A Distributed Constraint Optimization Approach to the Economic Dispatch with Demand Response

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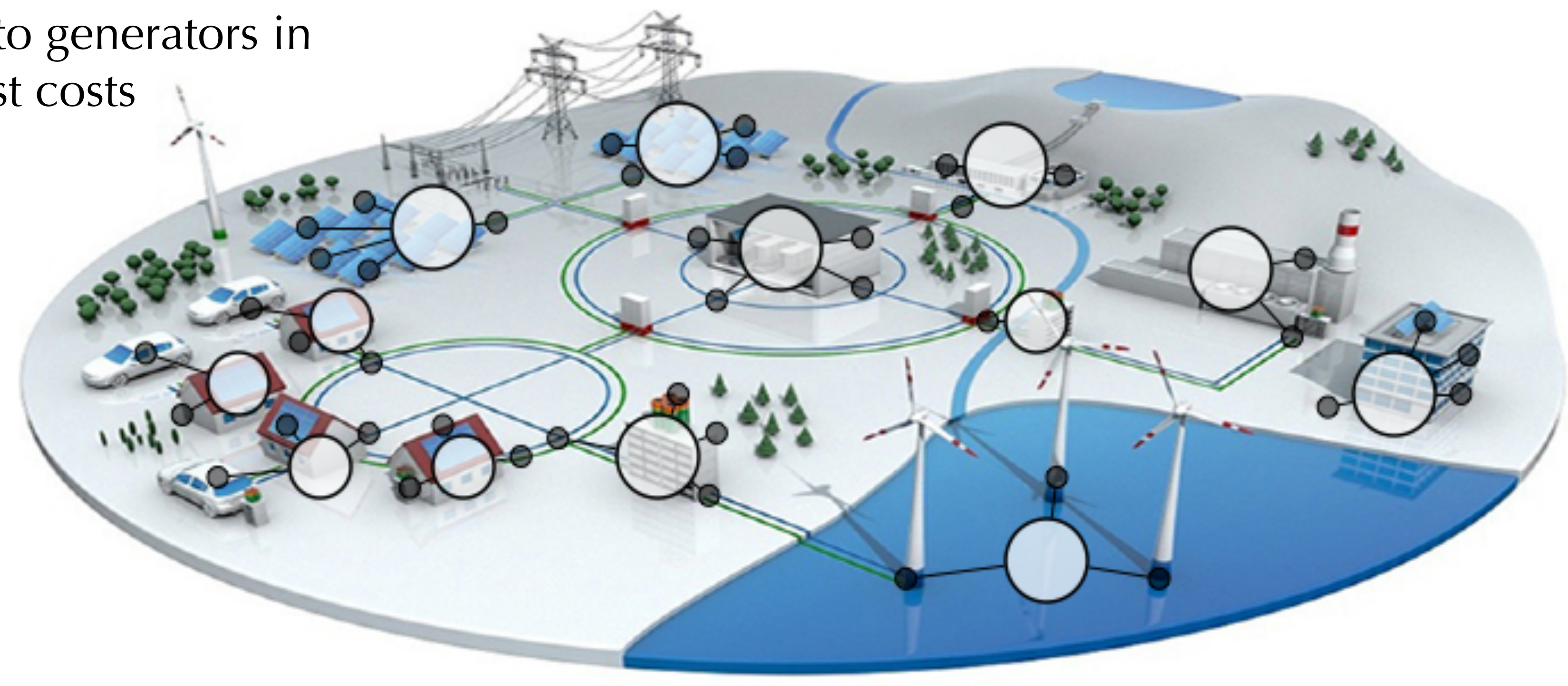
Economic Dispatch and Demand Response in the Smart Grid

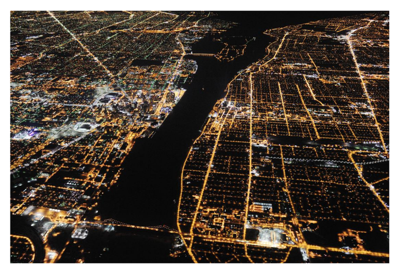
Economic Dispatch (ED): Power allocation to generators in order to meet the power load with the lowest costs

Demand Response (DR): Enables customers to make informed decisions regarding energy consumption

ED and DR are solved in isolation despite the clear inter-dependencies between them

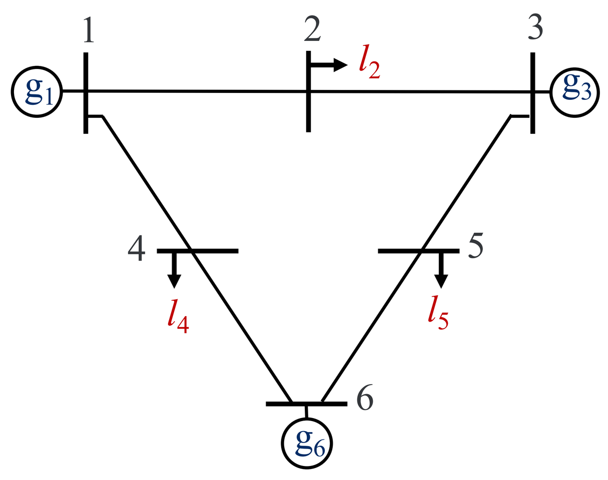


We propose a ED DR integrated model aimed at **maximize** the benefits of customers and **minimize** the generation costs



Power Grid

- Power generators $g \in \mathcal{G}$
- Power loads $l \in \mathcal{L}$
- Transmission lines
- Representation: Graph G = (V, E)
- Buses (network nodes)
- Lines (network edges)



Distributed ED with DR (D-EDDR)

- Given a time horizon H
- Load predictions $\dot{L}^t_l$ for each and load l time t

Maximize:
$$\sum_{t=1}^{H} \alpha^t \left(\sum_{l \in \mathcal{L}} u_l(L^t_l) - \sum_{g \in \mathcal{G}} c_g(G^t_g) \right)$$

Where:
$$c_g(G^t_g) = \alpha_g G^t_g + \beta_g (G^t_g)^2 + |\epsilon_g \sin(\phi_g(G^{min}_g - G^t_g))|$$
Non linear components
$$u_l(L^t_l) = \begin{cases} \beta_l L^t_l - \frac{1}{2}\alpha_l (L^t_l)^2 & \text{if } L^t_l \le \frac{\beta_l}{\alpha_l} \\ \frac{1}{2}\frac{(L^t_l)^2}{\beta_l} & \text{otherwise} \end{cases}$$

Subject to:

$G^{min}_g \le G^t_g \le G^{max}_g$	$\forall g \in \mathcal{G}; 0 < t \le H$	(4) Generators limits
$L^{min}_l \le L^t_l \le L^{max}_l$	$\forall l \in \mathcal{L}; 0 < t \le H$	(5) Loads limits
$L^t_l \le \dot{L}^t_l$	$\forall l \in \mathcal{L}; 0 < t \le H$	(6) Load predictions
$\sum_{l \in \mathcal{L}} L^t_l - \sum_{g \in \mathcal{G}} G^t_g = 0$	$0 < t \le H$	(7) Power supply-demand balance
$\vec{L}^t_{\mathcal{L}} - \vec{G}^t_{\mathcal{G}} - \hat{B}\vec{\theta}^t = 0$	$0 < t \le H$	(8-9) DC power flow
$\lvert f^t_{ij} \rvert \le f^{max}_{ij}$	$\forall (i,j) \in \mathcal{E}; 0 < t \le H$	
$f^t_{ij} = B_{ij}(\theta^t_i - \theta^t_j)$	$\forall (i,j) \in \mathcal{E}; 0 < t \le H$	(10) Lines thermal limits
$G^{t+1}_g = G^t_g + \Delta^t_{p_g}$	$\forall g \in \mathcal{G}; 0 < t \le H-1$	(11-12) Generators ramp rate
$-\Delta^{max}_{p_g} \le \Delta^t_{p_g} \le \Delta^{max}_{p_g}$	$\forall g \in \mathcal{G}; 0 < t \le H$	

Relaxation

- Ignore the line thermal limit constraints (typically, violations are allowed for small time intervals).
- Introduce soft constraints λ^t_{ij} with a penalty on the degree of the line thermal limit constraint violation.

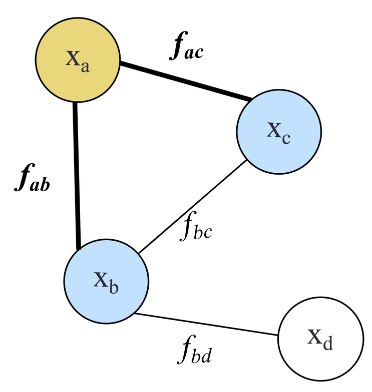
Maximize:
$$\sum_{t=1}^{H} \alpha^t \left(\sum_{l \in \mathcal{L}} u_l(L^t_l) - \sum_{g \in \mathcal{G}} c_g(G^t_g) - \sum_{(i,j) \in \mathcal{E}} \lambda^t_{ij} \right)$$

Distributed Constraint Optimization

- ***X***: Set of variables
- ***D***: Set of finite domains for each variable
- ***F***: Set of weighted constraints between variables
- ***A***: Set of agents, controlling the variables in ***X***

- GOAL: Find a cost maximal assignment

$$\mathbf{x}^* = \arg\max_{\mathbf{x}} \sum_{f \in \mathbf{F}} f(\mathbf{x}|_{\mathrm{scope}(f)})$$



Dynamic DCOP mapping

D-EDDR

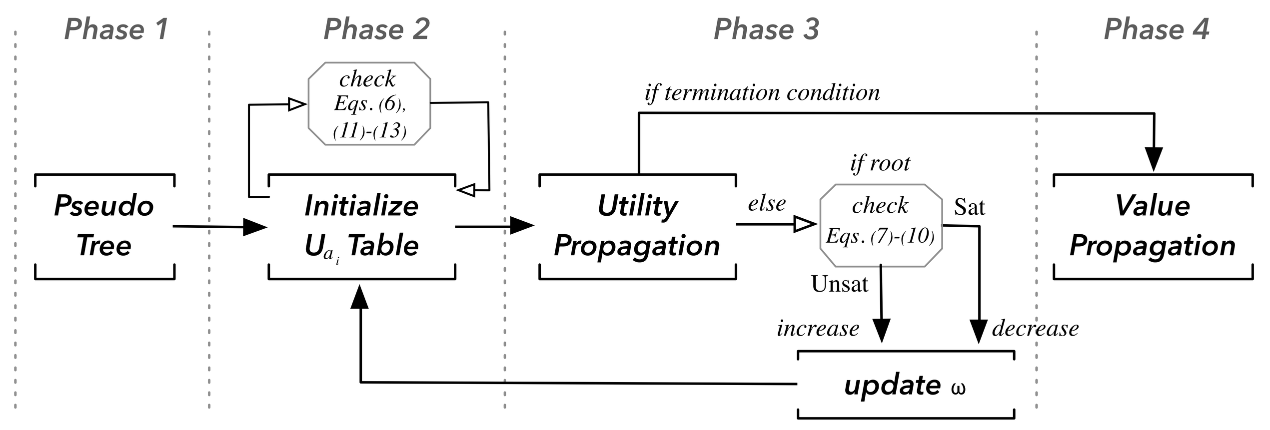
- Time steps
- Bus $b_i \in \mathcal{G} \cup \mathcal{L}$.
- Generator g_j (of b_i)
- Dispatchable load l_j (of b_i)
- Flow f_{ij}
- EDDR constraints
- *EDDR Objective*

DCOP

- Time steps of the dynamic DCOP
- Agent $a_i \in$ **A**
- Variable $x_j \in$ **X** (controlled by a_i) - Power injected
- Variable $x_j \in$ **X** (controlled by a_i) - Power withdrawn
- Environment variable
- DCOP hard constraints (within same DCOP P_i and across DCOPs P_i P_{i+1}
- Decomposed in $| \mathcal{G} \cup \mathcal{L} |$ unary functions

Solution Approach: Deeds

- Inference-based DCOP iterative solution



- Fine granularity in the domain representation (0.01 PU)
- Large number of combinations of power injections and withdrawn (big tables)
- Exploits Graphic Processing Unit (GPU) parallelism [Fioretto et al . CP-15]

(a)

G^1_1	L^1_1	…	f^1_{12}	f^1_{13}	…	Utility
10	23	…	21.3	1.3	…	70.4
9	23	…	20.3	2.2	…	71.3
…	…	…	…	…	…	…

G^1_2	L^1_2	…	f^1_{12}	f^1_{13}	…	Utility
5	10	…	1.6	2.2	…	10.0
6	10	…	3.2	-4.4	…	20.0
…	…	…	…	…	…	…

(b)

(c)

$G^1_{1\,2}$	$L^1_{1\,2}$	…	f^1_{12}	f^1_{13}	…	Utility
15	33	…	22.9	3.5	…	80.4
16	33	…	24.5	-3.1	…	90.4
15	33	…	21.9	4.4	…	81.3
15	33	…	23.5	-2.2	…	91.3
…	…	…	…	…	…	…

Experiments

- 5 non convex IEEE domains
- Evaluation Metrics:
  - *Simulated runtime*
  - *Solution quality (normalized social welfare)*
  - *Solution stability (Matlab Simulink SimPowerSystem) on the IEEE 30-Bus system (full load scenario)*

System	|G|	|L|	|E|
IEEE 5-Bus	1	5	7
IEEE 14-Bus	5	11	20
IEEE 30-Bus	6	27	41
IEEE 57-Bus	7	42	80
IEEE 118-Bus	54	91	177

	Simulated Runtime (sec)								Normalized Quality			
	CPU Implementation				GPU Implementation							
IEEE Buses H_{opt}	1	2	3	4	1	2	3	4	1	2	3	4
5	0.010	0.044	3.44	127.5	0.025 (0.4x)	0.038 (1.2x)	0.128 (26.9x)	2.12 (60.2x)	0.8732	0.8760	0.9569	1.00
14	0.103	509.7	–	–	0.077 (1.3x)	3.920 (130x)	61.70 (n/a)	–	0.6766	0.8334	1.00	–
30	0.575	9084	–	–	0.241 (2.4x)	79.51 (114x)	–	–	0.8156	1.00	–	–
57	4.301	–	–	–	0.676 (6.4x)	585.4 (n/a)	–	–	0.8135	1.00	–	–
118	174.4	–	–	–	4.971 (35.1x)	–	–	–	1.00	–	–	–

Main Results:

- *Solution quality improves as H increases*
- *GPU speedups up to 1 order of magnitude*
- *Satisfiable instances within 4 iterations*
- *System stability after deployment of ED-DR s olution (frequency deviation within 0.05 Hz)*
- *Total load reduction (up to 68.5%*
- *Frequency response of the ED-DR converges faster than that of ED only*