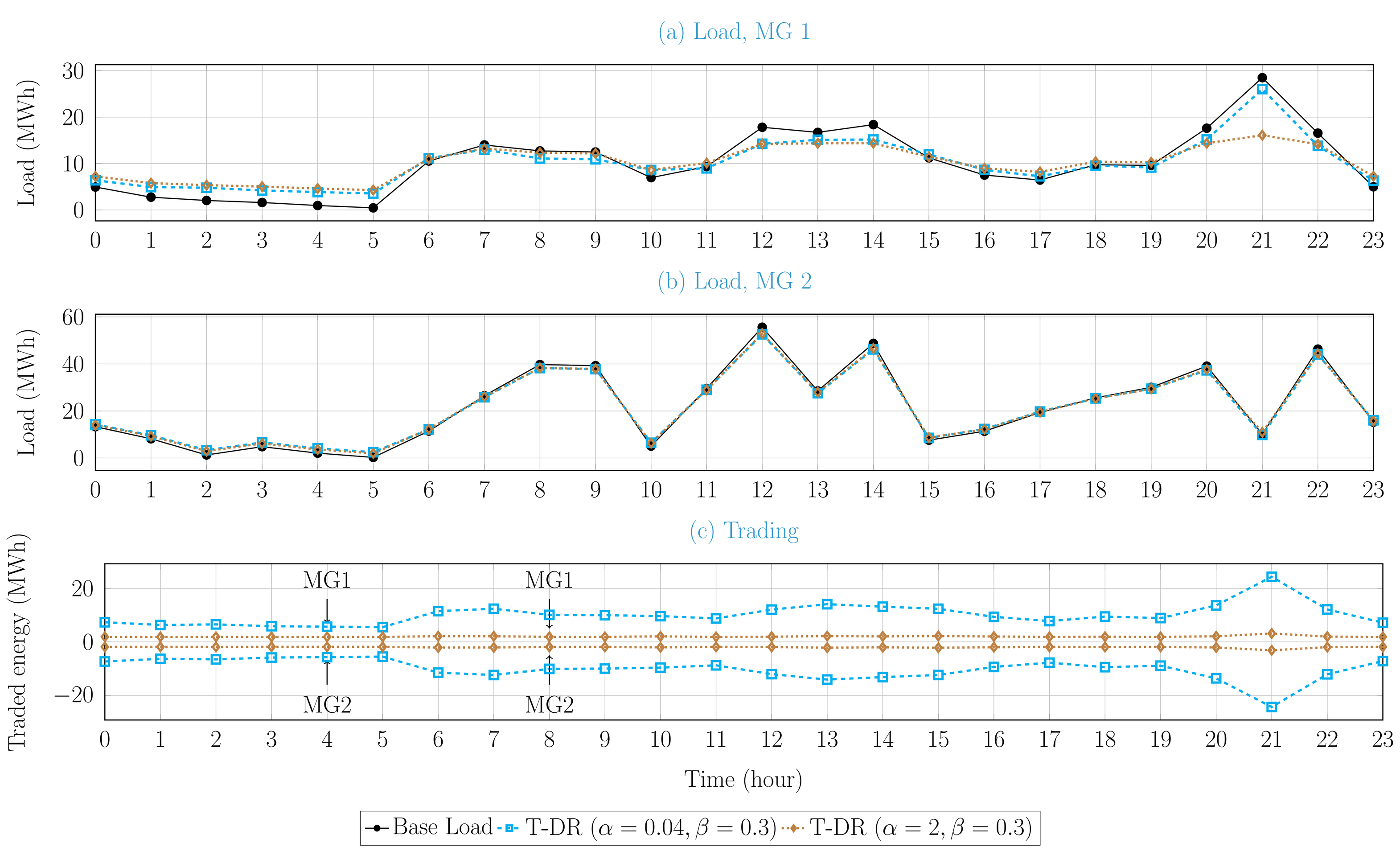
Variational solutions to the GNEP:

Proposition 1. *The variational solutions of the GNEP defined by (2), $\forall m = 1, \ldots, M$, are solutions of the following Network Utility Maximization (NUM) problem:*

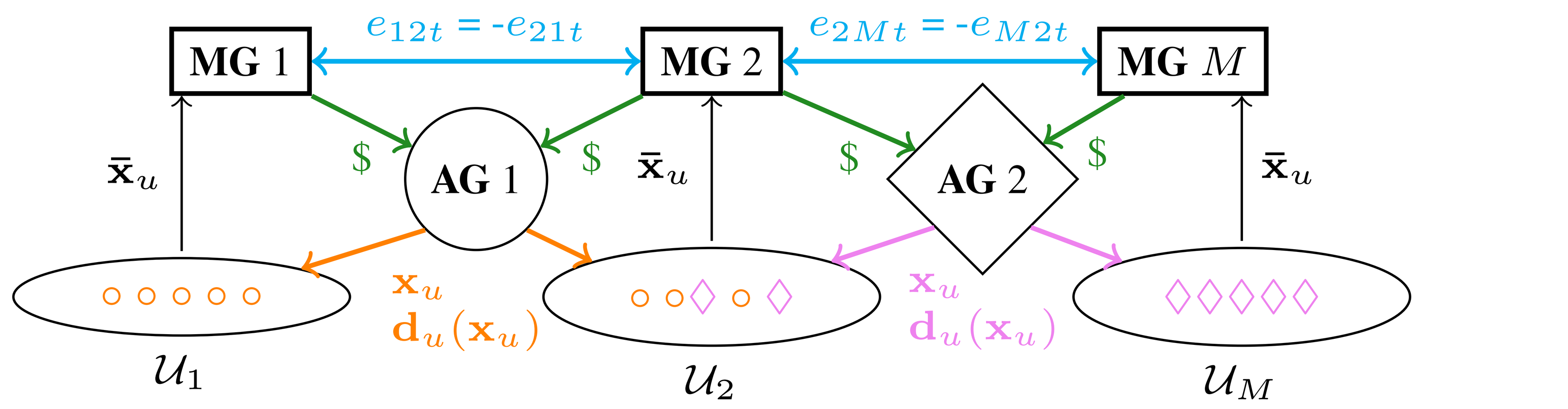
$$\min_{\mathbf{y}\in\mathcal{Y}} \sum_{m=1}^{M} f_m(\mathbf{y}_m), \quad (3)$$

where $\mathbf{y}$ contains the strategy of the different MGs, $\mathbf{y} \triangleq [\mathbf{g},\ \mathbf{e}]$ with $\mathbf{g} = (\mathbf{g}_m)_{m=1}^M$ and $\mathbf{e} = (\mathbf{e}_m)_{m=1}^M$, and where its associated feasible set is $\mathcal{Y} \triangleq \left\{\mathbf{e} \in \prod_{i=1}^M \mathcal{E}_i, \mathbf{g} \in \prod_{i=1}^M \mathcal{G}_i : g_{mt} = \sum_{u\in\mathcal{U}_m} \mathbf{1}_L^{\mathsf{T}}\bar{\mathbf{x}}_{ut} - \mathbf{1}_{|\mathcal{M}_m|}^{\mathsf{T}}\mathbf{e}_{mt}, \forall m, t, e_{mm't} + e_{m'mt} = 0, \forall (m, m') \in \mathcal{M}, \forall t\right\}$. Additionally, the converse implication holds true as well.

- The variational solutions of the GNEP are convenient equilibrium points as they achieve the same performance than a cooperative strategy aimed at minimizing the total cost.
- We obtain the variational solutions of the GNEP by solving (3) in a distributed way by means of dual decomposition.



Energy trading with DR aggregators



Problem formulation:

- AGs can shift user loads from $\bar{\mathbf{x}}_u$ to $\mathbf{x}_u$ to reduce MGs' costs.
- m-th MG offers a fraction $\Gamma_m \in [0, 1]$ of its savings to the AGs. In particular, AG a receives $\Gamma_{am}\Delta f_m(\mathbf{y}_m)$.

Design constraints:

- Design constraints 1, 2, and, 3 in the left column.

4. Load balancing: $g_{mt} = \left(\sum_{a=1}^A \sum_{u\in\mathcal{U}_{am}} \mathbf{1}_L^{\mathsf{T}}\mathbf{x}_{ut}\right) - \mathbf{1}_{|\mathcal{M}_m|}^{\mathsf{T}}\mathbf{e}_{mt}, \forall m, t.$
5. All requested loads must be scheduled within the time horizon $\mathcal{T}$, i.e.,
$$\mathcal{X}_u \triangleq \left\{\mathbf{x}_u \in \mathbb{R}_+^{LT} : \sum_{t\in\mathcal{T}} x_{\ell ut} = \sum_{t\in\mathcal{T}} \bar{x}_{\ell ut}, \forall \ell\right\}.$$

$(M + A)$-player GNEP:

- The m-th MG problem reads

$$\min_{\mathbf{y}_m} \quad f_m(\mathbf{y}_m)(1-\Gamma_m) \quad (4a)$$
$$\text{s.t.} \quad \mathbf{y}_m \in \mathcal{Y}_m(\mathbf{e}_{-m}, (\tilde{\mathbf{x}}_a)_{a=1}^A), \quad (4b)$$

where $\mathcal{Y}_m(\mathbf{e}_{-m}, (\tilde{\mathbf{x}}_a)_{a=1}^A) = \left\{\mathbf{g}_m \in \mathcal{G}_m, \mathbf{e}_m \in \mathcal{E}_m : e_{mm't} + e_{m'mt} = 0,\ \forall m' \in \mathcal{M}_m, \forall t, g_{mt} = \left(\sum_{a=1}^A \sum_{u\in\mathcal{U}_{am}} \mathbf{1}_L^{\mathsf{T}}\mathbf{x}_{ut}\right) - \mathbf{1}_{|\mathcal{M}_m|}^{\mathsf{T}}\mathbf{e}_{mt}, \forall t\right\}$.

- The problem of the a-th AG problem, whose actions are $\tilde{\mathbf{x}}_a \triangleq (\mathbf{x}_u)_{u\in\cup_{m=1}^M \mathcal{U}_{am}}$, is:

$$\min_{\tilde{\mathbf{x}}_a} \quad \sum_{m=1}^{M} \sum_{u\in\mathcal{U}_{am}} \mathbf{1}_{LT}^{\mathsf{T}}\mathbf{d}_u(\mathbf{x}_u) \quad (5a)$$
$$\text{s.t.} \quad \tilde{\mathbf{x}}_a \in \tilde{\mathcal{Y}}_a(\mathbf{e}, \tilde{\mathbf{x}}_{-a}), \quad \text{where} \quad (5b)$$

$$\tilde{\mathcal{Y}}_a(\mathbf{y}, \tilde{\mathbf{x}}_{-a}) = \left\{\mathbf{x}_u \in \mathcal{X}_u, u \in \cup_{m=1}^M \mathcal{U}_{am} : g_{mt} = \left(\sum_{a=1}^A \sum_{u\in\mathcal{U}_{am}} \mathbf{1}_L^{\mathsf{T}}\mathbf{x}_{ut}\right) - \mathbf{1}_{|\mathcal{M}_m|}^{\mathsf{T}}\mathbf{e}_{mt}, \forall m, t\right\}.$$

Variational solutions:

Proposition 2. *The variational solutions of the GNEP in (4) and (5) are equivalent to the solutions of the following optimization problem*

$$\min_{\mathbf{z}\in\mathcal{Z}} \quad \sum_{m=1}^{M} f_m(\mathbf{y}_m)(1-\Gamma_m) + \sum_{a=1}^{A}\sum_{m=1}^{M}\sum_{u\in\mathcal{U}_{am}} \mathbf{1}_{LT}^{\mathsf{T}}\mathbf{d}_u(\mathbf{x}_u) \quad (6a)$$
$$\text{s.t.} \quad e_{mm't} + e_{m'mt} = 0, \quad \forall (m,m') \in \mathcal{M}, \forall t \quad (6b)$$
$$g_{mt} + \mathbf{1}_{|\mathcal{M}_m|}^{\mathsf{T}}\mathbf{e}_{mt} - \sum_{a=1}^{A}\sum_{u\in\mathcal{U}_{am}} \mathbf{1}_L^{\mathsf{T}}\mathbf{x}_{ut} = 0, \forall m, t. \quad (6c)$$

where $\mathbf{z}$ stacks the vectors $\mathbf{y}_m$, $\forall m$, and $\tilde{\mathbf{x}}_a$, $\forall a$, with feasible set

$$\mathcal{Z} \triangleq \{\mathbf{z} : \mathbf{g}_m \in \mathcal{G}_m, \mathbf{e}_m \in \mathcal{E}_m, \mathbf{x}_u \in \mathcal{X}_u, \forall m, u\}.$$

Simulation Setup

- $M = 2$ MGs and one AG, slot duration is set to one hour.
- Oil generators with: $\mathcal{G}_1 = [0, 12]$ MWh and $\mathcal{G}_2 = [0, 100]$ MWh, $c_{1t}(x) = 86.39 + 56.56x + 0.33x^2$ and $c_{2t}(x) = 781.52 + 43.66x + 0.05x^2$.
- $\mathcal{E}_m = [-100, 100]$ MWh.
- $q_m = 200\$/\text{MWh}$.
- $\gamma_{mm't}(x) = \alpha x^2$, $\forall m, m', t$, where α is a constant in $\$/\text{MWh}^2$.
- $d_{\ell ut}(x_{\ell ut}) = \beta(x_{\ell ut} - \bar{x}_{\ell ut})^2$, $\forall \ell, u, t$, where β is a constant in $\$/(\text{MWh})^2$.